

Search for charged Higgs bosons through the violation of lepton universality in $t\bar{t}$ events using pp collision data at $\sqrt{s} = 7$ TeV with the ATLAS experiment



The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: In several extensions of the Standard Model, the top quark can decay into a bottom quark and a light charged Higgs boson H^+ , $t \rightarrow bH^+$, in addition to the Standard Model decay $t \rightarrow bW$. Since W bosons decay to the three lepton generations equally, while H^+ may predominantly decay into $\tau\nu$, charged Higgs bosons can be searched for using the violation of lepton universality in top quark decays. The analysis in this paper is based on 4.6 fb^{-1} of proton-proton collision data at $\sqrt{s} = 7$ TeV collected by the ATLAS experiment at the Large Hadron Collider. Signatures containing leptons (e or μ) and/or a hadronically decaying τ (τ_{had}) are used. Event yield ratios between $e + \tau_{\text{had}}$ and $e + \mu$, as well as between $\mu + \tau_{\text{had}}$ and $\mu + e$, final states are measured in the data and compared to predictions from simulations. This ratio-based method reduces the impact of systematic uncertainties in the analysis. No significant deviation from the Standard Model predictions is observed. With the assumption that the branching fraction $\mathcal{B}(H^+ \rightarrow \tau\nu)$ is 100%, upper limits in the range 3.2%–4.4% can be placed on the branching fraction $\mathcal{B}(t \rightarrow bH^+)$ for charged Higgs boson masses m_{H^+} in the range 90–140 GeV. After combination with results from a search for charged Higgs bosons in $t\bar{t}$ decays using the $\tau_{\text{had}} + \text{jets}$ final state, upper limits on $\mathcal{B}(t \rightarrow bH^+)$ can be set in the range 0.8%–3.4%, for m_{H^+} in the range 90–160 GeV.

KEYWORDS: Hadron-Hadron Scattering

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1 Introduction

Several non-minimal Higgs scenarios, e.g. Two Higgs Doublet Models (2HDM) [1] predict the existence of charged Higgs bosons (H^+ and H^-).¹ Their observation would clearly indicate physics beyond the Standard Model (SM), because this theory contains no elementary charged scalar particle. In several models, e.g. a type-II 2HDM describing the Higgs sector of the Minimal Supersymmetric extension of the Standard Model (MSSM) [2–6], the main production mode for charged Higgs bosons with a mass m_{H^+} smaller than the top quark mass (m_{top}) is through top quark decays $t \rightarrow bH^+$. The dominant source of top quarks at the Large Hadron Collider (LHC) is through $t\bar{t}$ production.²

The combined LEP lower limit on the charged Higgs boson mass is about 90 GeV [7]. Results from direct searches for charged Higgs bosons decaying via $H^+ \rightarrow \tau\nu$ using 4.6 fb⁻¹ of LHC data were recently presented by the ATLAS collaboration [8], with upper limits on the branching fraction $\mathcal{B}(t \rightarrow bH^+)$ between 5% and 1% for charged Higgs boson masses ranging from 90 GeV to 160 GeV, respectively. Using about 2 fb⁻¹ of LHC data, the CMS collaboration established upper limits on $\mathcal{B}(t \rightarrow bH^+)$ in the range 4–2% for charged Higgs boson masses between 80 GeV to 160 GeV [9]. In all of these measurements, as well as in this paper (unless otherwise specified), the assumption $\mathcal{B}(H^+ \rightarrow \tau\nu) = 100\%$ is made.

¹In the following, charged Higgs bosons are denoted H^+ , with the charge-conjugate H^- always implied. Hence, τ denotes a positively charged τ lepton.

²Since the cross section for H^+ production from events containing a single top quark is much smaller, this production mode is not considered here.

This paper uses an alternative technique [10] for H^+ searches in the mass range 90–160 GeV. Instead of using the shape of discriminating variables in order to search for a local excess of events above the predicted SM background, this analysis is based on the measurement of a ratio of event yields between two $t\bar{t}$ final states, which in turn allows for the cancellation of most of the systematic uncertainties. In top quark decays, W bosons decay equally to leptons of the three generations, while H^+ may decay predominantly into $\tau\nu$. Hence, an excess of $t\bar{t}$ events with at least one hadronically decaying τ lepton (τ_{had}) in the final state, as compared to the rate for $t\bar{t}$ events with only electrons and/or muons, is a signature for charged Higgs bosons. A measurement of event yield ratios R_l for $t\bar{t} \rightarrow b\bar{b} + l\tau_{\text{had}} + N\nu$ and $t\bar{t} \rightarrow b\bar{b} + l' + N\nu$, where $N\nu$ stands for any number of neutrinos and where l and l' are electrons and muons, with $l \neq l'$, is performed:

$$R_l = \frac{\mathcal{B}(t\bar{t} \rightarrow b\bar{b} + l\tau_{\text{had}} + N\nu)}{\mathcal{B}(t\bar{t} \rightarrow b\bar{b} + l' + N\nu)}. \tag{1.1}$$

This study is performed in a model-independent way, and so exclusion limits are given in terms of $\mathcal{B}(t \rightarrow bH^+)$, as well as in the m_h^{max} scenario [11] of the MSSM. The results are based on 4.6 fb^{-1} of data from pp collisions at $\sqrt{s} = 7 \text{ TeV}$, collected in 2011 with the ATLAS experiment [12] at the LHC. These data, as well as the simulated samples used in the analysis, are the same as in ref. [8] and are described briefly in section 2. Then, in section 3, an event selection aimed at collecting a data sample enriched in $t\bar{t}$ events is presented, together with the data-driven methods to estimate the backgrounds due to misidentified electrons, muons and hadronically decaying τ leptons. Exclusion limits in terms of $\mathcal{B}(t \rightarrow bH^+)$ and $\tan\beta$ are discussed in section 4, based on the measured ratios among event yields in $\tau_{\text{had}}+\text{lepton}$ and dilepton final states. Finally, a summary is given in section 5.

2 ATLAS data and simulated events

The ATLAS detector [12] consists of an inner tracking detector with coverage in pseudorapidity³ up to $|\eta| = 2.5$, surrounded by a thin 2 T superconducting solenoid, a calorimeter system extending up to $|\eta| = 4.9$ for the detection of electrons, photons and hadronic jets, and a large muon spectrometer extending up to $|\eta| = 2.7$ that measures the deflection of muon tracks in the field of three superconducting toroid magnets. A three-level trigger system is used, which reduces the recorded event rate to about 300 Hz.

In ATLAS, electrons are reconstructed by matching clustered energy deposits in the electromagnetic calorimeter to tracks reconstructed in the inner detector, and muons are required to contain matching inner detector and muon spectrometer tracks. The combination of all sub-systems provides precise lepton measurements in the pseudorapidity range

³ATLAS 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 upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$.

$|\eta| < 2.5$. Jets, as well as the magnitude of the missing transverse momentum, E_T^{miss} , are reconstructed using energy deposits over the full coverage of the calorimeters, up to $|\eta| = 4.9$. The anti- k_t algorithm [13, 14] with a radius parameter value of $R = 0.4$ is used for jet reconstruction. At least 75% of the tracks associated to a jet (weighted by their transverse momenta) must point to the primary vertex, corresponding to the hardest interaction. This requirement on the “Jet Vertex Fraction” [15] allows the identification of jets originating from the hard-scatter interaction. An algorithm combining impact-parameter information with the explicit observation of a secondary vertex [16] is used in order to identify jets initiated by b -quarks, within $|\eta| < 2.4$. The working point chosen for this study corresponds to an average efficiency of about 70% for b -jets with $p_T > 20$ GeV in $t\bar{t}$ events and a rejection factor of about 130 for light-quark jets. In order to reconstruct hadronically decaying τ leptons, anti- k_t jets with either one or three associated tracks, depositing $E_T > 10$ GeV in the calorimeter, are considered as τ candidates [17]. Dedicated algorithms are used to reject electrons and muons. The τ candidates are further required to have a visible transverse momentum $p_T^\tau > 20$ GeV and to be within $|\eta| < 2.3$. The hadronic τ decays are identified using a likelihood criterion designed to discriminate against quark- and gluon-initiated jets. The working point chosen for this study corresponds to an efficiency of about 30% for hadronically decaying τ leptons with $p_T^\tau > 20$ GeV in $Z \rightarrow \tau\tau$ events, leading to a rejection factor of about 100–1000 for jets. Selected τ candidates fulfilling the identification criteria are referred to as “ τ jets”. When objects selected using the criteria above overlap geometrically, the following procedures are applied, in this order: muons are rejected if found within $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.4$ of any jet with $p_T > 25$ GeV; a τ candidate is rejected if found within $\Delta R < 0.4$ of a b -tagged jet, or within $\Delta R < 0.2$ of a selected muon or electron; jets are removed if they are within $\Delta R < 0.2$ of a selected τ jet or electron.

The same full 2011 data set and simulated samples as the analysis in ref. [8] are used, corresponding to an integrated luminosity of 4.6 fb^{-1} , with an uncertainty of 3.9% [18, 19]. In addition to the SM pair production and decay of top quarks, $t\bar{t} \rightarrow b\bar{b}W^+W^-$,⁴ the background processes include the production of single top quark, W +jets, Z/γ^* +jets, diboson, and multi-jet events. Except for the last, which is estimated using data-driven methods, the SM backgrounds are determined using the simulated samples summarised in table 1. In addition to the SM background samples, three types of signal samples are produced with PYTHIA 6.425 [20] for $90 \text{ GeV} < m_{H^+} < 160 \text{ GeV}$: $t\bar{t} \rightarrow b\bar{b}H^+W^-$, $t\bar{t} \rightarrow b\bar{b}H^-W^+$ and $t\bar{t} \rightarrow b\bar{b}H^+H^-$, where charged Higgs bosons decay as $H^\pm \rightarrow \tau\nu$. TAUOLA 1.20 [21] is used for τ decays, and PHOTOS 2.15 [22] is used for photon radiation from charged leptons. All generated events are propagated through a detailed GEANT4 simulation [23, 24], and they are reconstructed using the same algorithms as the data.

3 Event selection and background determination

This analysis uses events passing a single-lepton trigger with an E_T threshold of 20 GeV or 22 GeV for electrons and a p_T threshold of 18 GeV for muons. In order to select a sample

⁴In the simulated SM $t\bar{t}$ events, all leptonic W decay modes have the same branching fraction (10.8%).

Process	Generator	Cross section [pb]
SM $t\bar{t}$ with at least one lepton $\ell = e, \mu, \tau$	MC@NLO 4.01 [25]	91 [26]
Single top quark t -channel (with ℓ)	AcerMC 3.8 [27]	21 [28]
Single top quark s -channel (with ℓ)	MC@NLO 4.01 [25]	1.5 [29]
Single top quark Wt -channel (inclusive)	MC@NLO 4.01 [25]	16 [30]
$W \rightarrow \ell\nu$	ALPGEN 2.13 [31]	3.1×10^4 [32]
$Z/\gamma^* \rightarrow \ell\ell$ with $m(\ell\ell) > 10$ GeV	ALPGEN 2.13 [31]	1.5×10^4 [33]
WW	HERWIG 6.520 [34]	17 [35]
ZZ	HERWIG 6.520 [34]	1.3 [35]
WZ	HERWIG 6.520 [34]	5.5 [35]
H^+ signal with $\mathcal{B}(t \rightarrow bH^+) = 3\%$	PYTHIA 6.425 [20]	9.9

Table 1. Cross sections for the simulated processes and the generators used to model them. All background cross sections are normalised to next-to-next-to-leading-order (NNLO) predictions, except for diboson event production where the next-to-leading-order prediction (NLO) is used. For the diboson events, a filter is applied at the generator level, by requiring at least one electron or muon with $p_T > 10$ GeV and $|\eta| < 2.8$.

enriched in $t\bar{t}$ events, the following requirements are made:

- one charged lepton l (e, μ) having $E_T > 25$ GeV (e) or $p_T > 25$ GeV (μ) and matched to the corresponding trigger object;
- at least two jets having $p_T > 20$ GeV and $|\eta| < 2.4$, including exactly two b -tags;
- either exactly one τ jet with $p_T^\tau > 25$ GeV and $|\eta| < 2.3$ with no additional charged lepton, or exactly one additional charged lepton l' with E_T or p_T above 25 GeV and a different flavour than the trigger-matched lepton;
- $E_T^{\text{miss}} > 40$ GeV.

At this stage, the selected events are classified into two categories according to the single-lepton trigger that they fire: an electron trigger (EL) or a muon trigger (MU). Each category contains τ_{had} +lepton and dilepton ($l'l'$) events. The lepton appearing first in the final state is, by convention, matched to the corresponding trigger object. The EL category therefore consists of $e + \tau_{\text{had}}$ and $e + \mu$ events, while the MU category contains $\mu + \tau_{\text{had}}$ and $\mu + e$ events. Events firing both a single-electron trigger and a single-muon trigger are assigned to both categories, and accounted for in the combined limit setting, see section 4.3.

The analysis uses the generalised transverse mass m_{T2}^H [36] as a selection variable. By construction, it gives an event-by-event lower bound on the mass of the charged (W or Higgs) boson produced in the top quark decay. Hence, it is larger than the true charged Higgs boson mass m_{H^+} and smaller than m_{top} . For incorrect pairings of τ jets or leptons with b -jets, the numerical determination of m_{T2}^H may fail, hence only events with $m_{T2}^H > 0$ are kept in the following.

3.1 Backgrounds due to misidentified electrons and muons

A significant background for the search described in this paper consists of events with reconstructed electrons and muons arising from the semileptonic decay of hadrons with b - or c -quarks, from the decay-in-flight of π or K mesons and, in the case of electrons, from π^0 mesons, photon conversions or shower fluctuations. These are referred to as “misidentified leptons” in the following. Two data samples are defined, which differ only in the lepton identification criteria. The *tight* sample corresponds to the selection used in the analysis and contains mostly events with real leptons. The *loose* sample is obtained by loosening the isolation and identification requirements, and it contains mostly events with misidentified leptons.⁵ The efficiencies p_r and p_m for a real or misidentified lepton, respectively, to be detected as a tight lepton, are determined from data, with the same method as in ref. [8]. In the final parameterisation of p_r and p_m , dependencies on the pseudorapidity of the lepton, its distance ΔR to the nearest jet and the leading jet p_T are taken into account. Based on these efficiencies, the number of misidentified leptons passing the final requirements can be calculated by weighting each event in the data sample with one loose lepton, according to the following per-lepton weights w_l :

- for a loose but not tight lepton, $w_{lL} = \frac{p_m p_r}{(p_r - p_m)}$;
- for a tight lepton, $w_{lT} = \frac{p_m (p_r - 1)}{(p_r - p_m)}$.

3.2 Backgrounds due to misidentified τ jets

About 51% of the simulated $t\bar{t}$ events in the $\tau_{\text{had}} + \text{lepton}$ final state contain a τ jet matched to a hadronically decaying τ lepton at the generator level. In the other events, the τ jet is called “misidentified”. It originates from leptons (e , μ) in 3% of the simulated events and hadronic objects (initiated by light quarks, b -quarks or gluons) in 46%. Data-driven methods are used in order to determine the probability of misidentification from electrons and hadronic jets. In the case of electrons, the misidentification probabilities are measured using a $Z \rightarrow ee$ control region in the data [17] and then applied to the simulated events, as in the analysis in ref. [8]. The majority of misidentified τ jets in the final event selection originate from jets, for which the misidentification probability depends on the initial parton (light quark, heavy-flavour quark or gluon). All jet types occur in $t\bar{t}$ events, and it is not possible to accurately predict the fraction of each of them, potentially leading to a large systematic uncertainty on the jet $\rightarrow \tau_{\text{had}}$ misidentification probability. However, the influence of all jet types other than light-quark jets can effectively be eliminated by categorising all events in terms of the charge of the lepton relative to the τ jet as opposite-sign (OS) or same-sign (SS) events. All processes with gluon and b -quark jets produce positively and negatively charged misidentified τ objects at the same rate. On the other hand, the light-quark jet component in SS events represents both charge misreconstruction and quarks which fragment such that the leading charged particle does not have the same charge as the initial quark. Giving a negative weight to the SS events therefore cancels, on

⁵By construction, the tight sample is a subset of the loose sample.

average, the gluon and heavy-flavour-quark jet contributions from the OS events, leaving only light-quark jets misidentified as τ jets.

The rate at which light-quark jets are misidentified as τ candidates is derived using a region enriched with $W + >2$ jets events⁶ in the data, selected by requiring:

- exactly one electron or muon with E_T or p_T larger than 25 GeV;
- at least one τ candidate;
- at least two jets in addition to the τ candidate(s), none of them being b -tagged;
- $E_T^{\text{miss}} > 40$ GeV.

In order to reduce the contribution from events with a true τ lepton, mostly from Z +jets events, a requirement on the transverse mass m_T is made:

$$m_T = \sqrt{2p_T^l E_T^{\text{miss}}(1 - \cos \Delta\phi_{l,\text{miss}})} > 30 \text{ GeV}, \quad (3.1)$$

where $\Delta\phi_{l,\text{miss}}$ is the azimuthal angle between the lepton and the direction of the missing momentum. The $W + >2$ jets events are classified as OS and SS events using the charges of the lepton and the τ candidate. Figure 1 shows the m_T distribution for OS, SS and OS-SS events fulfilling the $W + >2$ jets selection. This demonstrates the cancellation of heavy-flavour-quark and gluon contributions.

The number of tracks associated to jets misidentified as τ candidates is found to be poorly modelled in simulation. Events in the data tend to have fewer τ candidates with one or three tracks (this explains the differences between data and simulation in figure 1). In order to correct the τ candidate selection efficiencies in simulation, τ track multiplicity scale factors are derived using OS-SS events fulfilling the $W + >2$ jets selection, and are then applied to all jets misidentified as τ candidates in the simulation: 0.71 ± 0.03 for 1-track τ candidates; 0.92 ± 0.03 for 3-track τ candidates, where the errors are only statistical.

The probability for a light-quark jet to be misidentified as a τ jet is measured in the data and is binned in p_T^j , the number of associated tracks N_{track}^j (one or three), and the number of tracks $N_{\text{track}}^{\text{iso}}$ found within $0.2 < \Delta R < 0.4$ of the τ candidate. For each bin, the jet $\rightarrow \tau_{\text{had}}$ misidentification probability is defined as the number of objects passing the τ identification based on the likelihood criterion divided by the number prior to requiring identification. OS events are given a weight +1 and SS events are given a weight -1, in both the numerator and denominator of the jet $\rightarrow \tau_{\text{had}}$ misidentification probability. After OS-SS subtraction, the selected events mostly contain τ candidates coming from light-quark jets and, to a much lesser extent, electrons, muons, and true hadronically decaying τ leptons. Figure 2 shows the measured values of the jet $\rightarrow \tau_{\text{had}}$ misidentification probability in $W + >2$ jets events selected from the data, after OS-SS subtraction. These are used to scale all simulated events in the signal region. Events fulfilling the requirements listed in the beginning of this section, in which the selected τ object originates from a jet (of any type), are weighted by the misidentification probabilities. An additional weighting factor (+1 for OS events and -1 for SS events) is then used to perform the OS-SS subtraction.

⁶The leading process in this control region is $gq \rightarrow Wq'$.

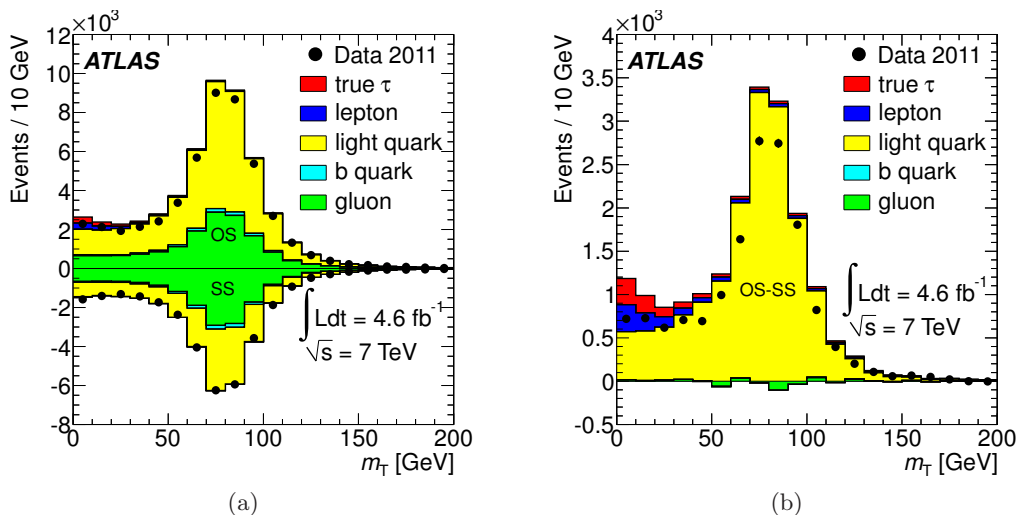


Figure 1. Distributions of the transverse mass m_T for events fulfilling the $W + >2$ jets selection, without the requirement $m_T > 30$ GeV. Each colour corresponds to a type of generator-level particle matched to a τ candidate (i.e. the highest energy particle within a cone of radius $\Delta R = 0.2$ around the τ candidate is considered). The SS events are (a) given a weight of -1 and (b) subtracted from the OS events. All simulated SM processes are considered.

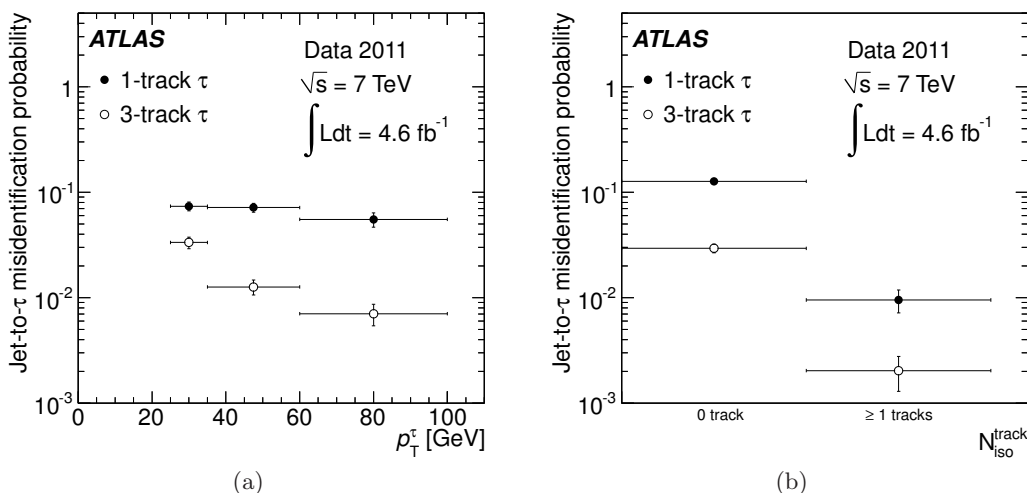


Figure 2. Probability for a light-quark jet to be misidentified as a 1-track or 3-track τ jet, measured in a region enriched with OS-SS $W + >2$ jets events in the data, as a function of (a) p_T^τ and (b) the number of tracks $N_{\text{track}}^{\text{iso}}$ found within $0.2 < \Delta R < 0.4$ of the τ jet.

4 Results

4.1 Computation of event yield ratios

For each of the four final states considered here ($e + \tau_{\text{had}}$, $e + \mu$, $\mu + \tau_{\text{had}}$ and $\mu + e$), the OS-SS event yield \mathcal{N} can be split into two contributions: from $t\bar{t}$ events (where the top quarks may decay into both bW and bH^+) and from all other SM processes except $t\bar{t} \rightarrow b\bar{b}W^+W^-$. The contributions from $t\bar{t}$ events are expressed as a function of the

cross section $\sigma_{t\bar{t}}$, the integrated luminosity \mathcal{L} , the branching fraction $B \equiv \mathcal{B}(t \rightarrow bH^+)$, as well as the selection efficiencies $\epsilon_{W^+W^-}$, $\epsilon_{H^+W^-}$, $\epsilon_{H^-W^+}$ and $\epsilon_{H^+H^-}$ for, respectively, $t\bar{t} \rightarrow b\bar{b}W^+W^-$, $t\bar{t} \rightarrow b\bar{b}H^+W^-$, $t\bar{t} \rightarrow b\bar{b}H^-W^+$ and $t\bar{t} \rightarrow b\bar{b}H^+H^-$ events, in each of the four final states considered here:

$$\mathcal{N} = \sigma_{t\bar{t}} \times \mathcal{L} \times [(1 - B)^2 \epsilon_{W^+W^-} + B(1 - B)(\epsilon_{H^+W^-} + \epsilon_{H^-W^+}) + B^2 \epsilon_{H^+H^-}] + \mathcal{N}_{\text{Others}}. \quad (4.1)$$

In turn, event yield ratios are defined as:

$$R_e = \frac{\mathcal{N}(e + \tau_{\text{had}})}{\mathcal{N}(e + \mu)} \quad \text{and} \quad R_\mu = \frac{\mathcal{N}(\mu + \tau_{\text{had}})}{\mathcal{N}(\mu + e)}. \quad (4.2)$$

The event yields in the τ_{had} +lepton and dilepton final states are summarised in table 2 for the background-only hypothesis, as well as in the presence of a 130 GeV charged Higgs boson in the top quark decay. The predicted values in the SM-only hypothesis and the measured values of the ratios R_e and R_μ are summarised in table 3. Note that the event yields for dilepton final states become smaller in the presence of a charged Higgs boson in top quark decays, despite the fact that a τ lepton decays into an electron or muon more often than a W boson. This results from the fact that electrons and muons produced in the decay chain $t \rightarrow bH^+ \rightarrow b\tau\nu \rightarrow bl + N\nu$ are, on average, softer than those coming from $t \rightarrow bW \rightarrow bl + N\nu$.

Figure 3 shows the variation of the event yields $\mathcal{N}(e + \tau_{\text{had}})$, $\mathcal{N}(e + \mu)$, $\mathcal{N}(\mu + \tau_{\text{had}})$ and $\mathcal{N}(\mu + e)$ with $\mathcal{B}(t \rightarrow bH^+)$, for a charged Higgs boson mass of 130 GeV. The presence of $H^+ \rightarrow \tau\nu$ in a fraction of the top quark decays leads to an increase of the number of $t\bar{t}$ events with a lepton and a τ jet. In combination with a small decrease of the number of dilepton $t\bar{t}$ events, this leads to an increase of the ratios R_e and R_μ . The sensitivity of this analysis to charged Higgs bosons is determined by the rate at which the ratios R_e and R_μ change with $\mathcal{B}(t \rightarrow bH^+)$, which depends on the selection efficiencies $\epsilon_{H^+W^-}$, $\epsilon_{H^-W^+}$, $\epsilon_{H^+H^-}$ and, in turn, on the charged Higgs boson mass. For $m_{H^+} = 150$ (160) GeV, the rate at which the ratios R_e and R_μ change with $\mathcal{B}(t \rightarrow bH^+)$ is found to be two (five) times smaller than for $m_{H^+} = 130$ GeV. Indeed, the selection efficiencies $\epsilon_{H^+W^-}$, $\epsilon_{H^-W^+}$, $\epsilon_{H^+H^-}$ are reduced for m_{H^+} values in the vicinity of m_{top} , because the b -jet arising from $t \rightarrow bH^+$ becomes softer when the mass difference $m_{\text{top}} - m_{H^+}$ is smaller.

4.2 Systematic uncertainties

Systematic uncertainties arise from the simulation of the electron and muon triggers, from the reconstruction and identification efficiencies of the physics objects, as well as from the energy/momentum scale and resolution for these objects. In order to assess their impact, the selection cuts of this analysis are re-applied after shifting a particular parameter by its ± 1 standard deviation uncertainty, while other parameters are fixed. The largest instrumental systematic uncertainties are for jets. In comparison, the systematic uncertainties arising from the reconstruction and identification of electrons, muons and τ jets are small. All instrumental systematic uncertainties are propagated to the reconstructed $E_{\text{T}}^{\text{miss}}$.

Sample	OS-SS event yields	
	$e + \tau_{\text{had}}$	$e + \mu$
Misidentified electrons or muons	-0.8 ± 3.0	94 ± 37
W/Z +jets & diboson	2.1 ± 0.9	0.7 ± 0.4
Single top quark	3.3 ± 0.8	24 ± 4
$t\bar{t}$	111 ± 25	980 ± 200
\sum SM	116 ± 25	1100 ± 210
Data	144	1247
$t\bar{t}$ with $t \rightarrow bH^+$ (130 GeV)	30 ± 4	27 ± 4
Prediction with signal	139 ± 28	1070 ± 200
	$\mu + \tau_{\text{had}}$	$\mu + e$
Misidentified electrons or muons	0.2 ± 1.0	74 ± 37
W/Z +jets & diboson	2.6 ± 1.6	0.7 ± 0.4
Single top quark	4.6 ± 0.9	18 ± 3
$t\bar{t}$	131 ± 28	740 ± 150
\sum SM	138 ± 29	830 ± 160
Data	153	929
$t\bar{t}$ with $t \rightarrow bH^+$ (130 GeV)	35 ± 4	20 ± 3
Prediction with signal	166 ± 32	810 ± 150

Table 2. Expected OS-SS event yields after all selection cuts in τ_{had} +lepton and dilepton channels, compared with 4.6 fb^{-1} of ATLAS data. The numbers shown for a hypothetical 130 GeV H^+ signal correspond to $\mathcal{B}(t \rightarrow bH^+) = 3\%$. The contribution of $t\bar{t} \rightarrow b\bar{b}WW$ events to the background is scaled accordingly. Statistical and systematic uncertainties are combined.

Ratio	R_e	R_μ
SM value	0.105 ± 0.012	0.166 ± 0.017
Measured value	0.115 ± 0.010 (stat)	0.165 ± 0.015 (stat)

Table 3. Predicted (in the SM-only hypothesis) and measured values of the event yield ratios R_e and R_μ . For the values of the ratios predicted using simulation, the statistical and systematic uncertainties are combined.

The $t\bar{t}$ cross section used in this analysis is $\sigma_{t\bar{t}} = 167^{+17}_{-18} \text{ pb}$ [26]. To estimate systematic uncertainties arising from the $t\bar{t}$ generation and the parton shower model, the acceptance is computed for $t\bar{t}$ events produced with either MC@NLO interfaced to HERWIG and JIMMY [37] for the hadronisation and the underlying event, or POWHEG [38] interfaced to PYTHIA. Systematic uncertainties on initial- and final-state radiation are computed using $t\bar{t}$ samples generated with AcerMC interfaced to PYTHIA, where the relevant parameters in PYTHIA are varied in a range given by current experimental data [39]. These systematic uncertainties are dominated by the difference in modelling the numbers of tracks N_{track}^τ and $N_{\text{track}}^{\text{iso}}$ in, respectively, the core and isolation regions of the jets misidentified as τ

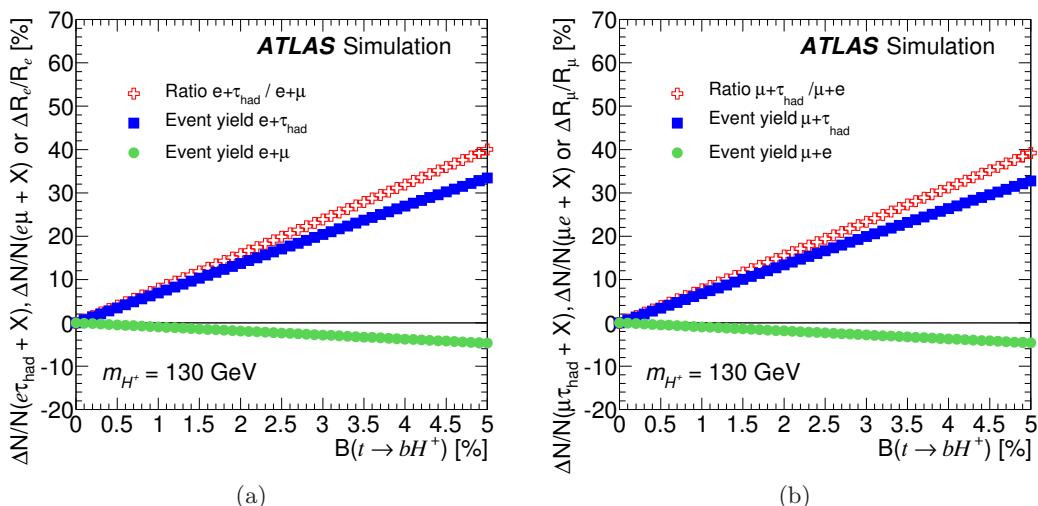


Figure 3. Relative variation with $\mathcal{B}(t \rightarrow bH^+)$ of (a) the event yields $\mathcal{N}(e + \tau_{\text{had}})$, $\mathcal{N}(e + \mu)$ and their ratio, as well as (b) $\mathcal{N}(\mu + \tau_{\text{had}})$, $\mathcal{N}(\mu + e)$ and their ratio, assuming the presence of a 130 GeV charged Higgs boson in $t\bar{t}$ events.

candidates. The various simulated $t\bar{t}$ samples are reweighted so that the N_{track}^τ and the $N_{\text{track}}^{\text{iso}}$ distributions match⁷ before the systematic uncertainties on the $t\bar{t}$ generation, the parton shower model, as well as initial- and final-state radiation, are evaluated.

For the signal samples, which are generated with PYTHIA (i.e. without higher-order corrections), no alternative generator is available, hence the systematic uncertainty is set to the relative difference in acceptance between $t\bar{t}$ events generated with MC@NLO interfaced to HERWIG/JIMMY and with AcerMC, which is also a leading-order generator, interfaced to PYTHIA. For the systematic uncertainty coming from initial- and final-state radiation, the same simulated samples as for the SM $t\bar{t}$ events are used. In the evaluation of the systematic uncertainties for the signal samples, only τ jets matched to true hadronically decaying τ leptons in the generated events are considered.

For the backgrounds with misidentified leptons, the largest systematic uncertainties arise from the sample dependence: the misidentification probabilities are calculated in a control region dominated by gluon-initiated events, but later used in a data sample with a higher fraction of quark-initiated events. The total systematic uncertainty on the backgrounds with misidentified leptons is 38% for electron-triggered events and 49% for muon-triggered events. It corresponds to the relative variation of the number of events with exactly one trigger-matched lepton and two jets, after having considered all systematic uncertainties. The requirement of having two b -jets in the event does not have a significant impact on these systematic uncertainties and neither does the presence of a second lepton.

For the estimation of backgrounds with jets misidentified as hadronically decaying τ leptons, the systematic uncertainty on the scale factors associated with the number of tracks is determined by varying the requirement on the jet multiplicity and the magnitude of the subtraction of τ candidates matched to a true electron, muon or τ lepton in the

⁷Both variables are reweighted in a correlated way.

generated events. This uncertainty is 7% for 1-track τ jets and 11% for 3-track τ jets. In addition, systematic uncertainties on the $\text{jet} \rightarrow \tau_{\text{had}}$ misidentification probability arise from statistical uncertainties due to the limited control sample size, the differences between misidentification probabilities computed in the region enriched with $W + >2$ jets events and the signal region, as well as the small contamination from true τ leptons (including those possibly coming from $H^+ \rightarrow \tau\nu$) in the region enriched with $W + >2$ jets events.

Some of the systematic uncertainties above affect the τ_{had} +lepton and dilepton event yields in the same manner and, as a result, have a limited impact on R_e and R_μ . Systematic uncertainties arising from jets and $E_{\text{T}}^{\text{miss}}$ are common to all reconstructed events in the simulation, hence they should cancel in the ratios R_e and R_μ . However, due to the use of data-driven background estimates and because of the removal of geometric overlaps between reconstructed objects, some of these systematic uncertainties still have a minor impact. In the EL (MU) category, the systematic uncertainties related to the trigger-matched electron (muon) are the same for the $e + \tau_{\text{had}}$ and $e + \mu$ ($\mu + \tau_{\text{had}}$ and $\mu + e$) events, thereby not affecting the predicted value of the ratio R_e (R_μ). Those coming from the reconstructed muon (electron) only affect event yields in the denominator, and hence the ratio. Similarly, the systematic uncertainties coming from the τ jets and their misidentification probabilities only affect the numerator of R_e and R_μ , hence they do have an impact on the analysis. This is also the case for systematic uncertainties on the backgrounds with misidentified leptons, which have a larger contribution in the dilepton events, i.e. on the denominator of R_e and R_μ . Table 4 shows how these ratios (in the SM-only hypothesis) change when shifting a particular parameter by its ± 1 standard deviation uncertainty.

4.3 Exclusion limits

To test the compatibility of the data with the background-only or the signal+background hypotheses, a profile likelihood ratio [40] is used with R_e and R_μ as the discriminating variables. The systematic uncertainties are incorporated via nuisance parameters, and the one-sided profile likelihood ratio, \tilde{q}_μ , is used as a test statistic. No significant deviation from the SM prediction is observed in 4.6 fb^{-1} of data. Exclusion limits are set on the branching fraction $\mathcal{B}(t \rightarrow bH^+)$ by rejecting the signal hypothesis at the 95% confidence level (CL) using the CL_s procedure [41]. These limits are based on the asymptotic distribution of the test statistic [40]. They are first set for electron-triggered and muon-triggered events separately (see figure 4), and then using a global event yield ratio $R_{e+\mu}$ defined as:

$$R_{e+\mu} = \frac{\mathcal{N}(e + \tau_{\text{had}}) + \mathcal{N}(\mu + \tau_{\text{had}})}{\mathcal{N}(e + \mu) + \mathcal{N}_{\text{OR}}(\mu + e)}, \tag{4.3}$$

where $\mathcal{N}_{\text{OR}}(\mu + e)$ is the event yield in the $\mu + e$ channel after removing the dilepton events that simultaneously fire a single-electron trigger and a single-muon trigger, as those already appear in $\mathcal{N}(e + \mu)$. The fraction of dilepton events common to the $\mu + e$ and $e + \mu$ final states is about 42% in the data. Using this global event yield ratio, upper limits in the range 3.2%–4.4% can be placed on $\mathcal{B}(t \rightarrow bH^+)$ for charged Higgs boson masses in the range 90–140 GeV, as shown in figure 5 and table 5.

Systematic uncertainty	ΔR_e	ΔR_μ
Integrated luminosity	0.3%	0.3%
Electron trigger efficiency	0.1%	N/A
Electron reco. and ID efficiencies	0.2%	1.9%
Electron energy resolution	0.1%	<0.1%
Electron energy scale	0.1%	0.3%
Muon trigger efficiency	N/A	0.1%
Muon reco. and ID efficiencies	1.0%	0.1%
Muon momentum resolution	<0.1%	<0.1%
Muon momentum scale	0.1%	<0.1%
τ ID efficiency	3.9%	3.9%
τ energy scale	2.9%	3.0%
τ mis-ID (data-driven): number of associated tracks	2.1%	2.1%
τ mis-ID (data-driven): true τ_{had} contamination	0.2%	0.2%
τ mis-ID (data-driven): H^+ signal contamination	0.6%	0.6%
τ mis-ID (data-driven): event environment	1.3%	1.2%
τ mis-ID (data-driven): statistical uncertainties	3.3%	3.2%
τ mis-ID (data-driven): electron veto uncertainties	0.6%	0.3%
b -tagging	1.9%	2.3%
Jet vertex fraction	0.1%	0.4%
Jet energy resolution	0.4%	<0.1%
Jet energy scale	0.7%	0.5%
Jet reconstruction efficiency	0.1%	0.4%
E_T^{miss}	0.3%	0.1%
$t\bar{t}$: cross section	0.7%	0.6%
$t\bar{t}$: generator and parton shower	5.7%	4.4%
$t\bar{t}$: initial- and final-state radiation	3.6%	3.7%
Backgrounds with misidentified leptons	3.5%	4.3%
Total (added in quadrature)	10.3%	10.1%

Table 4. Relative variation of the ratios R_e and R_μ in the SM-only hypothesis after shifting a particular parameter by its ± 1 standard deviation uncertainty.

m_{H^+} (GeV)	90	100	110	120	130	140	150	160
95% CL observed (expected) limit on $\mathcal{B}(t \rightarrow bH^+)$ using the ratio $R_{e+\mu}$	3.3% (3.1%)	3.6% (3.3%)	3.2% (3.0%)	3.4% (3.1%)	3.6% (3.3%)	4.4% (4.0%)	7.3% (6.7%)	18.3% (16.8%)

Table 5. Observed (expected) 95% CL upper limits on $\mathcal{B}(t \rightarrow bH^+)$ derived from the event yield ratio $R_{e+\mu}$, as a function of the charged Higgs boson mass, obtained for an integrated luminosity of 4.6 fb^{-1} and with the assumption that $\mathcal{B}(H^+ \rightarrow \tau\nu) = 1$.

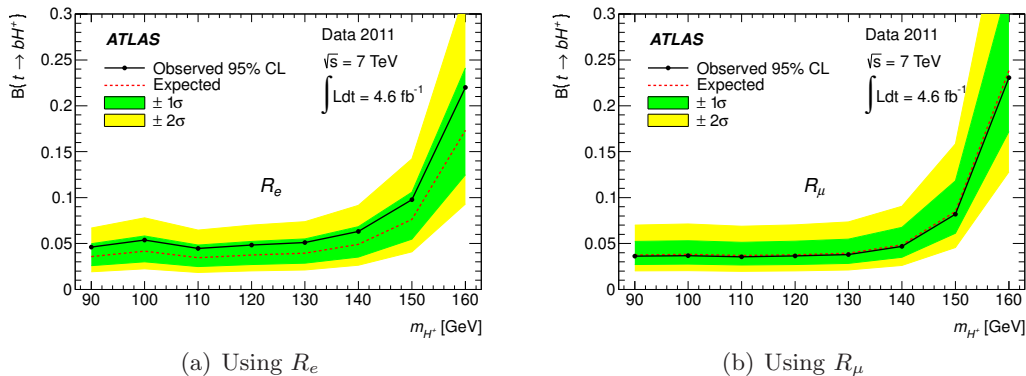


Figure 4. Upper limits on $\mathcal{B}(t \rightarrow bH^+)$ derived from the event yield ratios (a) R_e and (b) R_μ , as a function of the charged Higgs boson mass, obtained for an integrated luminosity of 4.6 fb^{-1} and with the assumption $\mathcal{B}(H^+ \rightarrow \tau\nu) = 1$. The solid line in the figure is used to denote the observed 95% CL upper limits, while the dashed line represents the expected exclusion limits. The green and yellow regions show the 1σ and 2σ error bands.

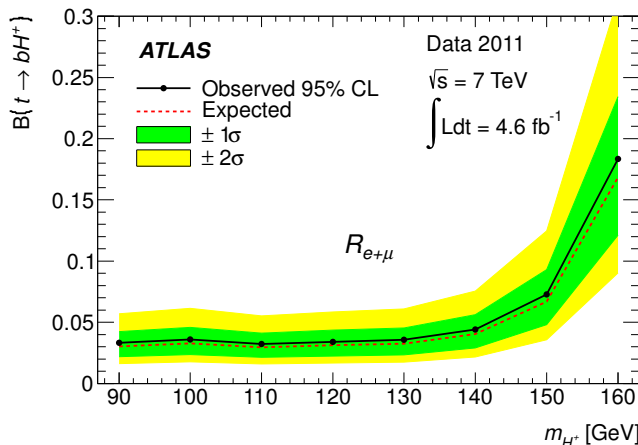


Figure 5. Upper limits on $\mathcal{B}(t \rightarrow bH^+)$ derived from the event yield ratio $R_{e+\mu}$, as a function of the charged Higgs boson mass, obtained for an integrated luminosity of 4.6 fb^{-1} and with the assumption $\mathcal{B}(H^+ \rightarrow \tau\nu) = 1$. The solid line in the figure is used to denote the observed 95% CL upper limits, while the dashed line represents the expected exclusion limits. The green and yellow regions show the 1σ and 2σ error bands.

In a previously published search for charged Higgs bosons [8], based on the data collected in 2011 with ATLAS, upper limits on $\mathcal{B}(t \rightarrow bH^+)$ were derived using various distributions of discriminating variables in $\tau_{\text{had}}+\text{jets}$, $\tau_{\text{had}}+\text{lepton}$ and $\text{lepton}+\text{jets}$ final states. The most sensitive channel was $\tau_{\text{had}}+\text{jets}$, except for low values of m_{H^+} . A new set of combined upper limits on $\mathcal{B}(t \rightarrow bH^+)$ is derived, using the transverse mass distribution of $\tau_{\text{had}}+\text{jets}$ events from ref. [8] and the global event yield ratio $R_{e+\mu}$, as shown in figure 6 and table 6. Since a lepton veto is applied for charged Higgs boson searches in $\tau_{\text{had}}+\text{jets}$ final states, there is no correlation between such events and those selected in this study to determine the event yield ratios. With this combination of upper limits, charged Higgs bosons can be excluded for values of the branching fraction $\mathcal{B}(t \rightarrow bH^+)$ larger than

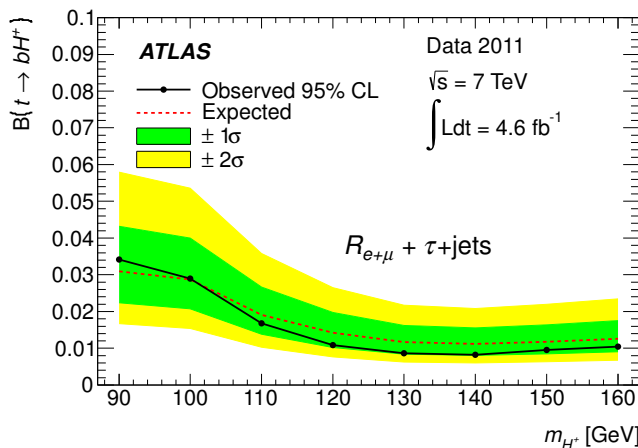


Figure 6. Upper limits on $\mathcal{B}(t \rightarrow bH^+)$ derived from the transverse mass distribution of $\tau_{\text{had}}+\text{jets}$ events in ref. [8] and the event yield ratio $R_{e+\mu}$, as a function of the charged Higgs boson mass, obtained for an integrated luminosity of 4.6fb^{-1} and with the assumption $\mathcal{B}(H^+ \rightarrow \tau\nu) = 1$. The solid line in the figure is used to denote the observed 95% CL upper limits, while the dashed line represents the expected exclusion limits. The green and yellow regions show the 1σ and 2σ error bands.

m_{H^+} (GeV)	90	100	110	120	130	140	150	160
95% CL observed								
(expected) limit on $\mathcal{B}(t \rightarrow bH^+)$ using $R_{e+\mu}$ and $\tau_{\text{had}}+\text{jets}$	3.4%	2.9%	1.7%	1.1%	0.9%	0.8%	1.0%	1.1%
	(3.1%)	(2.8%)	(1.9%)	(1.4%)	(1.2%)	(1.1%)	(1.2%)	(1.2%)
95% CL observed								
(expected) limit in ref. [8]	4.8%	3.4%	2.1%	1.3%	1.1%	1.0%	1.1%	1.0%
	(4.2%)	(3.5%)	(2.5%)	(1.9%)	(1.5%)	(1.3%)	(1.2%)	(1.3%)

Table 6. Observed (expected) 95% CL upper limits on $\mathcal{B}(t \rightarrow bH^+)$ derived using $\tau_{\text{had}}+\text{jets}$ events in ref. [8] and the ratio $R_{e+\mu}$, as a function of the charged Higgs boson mass, obtained for an integrated luminosity of 4.6fb^{-1} and assuming that $\mathcal{B}(H^+ \rightarrow \tau\nu) = 1$. The exclusion limits published in ref. [8] are also shown for comparison purposes.

0.8% to 3.4%, for m_{H^+} between 90 GeV and 160 GeV. These exclusion limits represent an improvement with respect to those published in ref. [8].

In figure 7, the combined limit on $\mathcal{B}(t \rightarrow bH^+) \times \mathcal{B}(H^+ \rightarrow \tau\nu)$ is interpreted in the context of the m_h^{max} scenario [11] of the MSSM. The following relative theoretical uncertainties on $\mathcal{B}(t \rightarrow bH^+)$ are considered [42, 43]: 5% for one-loop electroweak corrections missing from the calculations, 2% for missing two-loop QCD corrections, and about 1% (depending on $\tan\beta$) for Δ_b -induced uncertainties, where Δ_b is a correction factor for the running b -quark mass [44]. These uncertainties are added linearly, as recommended by the LHC Higgs cross-section working group [43].

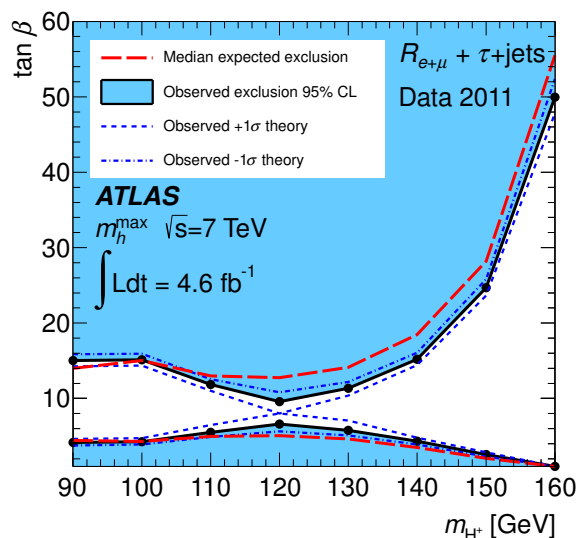


Figure 7. Limits for charged Higgs boson production from top quark decays in the m_{H^+} - $\tan\beta$ plane, derived using $\tau_{\text{had}}+\text{jets}$ events in ref. [8] and the ratio $R_{e+\mu}$, in the context of the m_h^{max} scenario of the MSSM. The 1σ band around the observed limit (dashed lines) shows the theoretical uncertainties. Values below $\tan\beta = 1$, where the calculations in the MSSM become non-perturbative, are not considered, as the results become unphysical.

Assuming that the boson recently discovered at the LHC [45, 46] is one of the neutral MSSM Higgs bosons, only a certain region in the m_{H^+} - $\tan\beta$ plane is still allowed for a given scenario [47]. If the new boson is the lightest neutral MSSM Higgs boson (h^0), it would imply $\tan\beta > 3$ and $m_{H^+} > 155$ GeV. However, the allowed region depends strongly on MSSM parameters which, on the other hand, do not affect the charged Higgs boson production and decay significantly. Thus, by adjusting these MSSM parameters, the region in which the Higgs boson mass can take a value of about 125 GeV can be changed significantly, while the ATLAS exclusion region shown here is relatively stable with respect to these changes. Should the recently discovered boson instead be the heavier CP-even Higgs boson (H^0), the additional constraint from $m_{H^0} \simeq 125$ GeV only leads to an upper limit of roughly $m_{H^+} < 150$ GeV, with suppressed couplings for h^0 . If the recently discovered particle is an MSSM Higgs boson, excluding a low-mass charged Higgs boson would thus imply that it is the lightest neutral state h^0 .

5 Conclusions

Charged Higgs bosons have been searched for in $t\bar{t}$ events, in the decay mode $t \rightarrow bH^+$ followed by $H^+ \rightarrow \tau\nu$. A total of 4.6 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV, recorded in 2011 with the ATLAS experiment at the LHC, is used. Event yield ratios are measured in the data and compared to the predictions from simulations, between electron-triggered $e + \tau_{\text{had}}$ and $e + \mu$ events, and between muon-triggered $\mu + \tau_{\text{had}}$ and $\mu + e$ events, in order to search for a violation of lepton universality in $t\bar{t}$ events. This method reduces the impact of several systematic uncertainties in the analysis. Data-driven methods and

simulation are employed to estimate the number of background events. The observed data are found to be in agreement with the SM predictions. Assuming $\mathcal{B}(H^+ \rightarrow \tau\nu) = 100\%$, upper limits at the 95% confidence level in the range 3.2%–4.4% have been placed on the branching fraction $\mathcal{B}(t \rightarrow bH^+)$ for charged Higgs boson masses in the range 90–140 GeV. For charged Higgs boson masses below 110 GeV, this analysis improves the previously published limits on $\mathcal{B}(t \rightarrow bH^+)$, based on direct searches for charged Higgs bosons in $t\bar{t}$ decays using the lepton+jets, $\tau_{\text{had}}+\text{jets}$ and $\tau_{\text{had}}+\text{lepton}$ final states. When the results of the present analysis are combined with the results from the search for charged Higgs bosons in $t\bar{t}$ decays using the $\tau_{\text{had}}+\text{jets}$ final state [8], upper limits on $\mathcal{B}(t \rightarrow bH^+)$ are set in the range 0.8%–3.4%, for m_{H^+} between 90 GeV and 160 GeV.

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The ATLAS collaboration

G. Aad⁴⁸, T. Abajyan²¹, B. Abbott¹¹¹, J. Abdallah¹², S. Abdel Khalek¹¹⁵, A.A. Abdelalim⁴⁹, O. Abidinov¹¹, R. Aben¹⁰⁵, B. Abi¹¹², M. Abolins⁸⁸, O.S. AbouZeid¹⁵⁸, H. Abramowicz¹⁵³, H. Abreu¹³⁶, B.S. Acharya^{164a,164b,a}, L. Adamczyk³⁸, D.L. Adams²⁵, T.N. Addy⁵⁶, J. Adelman¹⁷⁶, S. Adomeit⁹⁸, P. Adragna⁷⁵, T. Adye¹²⁹, S. Aefsky²³, J.A. Aguilar-Saavedra^{124b,b}, M. Agustoni¹⁷, M. Aharrouche⁸¹, S.P. Ahlen²², F. Ahles⁴⁸, A. Ahmad¹⁴⁸, M. Ahsan⁴¹, G. Aielli^{133a,133b}, T.P.A. Åkesson⁷⁹, G. Akimoto¹⁵⁵, A.V. Akimov⁹⁴, M.A. Alam⁷⁶, J. Albert¹⁶⁹, S. Albrand⁵⁵, M. Aleksa³⁰, I.N. Aleksandrov⁶⁴, F. Alessandria^{89a}, C. Alexa^{26a}, G. Alexander¹⁵³, G. Alexandre⁴⁹, T. Alexopoulos¹⁰, M. Alhroob^{164a,164c}, M. Aliev¹⁶, G. Alimonti^{89a}, J. Alison¹²⁰, B.M.M. Allbrooke¹⁸, P.P. Allport⁷³, S.E. Allwood-Spiers⁵³, J. Almond⁸², A. Aloisio^{102a,102b}, R. Alon¹⁷², A. Alonso³⁶, F. Alonso⁷⁰, A. Altheimer³⁵, B. Alvarez Gonzalez⁸⁸, M.G. Alviggi^{102a,102b}, K. Amako⁶⁵, C. Amelung²³, V.V. Ammosov^{128,*}, S.P. Amor Dos Santos^{124a}, A. Amorim^{124a,c}, N. Amram¹⁵³, C. Anastopoulos³⁰, L.S. Ancu¹⁷, N. Andari¹¹⁵, T. Andeen³⁵, C.F. Anders^{58b}, G. Anders^{58a}, K.J. Anderson³¹, A. Andreazza^{89a,89b}, V. Andrei^{58a}, M-L. Andrieux⁵⁵, X.S. Anduaga⁷⁰, S. Angelidakis⁹, P. Anger⁴⁴, A. Angerami³⁵, F. Anghinolfi³⁰, A. Anisenkov¹⁰⁷, N. Anjos^{124a}, A. Annovi⁴⁷, A. Antonaki⁹, M. Antonelli⁴⁷, A. Antonov⁹⁶, J. Antos^{144b}, F. Anulli^{132a}, M. Aoki¹⁰¹, S. Aoun⁸³, L. Aperio Bella⁵, R. Apolle^{118,d}, G. Arabidze⁸⁸, I. Aracena¹⁴³, Y. Arai⁶⁵, A.T.H. Arce⁴⁵, S. Arfaoui¹⁴⁸, J-F. Arguin⁹³, S. Argyropoulos⁴², E. Arik^{19a,*}, M. Arik^{19a}, A.J. Armbruster⁸⁷, O. Arnaez⁸¹, V. Arnal⁸⁰, A. Artamonov⁹⁵, G. Artoni^{132a,132b}, D. Arutinov²¹, S. Asai¹⁵⁵, S. Ask²⁸, B. Åsman^{146a,146b}, D. Asner²⁹, L. Asquith⁶, K. Assamagan^{25,e}, A. Astbury¹⁶⁹, M. Atkinson¹⁶⁵, B. Aubert⁵, E. Auge¹¹⁵, K. Augsten¹²⁶, M. Aurousseau^{145a}, G. Avolio³⁰, D. Axen¹⁶⁸, G. Azuelos^{93,f}, Y. Azuma¹⁵⁵, M.A. Baak³⁰, G. Baccaglioni^{89a}, C. Bacci^{134a,134b}, A.M. Bach¹⁵, H. Bachacou¹³⁶, K. Bachas¹⁵⁴, M. Backes⁴⁹, M. Backhaus²¹, J. Backus Mayes¹⁴³, E. Badescu^{26a}, P. Bagnaia^{132a,132b}, S. Bahinipati³, Y. Bai^{33a}, D.C. Bailey¹⁵⁸, T. Bain³⁵, J.T. Baines¹²⁹, O.K. Baker¹⁷⁶, M.D. Baker²⁵, S. Baker⁷⁷, P. Balek¹²⁷, E. Banas³⁹, P. Banerjee⁹³, Sw. Banerjee¹⁷³, D. Banfi³⁰, A. Bangert¹⁵⁰, V. Bansal¹⁶⁹, H.S. Bansil¹⁸, L. Barak¹⁷², S.P. Baranov⁹⁴, A. Barbaro Galtieri¹⁵, T. Barber⁴⁸, E.L. Barberio⁸⁶, D. Barberis^{50a,50b}, M. Barbero²¹, D.Y. Bardin⁶⁴, T. Barillari⁹⁹, M. Barisonzi¹⁷⁵, T. Barklow¹⁴³, N. Barlow²⁸, B.M. Barnett¹²⁹, R.M. Barnett¹⁵, A. Baroncelli^{134a}, G. Barone⁴⁹, A.J. Barr¹¹⁸, F. Barreiro⁸⁰, J. Barreiro Guimarães da Costa⁵⁷, R. Bartoldus¹⁴³, A.E. Barton⁷¹, V. Bartsch¹⁴⁹, A. Basye¹⁶⁵, R.L. Bates⁵³, L. Batkova^{144a}, J.R. Batley²⁸, A. Battaglia¹⁷, M. Battistin³⁰, F. Bauer¹³⁶, H.S. Bawa^{143,g}, S. Beale⁹⁸, T. Beau⁷⁸, P.H. Beauchemin¹⁶¹, R. Beccherle^{50a}, P. Bechtel²¹, H.P. Beck¹⁷, K. Becker¹⁷⁵, S. Becker⁹⁸, M. Beckingham¹³⁸, K.H. Becks¹⁷⁵, A.J. Beddall^{19c}, A. Beddall^{19c}, S. Bedikian¹⁷⁶, V.A. Bednyakov⁶⁴, C.P. Bee⁸³, L.J. Beamster¹⁰⁵, M. Begel²⁵, S. Behar Harpaz¹⁵², P.K. Behera⁶², M. Beimforde⁹⁹, C. Belanger-Champagne⁸⁵, P.J. Bell⁴⁹, W.H. Bell⁴⁹, G. Bella¹⁵³, L. Bellagamba^{20a}, M. Bellomo³⁰, A. Belloni⁵⁷, O. Beloborodova^{107,h}, K. Belotskiy⁹⁶, O. Beltramello³⁰, O. Benary¹⁵³, D. Benchekroun^{135a}, K. Bendtz^{146a,146b}, N. Benekos¹⁶⁵, Y. Benhammou¹⁵³, E. Benhar Nocchioli⁴⁹, J.A. Benitez Garcia^{159b}, D.P. Benjamin⁴⁵, M. Benoit¹¹⁵, J.R. Bensinger²³, K. Benslama¹³⁰, S. Bentvelsen¹⁰⁵, D. Berge³⁰, E. Bergeas Kuutmann⁴², N. Berger⁵, F. Berghaus¹⁶⁹, E. Berglund¹⁰⁵, J. Beringer¹⁵, P. Bernat⁷⁷, R. Bernhard⁴⁸, C. Bernius²⁵, T. Berry⁷⁶, C. Bertella⁸³, A. Bertin^{20a,20b}, F. Bertolucci^{122a,122b}, M.I. Besana^{89a,89b}, G.J. Besjes¹⁰⁴, N. Besson¹³⁶, S. Bethke⁹⁹, W. Bhimji⁴⁶, R.M. Bianchi³⁰, L. Bianchini²³, M. Bianco^{72a,72b}, O. Biebel⁹⁸, S.P. Bieniek⁷⁷, K. Bierwagen⁵⁴, J. Biesiada¹⁵, M. Biglietti^{134a}, H. Bilokon⁴⁷, M. Bindi^{20a,20b}, S. Binet¹¹⁵, A. Bingul^{19c}, C. Bini^{132a,132b}, C. Biscarat¹⁷⁸, B. Bittner⁹⁹, C.W. Black¹⁵⁰, K.M. Black²², R.E. Blair⁶, J.-B. Blanchard¹³⁶, T. Blazek^{144a}, I. Bloch⁴², C. Blocker²³, J. Blocki³⁹, A. Blondel⁴⁹, W. Blum⁸¹, U. Blumenschein⁵⁴, G.J. Bobbink¹⁰⁵, V.S. Bobrovnikov¹⁰⁷, S.S. Bocchetta⁷⁹, A. Bocci⁴⁵, C.R. Boddy¹¹⁸, M. Boehler⁴⁸, J. Boek¹⁷⁵, T.T. Boek¹⁷⁵, N. Boelaert³⁶, J.A. Bogaerts³⁰, A. Bogdanchikov¹⁰⁷, A. Bogouch^{90,*}, C. Bohm^{146a}, J. Bohm¹²⁵, V. Boisvert⁷⁶, T. Bold³⁸, V. Boldea^{26a}, N.M. Bolnet¹³⁶, M. Bomben⁷⁸, M. Bona⁷⁵, M. Boonekamp¹³⁶, S. Bordini⁷⁸, C. Borer¹⁷, A. Borisov¹²⁸, G. Borisso⁷¹, I. Borjanovic^{13a}, M. Borri⁸², S. Borroni⁸⁷, J. Bortfeldt⁹⁸,

V. Bortolotto^{134a,134b}, K. Bos¹⁰⁵, D. Boscherini^{20a}, M. Bosman¹², H. Boterenbrood¹⁰⁵, J. Bouchami⁹³, J. Boudreau¹²³, E.V. Bouhova-Thacker⁷¹, D. Boumediene³⁴, C. Bourdarios¹¹⁵, N. Bousson⁸³, A. Boveia³¹, J. Boyd³⁰, I.R. Boyko⁶⁴, I. Bozovic-Jelisavcic^{13b}, J. Bracinik¹⁸, P. Branchini^{134a}, A. Brandt⁸, G. Brandt¹¹⁸, O. Brandt⁵⁴, U. Bratzler¹⁵⁶, B. Brau⁸⁴, J.E. Brau¹¹⁴, H.M. Braun^{175,*}, S.F. Brazzale^{164a,164c}, B. Brelier¹⁵⁸, J. Bremer³⁰, K. Brendlinger¹²⁰, R. Brenner¹⁶⁶, S. Bressler¹⁷², T.M. Bristow^{145b}, D. Britton⁵³, F.M. Brochu²⁸, I. Brock²¹, R. Brock⁸⁸, F. Broggi^{89a}, C. Bromberg⁸⁸, J. Bronner⁹⁹, G. Brooijmans³⁵, T. Brooks⁷⁶, W.K. Brooks^{32b}, G. Brown⁸², P.A. Bruckman de Renstrom³⁹, D. Bruncko^{144b}, R. Bruneliere⁴⁸, S. Brunet⁶⁰, A. Bruni^{20a}, G. Bruni^{20a}, M. Bruschi^{20a}, L. Bryngemark⁷⁹, T. Buanes¹⁴, Q. Buat⁵⁵, F. Bucci⁴⁹, J. Buchanan¹¹⁸, P. Buchholz¹⁴¹, R.M. Buckingham¹¹⁸, A.G. Buckley⁴⁶, S.I. Buda^{26a}, I.A. Budagov⁶⁴, B. Budick¹⁰⁸, V. Büscher⁸¹, L. Bugge¹¹⁷, O. Bulekov⁹⁶, A.C. Bundock⁷³, M. Bunse⁴³, T. Buran¹¹⁷, H. Burckhart³⁰, S. Burdin⁷³, T. Burgess¹⁴, S. Burke¹²⁹, E. Busato³⁴, P. Bussey⁵³, C.P. Buszello¹⁶⁶, B. Butler¹⁴³, J.M. Butler²², C.M. Buttar⁵³, J.M. Butterworth⁷⁷, W. Buttinger²⁸, M. Byszewski³⁰, S. Cabrera Urbán¹⁶⁷, D. Caforio^{20a,20b}, O. Cakir^{4a}, P. Calafiura¹⁵, G. Calderini⁷⁸, P. Calfayan⁹⁸, R. Calkins¹⁰⁶, L.P. Caloba^{24a}, R. Caloi^{132a,132b}, D. Calvet³⁴, S. Calvet³⁴, R. Camacho Toro³⁴, P. Camarri^{133a,133b}, D. Cameron¹¹⁷, L.M. Caminada¹⁵, R. Caminal Armadans¹², S. Campana³⁰, M. Campanelli⁷⁷, V. Canale^{102a,102b}, F. Canelli³¹, A. Canepa^{159a}, J. Cantero⁸⁰, R. Cantrill⁷⁶, L. Capasso^{102a,102b}, M.D.M. Capeans Garrido³⁰, I. Caprini^{26a}, M. Caprini^{26a}, D. Capriotti⁹⁹, M. Capua^{37a,37b}, R. Caputo⁸¹, R. Cardarelli^{133a}, T. Carli³⁰, G. Carlino^{102a}, L. Carminati^{89a,89b}, B. Caron⁸⁵, S. Caron¹⁰⁴, E. Carquin^{32b}, G.D. Carrillo-Montoya^{145b}, A.A. Carter⁷⁵, J.R. Carter²⁸, J. Carvalho^{124a,i}, D. Casadei¹⁰⁸, M.P. Casado¹², M. Cascella^{122a,122b}, C. Caso^{50a,50b,*}, A.M. Castaneda Hernandez^{173,j}, E. Castaneda-Miranda¹⁷³, V. Castillo Gimenez¹⁶⁷, N.F. Castro^{124a}, G. Cataldi^{72a}, P. Catastini⁵⁷, A. Catinaccio³⁰, J.R. Catmore³⁰, A. Cattai³⁰, G. Cattani^{133a,133b}, S. Caughron⁸⁸, V. Cavaliere¹⁶⁵, P. Cavalleri⁷⁸, D. Cavalli^{89a}, M. Cavalli-Sforza¹², V. Cavasinni^{122a,122b}, F. Ceradini^{134a,134b}, A.S. Cerqueira^{24b}, A. Cerri¹⁵, L. Cerrito⁷⁵, F. Cerutti¹⁵, S.A. Cetin^{19b}, A. Chafaq^{135a}, D. Chakraborty¹⁰⁶, I. Chalupkova¹²⁷, K. Chan³, P. Chang¹⁶⁵, B. Chapleau⁸⁵, J.D. Chapman²⁸, J.W. Chapman⁸⁷, D.G. Charlton¹⁸, V. Chavda⁸², C.A. Chavez Barajas³⁰, S. Cheatham⁸⁵, S. Chekanov⁶, S.V. Chekulaev^{159a}, G.A. Chelkov⁶⁴, M.A. Chelstowska¹⁰⁴, C. Chen⁶³, H. Chen²⁵, S. Chen^{33c}, X. Chen¹⁷³, Y. Chen³⁵, Y. Cheng³¹, A. Cheplakov⁶⁴, R. Cherkaoui El Moursli^{135e}, V. Chernyatin²⁵, E. Cheu⁷, S.L. Cheung¹⁵⁸, L. Chevalier¹³⁶, G. Chiefari^{102a,102b}, L. Chikovani^{51a,*}, J.T. Childers³⁰, A. Chilingarov⁷¹, G. Chiodini^{72a}, A.S. Chisholm¹⁸, R.T. Chislett⁷⁷, A. Chitan^{26a}, M.V. Chizhov⁶⁴, G. Choudalakis³¹, S. Chouridou¹³⁷, I.A. Christidi⁷⁷, A. Christov⁴⁸, D. Chromek-Burckhart³⁰, M.L. Chu¹⁵¹, J. Chudoba¹²⁵, G. Ciapetti^{132a,132b}, A.K. Ciftci^{4a}, R. Ciftci^{4a}, D. Cinca³⁴, V. Cindro⁷⁴, A. Ciochio¹⁵, M. Cirilli⁸⁷, P. Cirkovic^{13b}, Z.H. Citron¹⁷², M. Citterio^{89a}, M. Ciubancan^{26a}, A. Clark⁴⁹, P.J. Clark⁴⁶, R.N. Clarke¹⁵, W. Cleland¹²³, J.C. Clemens⁸³, B. Clement⁵⁵, C. Clement^{146a,146b}, Y. Coadou⁸³, M. Cobal^{164a,164c}, A. Coccaro¹³⁸, J. Cochran⁶³, L. Coffey²³, J.G. Cogan¹⁴³, J. Coggeshall¹⁶⁵, J. Colas⁵, S. Cole¹⁰⁶, A.P. Colijn¹⁰⁵, N.J. Collins¹⁸, C. Collins-Tooth⁵³, J. Collot⁵⁵, T. Colombo^{119a,119b}, G. Colon⁸⁴, G. Compostella⁹⁹, P. Conde Muiño^{124a}, E. Coniavitis¹⁶⁶, M.C. Conidi¹², S.M. Consonni^{89a,89b}, V. Consorti⁴⁸, S. Constantinescu^{26a}, C. Conta^{119a,119b}, G. Conti⁵⁷, F. Conventi^{102a,k}, M. Cooke¹⁵, B.D. Cooper⁷⁷, A.M. Cooper-Sarkar¹¹⁸, K. Copic¹⁵, T. Cornelissen¹⁷⁵, M. Corradi^{20a}, F. Corriveau^{85,l}, A. Cortes-Gonzalez¹⁶⁵, G. Cortiana⁹⁹, G. Costa^{89a}, M.J. Costa¹⁶⁷, D. Costanzo¹³⁹, D. Côté³⁰, L. Courneyea¹⁶⁹, G. Cowan⁷⁶, B.E. Cox⁸², K. Cranmer¹⁰⁸, F. Crescioli⁷⁸, M. Cristinziani²¹, G. Crosetti^{37a,37b}, S. Crépe-Renaudin⁵⁵, C.-M. Cuciuc^{26a}, C. Cuenca Almenar¹⁷⁶, T. Cuhadar Donszelmann¹³⁹, J. Cummings¹⁷⁶, M. Curatolo⁴⁷, C.J. Curtis¹⁸, C. Cuthbert¹⁵⁰, P. Cwetanski⁶⁰, H. Czirr¹⁴¹, P. Czodrowski⁴⁴, Z. Czyczula¹⁷⁶, S. D'Auria⁵³, M. D'Onofrio⁷³, A. D'Orazio^{132a,132b}, M.J. Da Cunha Sargedas De Sousa^{124a}, C. Da Via⁸², W. Dabrowski³⁸, A. Dafinca¹¹⁸, T. Dai⁸⁷, F. Dallaire⁹³, C. Dallapiccola⁸⁴, M. Dam³⁶, M. Dameri^{50a,50b}, D.S. Damiani¹³⁷, H.O. Danielsson³⁰, V. Dao⁴⁹, G. Darbo^{50a}, G.L. Darlea^{26b}, J.A. Dassoulas⁴², W. Davey²¹, T. Davidek¹²⁷, N. Davidson⁸⁶, R. Davidson⁷¹,

E. Davies^{118,d}, M. Davies⁹³, O. Davignon⁷⁸, A.R. Davison⁷⁷, Y. Davygora^{58a}, E. Dawe¹⁴²,
 I. Dawson¹³⁹, R.K. Daya-Ishmukhametova²³, K. De⁸, R. de Asmundis^{102a}, S. De Castro^{20a,20b},
 S. De Cecco⁷⁸, J. de Graat⁹⁸, N. De Groot¹⁰⁴, P. de Jong¹⁰⁵, C. De La Taille¹¹⁵, H. De la Torre⁸⁰,
 F. De Lorenzi⁶³, L. de Mora⁷¹, L. De Nooij¹⁰⁵, D. De Pedis^{132a}, A. De Salvo^{132a},
 U. De Sanctis^{164a,164c}, A. De Santo¹⁴⁹, J.B. De Vivie De Regie¹¹⁵, G. De Zorzi^{132a,132b},
 W.J. Dearnaley⁷¹, R. Debbe²⁵, C. Debenedetti⁴⁶, B. Dechenaux⁵⁵, D.V. Dedovich⁶⁴,
 J. Degenhardt¹²⁰, J. Del Peso⁸⁰, T. Del Prete^{122a,122b}, T. Delemontex⁵⁵, M. Deliyergiyev⁷⁴,
 A. Dell'Acqua³⁰, L. Dell'Asta²², M. Della Pietra^{102a,k}, D. della Volpe^{102a,102b}, M. Delmastro⁵,
 P.A. Delsart⁵⁵, C. Deluca¹⁰⁵, S. Demers¹⁷⁶, M. Demichev⁶⁴, B. Demirkoz^{12,m}, S.P. Denisov¹²⁸,
 D. Derendarz³⁹, J.E. Derkaoui^{135d}, F. Derue⁷⁸, P. Dervan⁷³, K. Desch²¹, E. Devetak¹⁴⁸,
 P.O. Deviveiros¹⁰⁵, A. Dewhurst¹²⁹, B. DeWilde¹⁴⁸, S. Dhaliwal¹⁵⁸, R. Dhullipudi^{25,n},
 A. Di Ciaccio^{133a,133b}, L. Di Ciaccio⁵, C. Di Donato^{102a,102b}, A. Di Girolamo³⁰, B. Di Girolamo³⁰,
 S. Di Luise^{134a,134b}, A. Di Mattia¹⁵², B. Di Micco³⁰, R. Di Nardo⁴⁷, A. Di Simone^{133a,133b},
 R. Di Sipio^{20a,20b}, M.A. Diaz^{32a}, E.B. Diehl⁸⁷, J. Dietrich⁴², T.A. Dietzsch^{58a}, S. Diglio⁸⁶,
 K. Dindar Yagci⁴⁰, J. Dingfelder²¹, F. Dinut^{26a}, C. Dionisi^{132a,132b}, P. Dita^{26a}, S. Dita^{26a},
 F. Dittus³⁰, F. Djama⁸³, T. Djobava^{51b}, M.A.B. do Vale^{24c}, A. Do Valle Wemans^{124a,o},
 T.K.O. Doan⁵, M. Dobbs⁸⁵, D. Dobos³⁰, E. Dobson^{30,p}, J. Dodd³⁵, C. Doglioni⁴⁹, T. Doherty⁵³,
 Y. Doi^{65,*}, J. Dolejsi¹²⁷, Z. Dolezal¹²⁷, B.A. Dolgoshein^{96,*}, T. Dohmae¹⁵⁵, M. Donadelli^{24d},
 J. Donini³⁴, J. Dopke³⁰, A. Doria^{102a}, A. Dos Anjos¹⁷³, A. Dotti^{122a,122b}, M.T. Dova⁷⁰,
 A.D. Doxiadis¹⁰⁵, A.T. Doyle⁵³, N. Dressnandt¹²⁰, M. Dris¹⁰, J. Dubbert⁹⁹, S. Dube¹⁵,
 E. Duchovni¹⁷², G. Duckeck⁹⁸, D. Duda¹⁷⁵, A. Dudarev³⁰, F. Dudziak⁶³, M. Dührssen³⁰,
 I.P. Duerdoth⁸², L. Duflot¹¹⁵, M-A. Dufour⁸⁵, L. Duguid⁷⁶, M. Dunford^{58a}, H. Duran Yildiz^{4a},
 R. Duxfield¹³⁹, M. Dwuznik³⁸, M. Düren⁵², W.L. Ebenstein⁴⁵, J. Ebke⁹⁸, S. Eckweiler⁸¹,
 W. Edson², C.A. Edwards⁷⁶, N.C. Edwards⁵³, W. Ehrenfeld⁴², T. Eifert¹⁴³, G. Eigen¹⁴,
 K. Einsweiler¹⁵, E. Eisenhandler⁷⁵, T. Ekelof¹⁶⁶, M. El Kacimi^{135c}, M. Ellert¹⁶⁶, S. Elles⁵,
 F. Ellinghaus⁸¹, K. Ellis⁷⁵, N. Ellis³⁰, J. Elmsheuser⁹⁸, M. Elsing³⁰, D. Emeliyanov¹²⁹,
 R. Engelmann¹⁴⁸, A. Engl⁹⁸, B. Epp⁶¹, J. Erdmann¹⁷⁶, A. Ereditato¹⁷, D. Eriksson^{146a}, J. Ernst²,
 M. Ernst²⁵, J. Ernwein¹³⁶, D. Errede¹⁶⁵, S. Errede¹⁶⁵, E. Ertel⁸¹, M. Escalier¹¹⁵, H. Esch⁴³,
 C. Escobar¹²³, X. Espinal Curull¹², B. Esposito⁴⁷, F. Etienne⁸³, A.I. Etienvre¹³⁶, E. Etzion¹⁵³,
 D. Evangelakou⁵⁴, H. Evans⁶⁰, L. Fabbri^{20a,20b}, C. Fabre³⁰, R.M. Fakhruddinov¹²⁸,
 S. Falciano^{132a}, Y. Fang^{33a}, M. Fanti^{89a,89b}, A. Farbin⁸, A. Farilla^{134a}, J. Farley¹⁴⁸,
 T. Farooque¹⁵⁸, S. Farrell¹⁶³, S.M. Farrington¹⁷⁰, P. Farthouat³⁰, F. Fassi¹⁶⁷, P. Fassnacht³⁰,
 D. Fassouliotis⁹, B. Fatholahzadeh¹⁵⁸, A. Favareto^{89a,89b}, L. Fayard¹¹⁵, P. Federic^{144a},
 O.L. Fedin¹²¹, W. Fedorko⁸⁸, M. Fehling-Kaschek⁴⁸, L. Feligioni⁸³, C. Feng^{33d}, E.J. Feng⁶,
 A.B. Fenyuk¹²⁸, J. Ferencei^{144b}, W. Fernando⁶, S. Ferrag⁵³, J. Ferrando⁵³, V. Ferrara⁴²,
 A. Ferrari¹⁶⁶, P. Ferrari¹⁰⁵, R. Ferrari^{119a}, D.E. Ferreira de Lima⁵³, A. Ferrer¹⁶⁷, D. Ferrere⁴⁹,
 C. Ferretti⁸⁷, A. Ferretto Parodi^{50a,50b}, M. Fiascaris³¹, F. Fiedler⁸¹, A. Filipčič⁷⁴, F. Filthaut¹⁰⁴,
 M. Fincke-Keeler¹⁶⁹, M.C.N. Fiolhais^{124a,i}, L. Fiorini¹⁶⁷, A. Firan⁴⁰, G. Fischer⁴², M.J. Fisher¹⁰⁹,
 M. Flechl⁴⁸, I. Fleck¹⁴¹, J. Fleckner⁸¹, P. Fleischmann¹⁷⁴, S. Fleischmann¹⁷⁵, T. Flick¹⁷⁵,
 A. Floderus⁷⁹, L.R. Flores Castillo¹⁷³, A.C. Florez Bustos^{159b}, M.J. Flowerdew⁹⁹,
 T. Fonseca Martin¹⁷, A. Formica¹³⁶, A. Forti⁸², D. Fortin^{159a}, D. Fournier¹¹⁵, A.J. Fowler⁴⁵,
 H. Fox⁷¹, P. Francavilla¹², M. Franchini^{20a,20b}, S. Franchino^{119a,119b}, D. Francis³⁰, T. Frank¹⁷²,
 M. Franklin⁵⁷, S. Franz³⁰, M. Fraternali^{119a,119b}, S. Fratina¹²⁰, S.T. French²⁸, C. Friedrich⁴²,
 F. Friedrich⁴⁴, D. Froidevaux³⁰, J.A. Frost²⁸, C. Fukunaga¹⁵⁶, E. Fullana Torregrosa¹²⁷,
 B.G. Fulsom¹⁴³, J. Fuster¹⁶⁷, C. Gabaldon³⁰, O. Gabizon¹⁷², T. Gadfort²⁵, S. Gadomski⁴⁹,
 G. Gagliardi^{50a,50b}, P. Gagnon⁶⁰, C. Galea⁹⁸, B. Galhardo^{124a}, E.J. Gallas¹¹⁸, V. Gallo¹⁷,
 B.J. Gallop¹²⁹, P. Gallus¹²⁵, K.K. Gan¹⁰⁹, Y.S. Gao^{143,g}, A. Gaponenko¹⁵, F. Garbersen¹⁷⁶,
 M. Garcia-Sciveres¹⁵, C. García¹⁶⁷, J.E. García Navarro¹⁶⁷, R.W. Gardner³¹, N. Garelli³⁰,
 V. Garonne³⁰, C. Gatti⁴⁷, G. Gaudio^{119a}, B. Gaur¹⁴¹, L. Gauthier¹³⁶, P. Gauzzi^{132a,132b},
 I.L. Gavrilenko⁹⁴, C. Gay¹⁶⁸, G. Gaycken²¹, E.N. Gazis¹⁰, P. Ge^{33d}, Z. Gecse¹⁶⁸, C.N.P. Gee¹²⁹,
 D.A.A. Geerts¹⁰⁵, Ch. Geich-Gimbel²¹, K. Gellerstedt^{146a,146b}, C. Gemme^{50a}, A. Gemmell⁵³,
 M.H. Genest⁵⁵, S. Gentile^{132a,132b}, M. George⁵⁴, S. George⁷⁶, D. Gerbaudo¹², P. Gerlach¹⁷⁵,

A. Gershon¹⁵³, C. Geweniger^{58a}, H. Ghazlane^{135b}, N. Ghodbane³⁴, B. Giacobbe^{20a},
 S. Giagu^{132a,132b}, V. Giangiobbe¹², F. Gianotti³⁰, B. Gibbard²⁵, A. Gibson¹⁵⁸, S.M. Gibson³⁰,
 M. Gilchriese¹⁵, D. Gillberg²⁹, A.R. Gillman¹²⁹, D.M. Gingrich^{3,f}, J. Ginzburg¹⁵³, N. Giokaris⁹,
 M.P. Giordani^{164c}, R. Giordano^{102a,102b}, F.M. Giorgi¹⁶, P. Giovannini⁹⁹, P.F. Giraud¹³⁶,
 D. Giugni^{89a}, M. Giunta⁹³, B.K. Gjelsten¹¹⁷, L.K. Gladilin⁹⁷, C. Glasman⁸⁰, J. Glatzer²¹,
 A. Glazov⁴², K.W. Glitza¹⁷⁵, G.L. Glonti⁶⁴, J.R. Goddard⁷⁵, J. Godfrey¹⁴², J. Godlewski³⁰,
 M. Goebel⁴², T. Göpfert⁴⁴, C. Goeringer⁸¹, C. Gössling⁴³, S. Goldfarb⁸⁷, T. Golling¹⁷⁶,
 D. Golubkov¹²⁸, A. Gomes^{124a,c}, L.S. Gomez Fajardo⁴², R. Gonçalo⁷⁶,
 J. Goncalves Pinto Firmino Da Costa⁴², L. Gonella²¹, S. González de la Hoz¹⁶⁷,
 G. Gonzalez Parra¹², M.L. Gonzalez Silva²⁷, S. Gonzalez-Sevilla⁴⁹, J.J. Goodson¹⁴⁸,
 L. Goossens³⁰, P.A. Gorbounov⁹⁵, H.A. Gordon²⁵, I. Gorelov¹⁰³, G. Gorfine¹⁷⁵, B. Gorini³⁰,
 E. Gorini^{72a,72b}, A. Gorišek⁷⁴, E. Gornicki³⁹, A.T. Goshaw⁶, M. Gosselink¹⁰⁵, M.I. Gostkin⁶⁴,
 I. Gough Eschrich¹⁶³, M. Gouighri^{135a}, D. Goujdami^{135c}, M.P. Goulette⁴⁹, A.G. Goussiou¹³⁸,
 C. Goy⁵, S. Gozpinar²³, I. Grabowska-Bold³⁸, P. Grafström^{20a,20b}, K.-J. Grah⁴², E. Gramstad¹¹⁷,
 F. Grancagnolo^{72a}, S. Grancagnolo¹⁶, V. Grassi¹⁴⁸, V. Gratchev¹²¹, N. Grau³⁵, H.M. Gray³⁰,
 J.A. Gray¹⁴⁸, E. Graziani^{134a}, O.G. Grebenyuk¹²¹, T. Greenshaw⁷³, Z.D. Greenwood^{25,n},
 K. Gregersen³⁶, I.M. Gregor⁴², P. Grenier¹⁴³, J. Griffiths⁸, N. Grigalashvili⁶⁴, A.A. Grillo¹³⁷,
 K. Grimm⁷¹, S. Grinstein¹², Ph. Gris³⁴, Y.V. Grishkevich⁹⁷, J.-F. Grivaz¹¹⁵, A. Grohsjean⁴²,
 E. Gross¹⁷², J. Grosse-Knetter⁵⁴, J. Groth-Jensen¹⁷², K. Grybel¹⁴¹, D. Guest¹⁷⁶, C. Guicheney³⁴,
 E. Guido^{50a,50b}, S. Guindon⁵⁴, U. Gul⁵³, J. Gunther¹²⁵, B. Guo¹⁵⁸, J. Guo³⁵, P. Gutierrez¹¹¹,
 N. Guttman¹⁵³, O. Gutzwiller¹⁷³, C. Guyot¹³⁶, C. Gwenlan¹¹⁸, C.B. Gwilliam⁷³, A. Haas¹⁰⁸,
 S. Haas³⁰, C. Haber¹⁵, H.K. Hadavand⁸, D.R. Hadley¹⁸, P. Haefner²¹, F. Hahn³⁰, Z. Hajduk³⁹,
 H. Hakobyan¹⁷⁷, D. Hall¹¹⁸, K. Hamacher¹⁷⁵, P. Hamal¹¹³, K. Hamano⁸⁶, M. Hamer⁵⁴,
 A. Hamilton^{145b,q}, S. Hamilton¹⁶¹, L. Han^{33b}, K. Hanagaki¹¹⁶, K. Hanawa¹⁶⁰, M. Hance¹⁵,
 C. Handel⁸¹, P. Hanke^{58a}, J.R. Hansen³⁶, J.B. Hansen³⁶, J.D. Hansen³⁶, P.H. Hansen³⁶,
 P. Hansson¹⁴³, K. Hara¹⁶⁰, T. Harenberg¹⁷⁵, S. Harkusha⁹⁰, D. Harper⁸⁷, R.D. Harrington⁴⁶,
 O.M. Harris¹³⁸, J. Hartert⁴⁸, F. Hartjes¹⁰⁵, T. Haruyama⁶⁵, A. Harvey⁵⁶, S. Hasegawa¹⁰¹,
 Y. Hasegawa¹⁴⁰, S. Hassani¹³⁶, S. Haug¹⁷, M. Hauschild³⁰, R. Hauser⁸⁸, M. Havranek²¹,
 C.M. Hawkes¹⁸, R.J. Hawkings³⁰, A.D. Hawkins⁷⁹, T. Hayakawa⁶⁶, T. Hayashi¹⁶⁰, D. Hayden⁷⁶,
 C.P. Hays¹¹⁸, H.S. Hayward⁷³, S.J. Haywood¹²⁹, S.J. Head¹⁸, V. Hedberg⁷⁹, L. Heelan⁸,
 S. Heim¹²⁰, B. Heinemann¹⁵, S. Heisterkamp³⁶, L. Helary²², C. Heller⁹⁸, M. Heller³⁰,
 S. Hellman^{146a,146b}, D. Hellmich²¹, C. Helsens¹², R.C.W. Henderson⁷¹, M. Henke^{58a},
 A. Henrichs¹⁷⁶, A.M. Henriques Correia³⁰, S. Henrot-Versille¹¹⁵, C. Hensel⁵⁴, C.M. Hernandez⁸,
 Y. Hernández Jiménez¹⁶⁷, R. Herrberg¹⁶, G. Herten⁴⁸, R. Hertenberger⁹⁸, L. Hervas³⁰,
 G.G. Hesketh⁷⁷, N.P. Hessey¹⁰⁵, E. Higón-Rodríguez¹⁶⁷, J.C. Hill²⁸, K.H. Hiller⁴², S. Hillert²¹,
 S.J. Hillier¹⁸, I. Hinchliffe¹⁵, E. Hines¹²⁰, M. Hirose¹¹⁶, F. Hirsch⁴³, D. Hirschbuehl¹⁷⁵,
 J. Hobbs¹⁴⁸, N. Hod¹⁵³, M.C. Hodgkinson¹³⁹, P. Hodgson¹³⁹, A. Hoecker³⁰, M.R. Hoferkamp¹⁰³,
 J. Hoffman⁴⁰, D. Hoffmann⁸³, M. Hohlfield⁸¹, M. Holder¹⁴¹, S.O. Holmgren^{146a}, T. Holy¹²⁶,
 J.L. Holzbauer⁸⁸, T.M. Hong¹²⁰, L. Hooft van Huysduynen¹⁰⁸, S. Horner⁴⁸, J.-Y. Hostachy⁵⁵,
 S. Hou¹⁵¹, A. Hoummada^{135a}, J. Howard¹¹⁸, J. Howarth⁸², I. Hristova¹⁶, J. Hrivnac¹¹⁵,
 T. Hryn'ova⁵, P.J. Hsu⁸¹, S.-C. Hsu¹³⁸, D. Hu³⁵, Z. Hubacek³⁰, F. Hubaut⁸³, F. Huegging²¹,
 A. Huettmann⁴², T.B. Huffman¹¹⁸, E.W. Hughes³⁵, G. Hughes⁷¹, M. Huhtinen³⁰, M. Hurwitz¹⁵,
 N. Huseynov^{64,r}, J. Huston⁸⁸, J. Huth⁵⁷, G. Iacobucci⁴⁹, G. Iakovidis¹⁰, M. Ibbotson⁸²,
 I. Ibragimov¹⁴¹, L. Iconomidou-Fayard¹¹⁵, J. Idarraga¹¹⁵, P. Iengo^{102a}, O. Igonkina¹⁰⁵,
 Y. Ikegami⁶⁵, M. Ikeno⁶⁵, D. Iliadis¹⁵⁴, N. Ilic¹⁵⁸, T. Ince⁹⁹, P. Ioannou⁹, M. Iodice^{134a},
 K. Iordanidou⁹, V. Ippolito^{132a,132b}, A. Irls Quiles¹⁶⁷, C. Isaksson¹⁶⁶, M. Ishino⁶⁷,
 M. Ishitsuka¹⁵⁷, R. Ishmukhametov¹⁰⁹, C. Issever¹¹⁸, S. Istin^{19a}, A.V. Ivashin¹²⁸, W. Iwanski³⁹,
 H. Iwasaki⁶⁵, J.M. Izen⁴¹, V. Izzo^{102a}, B. Jackson¹²⁰, J.N. Jackson⁷³, P. Jackson¹, M.R. Jaekel³⁰,
 V. Jain², K. Jakobs⁴⁸, S. Jakobsen³⁶, T. Jakoubek¹²⁵, J. Jakubek¹²⁶, D.O. Jamin¹⁵¹,
 D.K. Jana¹¹¹, E. Jansen⁷⁷, H. Jansen³⁰, J. Janssen²¹, A. Jantsch⁹⁹, M. Janus⁴⁸, R.C. Jared¹⁷³,
 G. Jarlskog⁷⁹, L. Jeanty⁵⁷, I. Jen-La Plante³¹, G.-Y. Jeng¹⁵⁰, D. Jennens⁸⁶, P. Jenni³⁰,
 A.E. Loevschall-Jensen³⁶, P. Jež³⁶, S. Jézéquel⁵, M.K. Jha^{20a}, H. Ji¹⁷³, W. Ji⁸¹, J. Jia¹⁴⁸,

Y. Jiang^{33b}, M. Jimenez Belenguer⁴², S. Jin^{33a}, O. Jinnouchi¹⁵⁷, M.D. Joergensen³⁶, D. Joffe⁴⁰,
 M. Johansen^{146a,146b}, K.E. Johansson^{146a}, P. Johansson¹³⁹, S. Johnert⁴², K.A. Johns⁷,
 K. Jon-And^{146a,146b}, G. Jones¹⁷⁰, R.W.L. Jones⁷¹, T.J. Jones⁷³, C. Joram³⁰, P.M. Jorge^{124a},
 K.D. Joshi⁸², J. Jovicevic¹⁴⁷, T. Jovin^{13b}, X. Ju¹⁷³, C.A. Jung⁴³, R.M. Jungst³⁰, V. Juranek¹²⁵,
 P. Jussel⁶¹, A. Juste Rozas¹², S. Kabana¹⁷, M. Kaci¹⁶⁷, A. Kaczmarska³⁹, P. Kadlecik³⁶,
 M. Kado¹¹⁵, H. Kagan¹⁰⁹, M. Kagan⁵⁷, E. Kajomovitz¹⁵², S. Kalinin¹⁷⁵, L.V. Kalinovskaya⁶⁴,
 S. Kama⁴⁰, N. Kanaya¹⁵⁵, M. Kaneda³⁰, S. Kaneti²⁸, T. Kanno¹⁵⁷, V.A. Kantserov⁹⁶,
 J. Kanzaki⁶⁵, B. Kaplan¹⁰⁸, A. Kapliy³¹, D. Kar⁵³, M. Karagounis²¹, K. Karakostas¹⁰,
 M. Karnevskiy^{58b}, V. Kartvelishvili⁷¹, A.N. Karyukhin¹²⁸, L. Kashif¹⁷³, G. Kasieczka^{58b},
 R.D. Kass¹⁰⁹, A. Kastanas¹⁴, Y. Kataoka¹⁵⁵, J. Katzy⁴², V. Kaushik⁷, K. Kawagoe⁶⁹,
 T. Kawamoto¹⁵⁵, G. Kawamura⁸¹, M.S. Kayl¹⁰⁵, S. Kazama¹⁵⁵, V.F. Kazanin¹⁰⁷,
 M.Y. Kazarinov⁶⁴, R. Keeler¹⁶⁹, P.T. Keener¹²⁰, R. Kehoe⁴⁰, M. Keil⁵⁴, G.D. Kekelidze⁶⁴,
 J.S. Keller¹³⁸, M. Kenyon⁵³, O. Kepka¹²⁵, N. Kerschen³⁰, B.P. Kerševan⁷⁴, S. Kersten¹⁷⁵,
 K. Kessoku¹⁵⁵, J. Keung¹⁵⁸, F. Khalil-zada¹¹, H. Khandanyan^{146a,146b}, A. Khanov¹¹²,
 D. Kharchenko⁶⁴, A. Khodinov⁹⁶, A. Khomich^{58a}, T.J. Khoo²⁸, G. Khoriauli²¹, A. Khoroshilov¹⁷⁵,
 V. Khovanskiy⁹⁵, E. Khramov⁶⁴, J. Khubua^{51b}, H. Kim^{146a,146b}, S.H. Kim¹⁶⁰, N. Kimura¹⁷¹,
 O. Kind¹⁶, B.T. King⁷³, M. King⁶⁶, R.S.B. King¹¹⁸, J. Kirk¹²⁹, A.E. Kiryunin⁹⁹, T. Kishimoto⁶⁶,
 D. Kisielewska³⁸, T. Kitamura⁶⁶, T. Kittelmann¹²³, K. Kiuchi¹⁶⁰, E. Kladiva^{144b}, M. Klein⁷³,
 U. Klein⁷³, K. Kleinknecht⁸¹, M. Klemetti⁸⁵, A. Klier¹⁷², P. Klimek^{146a,146b}, A. Klimentov²⁵,
 R. Klingenberg⁴³, J.A. Klinger⁸², E.B. Klinkby³⁶, T. Klioutchnikova³⁰, P.F. Klok¹⁰⁴, S. Klous¹⁰⁵,
 E.-E. Kluge^{58a}, T. Kluge⁷³, P. Kluit¹⁰⁵, S. Kluth⁹⁹, E. Kneringer⁶¹, E.B.F.G. Knoops⁸³,
 A. Knue⁵⁴, B.R. Ko⁴⁵, T. Kobayashi¹⁵⁵, M. Kobel⁴⁴, M. Kocian¹⁴³, P. Kodys¹²⁷, K. Köneke³⁰,
 A.C. König¹⁰⁴, S. Koenig⁸¹, L. Köpke⁸¹, F. Koetsveld¹⁰⁴, P. Koesvarko²¹, T. Koffas²⁹,
 E. Koffeman¹⁰⁵, L.A. Kogan¹¹⁸, S. Kohlmann¹⁷⁵, F. Kohn⁵⁴, Z. Kohout¹²⁶, T. Kohriki⁶⁵,
 T. Koi¹⁴³, G.M. Kolachev^{107,*}, H. Kolanoski¹⁶, V. Kolesnikov⁶⁴, I. Koletsou^{89a}, J. Koll⁸⁸,
 A.A. Komar⁹⁴, Y. Komori¹⁵⁵, T. Kondo⁶⁵, T. Kono^{42,s}, A.I. Kononov⁴⁸, R. Konoplich^{108,t},
 N. Konstantinidis⁷⁷, R. Kopeliansky¹⁵², S. Koperny³⁸, K. Korcyl³⁹, K. Kordas¹⁵⁴, A. Korn¹¹⁸,
 A. Korol¹⁰⁷, I. Korolkov¹², E.V. Korolkova¹³⁹, V.A. Korotkov¹²⁸, O. Kortner⁹⁹, S. Kortner⁹⁹,
 V.V. Kostyukhin²¹, S. Kotov⁹⁹, V.M. Kotov⁶⁴, A. Kotwal⁴⁵, C. Kourkoumelis⁹, V. Kouskoura¹⁵⁴,
 A. Koutsman^{159a}, R. Kowalewski¹⁶⁹, T.Z. Kowalski³⁸, W. Kozanecki¹³⁶, A.S. Kozhin¹²⁸,
 V. Kral¹²⁶, V.A. Kramarenko⁹⁷, G. Kramberger⁷⁴, M.W. Krasny⁷⁸, A. Krasznahorkay¹⁰⁸,
 J.K. Kraus²¹, A. Kravchenko²⁵, S. Kreiss¹⁰⁸, F. Krejci¹²⁶, J. Kretzschmar⁷³, K. Kreutzfeldt⁵²,
 N. Krieger⁵⁴, P. Krieger¹⁵⁸, K. Kroeninger⁵⁴, H. Kroha⁹⁹, J. Kroll¹²⁰, J. Kroseberg²¹, J. Krstic^{13a},
 U. Kruchonak⁶⁴, H. Krüger²¹, T. Kruker¹⁷, N. Krumnack⁶³, Z.V. Krumshteyn⁶⁴, M.K. Kruse⁴⁵,
 T. Kubota⁸⁶, S. Kuday^{4a}, S. Kuehn⁴⁸, A. Kugel^{58c}, T. Kuhl⁴², D. Kuhn⁶¹, V. Kukhtin⁶⁴,
 Y. Kulchitsky⁹⁰, S. Kuleshov^{32b}, C. Kummer⁹⁸, M. Kuna⁷⁸, J. Kunkle¹²⁰, A. Kupco¹²⁵,
 H. Kurashige⁶⁶, M. Kurata¹⁶⁰, Y.A. Kurochkin⁹⁰, V. Kus¹²⁵, E.S. Kuwertz¹⁴⁷, M. Kuze¹⁵⁷,
 J. Kvita¹⁴², R. Kwee¹⁶, A. La Rosa⁴⁹, L. La Rotonda^{37a,37b}, L. Labarga⁸⁰, S. Lablak^{135a},
 C. Lacasta¹⁶⁷, F. Lacava^{132a,132b}, J. Lacey²⁹, H. Lacker¹⁶, D. Lacour⁷⁸, V.R. Lacuesta¹⁶⁷,
 E. Ladygin⁶⁴, R. Lafaye⁵, B. Laforge⁷⁸, T. Lagouri¹⁷⁶, S. Lai⁴⁸, E. Laisne⁵⁵, L. Lambourne⁷⁷,
 C.L. Lampen⁷, W. Lampl⁷, E. Lancon¹³⁶, U. Landgraf⁴⁸, M.P.J. Landon⁷⁵, V.S. Lang^{58a},
 C. Lange⁴², A.J. Lankford¹⁶³, F. Lanni²⁵, K. Lantzscho³⁰, A. Lanza^{119a}, S. Laplace⁷⁸,
 C. Lapoire²¹, J.F. Laporte¹³⁶, T. Lari^{89a}, A. Lerner¹¹⁸, M. Lassnig³⁰, P. Laurelli⁴⁷,
 V. Lavorini^{37a,37b}, W. Lavrijsen¹⁵, P. Laycock⁷³, O. Le Dortz⁷⁸, E. Le Guirriec⁸³,
 E. Le Menedeu¹², T. LeCompte⁶, F. Ledroit-Guillon⁵⁵, H. Lee¹⁰⁵, J.S.H. Lee¹¹⁶, S.C. Lee¹⁵¹,
 L. Lee¹⁷⁶, M. Lefebvre¹⁶⁹, M. Legendre¹³⁶, F. Legger⁹⁸, C. Leggett¹⁵, M. Lehmacher²¹,
 G. Lehmann Miotto³⁰, A.G. Leister¹⁷⁶, M.A.L. Leite^{24d}, R. Leitner¹²⁷, D. Lellouch¹⁷²,
 B. Lemmer⁵⁴, V. Lendermann^{58a}, K.J.C. Leney^{145b}, T. Lenz¹⁰⁵, G. Lenzen¹⁷⁵, B. Lenzi³⁰,
 K. Leonhardt⁴⁴, S. Leontsinis¹⁰, F. Lepold^{58a}, C. Leroy⁹³, J-R. Lessard¹⁶⁹, C.G. Lester²⁸,
 C.M. Lester¹²⁰, J. Levêque⁵, D. Levin⁸⁷, L.J. Levinson¹⁷², A. Lewis¹¹⁸, G.H. Lewis¹⁰⁸,
 A.M. Leyko²¹, M. Leyton¹⁶, B. Li^{33b}, B. Li⁸³, H. Li¹⁴⁸, H.L. Li³¹, S. Li^{33b,u}, X. Li⁸⁷,
 Z. Liang^{118,v}, H. Liao³⁴, B. Liberti^{133a}, P. Lichard³⁰, M. Lichtnecker⁹⁸, K. Lie¹⁶⁵, W. Liebig¹⁴,

C. Limbach²¹, A. Limosani⁸⁶, M. Limper⁶², S.C. Lin^{151,w}, F. Linde¹⁰⁵, J.T. Linnemann⁸⁸, E. Lipeles¹²⁰, A. Lipniacka¹⁴, T.M. Liss¹⁶⁵, D. Lissauer²⁵, A. Lister⁴⁹, A.M. Litke¹³⁷, C. Liu²⁹, D. Liu¹⁵¹, J.B. Liu⁸⁷, L. Liu⁸⁷, M. Liu^{33b}, Y. Liu^{33b}, M. Livan^{119a,119b}, S.S.A. Livermore¹¹⁸, A. Lleres⁵⁵, J. Llorente Merino⁸⁰, S.L. Lloyd⁷⁵, E. Lobodzinska⁴², P. Loch⁷, W.S. Lockman¹³⁷, T. Loddenkoetter²¹, F.K. Loebinger⁸², A. Loginov¹⁷⁶, C.W. Loh¹⁶⁸, T. Lohse¹⁶, K. Lohwasser⁴⁸, M. Lokajicek¹²⁵, V.P. Lombardo⁵, R.E. Long⁷¹, L. Lopes^{124a}, D. Lopez Mateos⁵⁷, J. Lorenz⁹⁸, N. Lorenzo Martinez¹¹⁵, M. Losada¹⁶², P. Loscutoff¹⁵, F. Lo Sterzo^{132a,132b}, M.J. Losty^{159a,*}, X. Lou⁴¹, A. Lounis¹¹⁵, K.F. Loureiro¹⁶², J. Love⁶, P.A. Love⁷¹, A.J. Lowe^{143.g}, F. Lu^{33a}, H.J. Lubatti¹³⁸, C. Luci^{132a,132b}, A. Lucotte⁵⁵, D. Ludwig⁴², I. Ludwig⁴⁸, J. Ludwig⁴⁸, F. Luehring⁶⁰, G. Luijckx¹⁰⁵, W. Lukas⁶¹, L. Luminari^{132a}, E. Lund¹¹⁷, B. Lund-Jensen¹⁴⁷, B. Lundberg⁷⁹, J. Lundberg^{146a,146b}, O. Lundberg^{146a,146b}, J. Lundquist³⁶, M. Lungwitz⁸¹, D. Lynn²⁵, E. Lytken⁷⁹, H. Ma²⁵, L.L. Ma¹⁷³, G. Maccarrone⁴⁷, A. Macchiolo⁹⁹, B. Maček⁷⁴, J. Machado Miguens^{124a}, D. Macina³⁰, R. Mackeprang³⁶, R.J. Madaras¹⁵, H.J. Maddocks⁷¹, W.F. Mader⁴⁴, R. Maenner^{58c}, M. Maeno⁵, T. Maeno²⁵, P. Mättig¹⁷⁵, S. Mättig⁴², L. Magnoni¹⁶³, E. Magradze⁵⁴, K. Mahboubi⁴⁸, J. Mahlstedt¹⁰⁵, S. Mahmoud⁷³, G. Mahout¹⁸, C. Maiani¹³⁶, C. Maidantchik^{24a}, A. Maio^{124a,c}, S. Majewski²⁵, Y. Makida⁶⁵, N. Makovec¹¹⁵, P. Mal¹³⁶, B. Malaescu³⁰, Pa. Malecki³⁹, P. Malecki³⁹, V.P. Maleev¹²¹, F. Malek⁵⁵, U. Mallik⁶², D. Malon⁶, C. Malone¹⁴³, S. Maltezos¹⁰, V. Malyshev¹⁰⁷, S. Malyukov³⁰, J. Mamuzic^{13b}, A. Manabe⁶⁵, L. Mandelli^{89a}, I. Mandić⁷⁴, R. Mandrysch⁶², J. Maneira^{124a}, A. Manfredini⁹⁹, L. Manhaes de Andrade Filho^{24b}, J.A. Manjarres Ramos¹³⁶, A. Mann⁹⁸, P.M. Manning¹³⁷, A. Manousakis-Katsikakis⁹, B. Mansoulie¹³⁶, R. Mantifel⁸⁵, A. Mapelli³⁰, L. Mapelli³⁰, L. March¹⁶⁷, J.F. Marchand²⁹, F. Marchese^{133a,133b}, G. Marchiori⁷⁸, M. Marcisovsky¹²⁵, C.P. Marino¹⁶⁹, F. Marroquim^{24a}, Z. Marshall³⁰, L.F. Marti¹⁷, S. Marti-Garcia¹⁶⁷, B. Martin³⁰, B. Martin⁸⁸, J.P. Martin⁹³, T.A. Martin¹⁸, V.J. Martin⁴⁶, B. Martin dit Latour⁴⁹, S. Martin-Haugh¹⁴⁹, H. Martinez¹³⁶, M. Martinez¹², V. Martinez Outschoorn⁵⁷, A.C. Martyniuk¹⁶⁹, M. Marx⁸², F. Marzano^{132a}, A. Marzin¹¹¹, L. Masetti⁸¹, T. Mashimo¹⁵⁵, R. Mashinistov⁹⁴, J. Masik⁸², A.L. Maslennikov¹⁰⁷, I. Massa^{20a,20b}, G. Massaro¹⁰⁵, N. Massol⁵, P. Mastrandrea¹⁴⁸, A. Mastroberardino^{37a,37b}, T. Masubuchi¹⁵⁵, H. Matsunaga¹⁵⁵, T. Matsushita⁶⁶, C. Mattraversi^{118,d}, J. Maurer⁸³, S.J. Maxfield⁷³, D.A. Maximov^{107,h}, A. Mayne¹³⁹, R. Mazini¹⁵¹, M. Mazur²¹, L. Mazzaferro^{133a,133b}, M. Mazzanti^{89a}, J. Mc Donald⁸⁵, S.P. Mc Kee⁸⁷, A. McCarn¹⁶⁵, R.L. McCarthy¹⁴⁸, T.G. McCarthy²⁹, N.A. McCubbin¹²⁹, K.W. McFarlane^{56,*}, J.A. McFayden¹³⁹, G. Mchedlize^{51b}, T. Mclaughlan¹⁸, S.J. McMahon¹²⁹, R.A. McPherson^{169,i}, A. Meade⁸⁴, J. Mechnich¹⁰⁵, M. Mechtel¹⁷⁵, M. Medinnis⁴², S. Meehan³¹, R. Meera-Lebbai¹¹¹, T. Meguro¹¹⁶, S. Mehlhase³⁶, A. Mehta⁷³, K. Meier^{58a}, B. Meirose⁷⁹, C. Melachrinou³¹, B.R. Mellado Garcia¹⁷³, F. Meloni^{89a,89b}, L. Mendoza Navas¹⁶², Z. Meng^{151,x}, A. Mengarelli^{20a,20b}, S. Menke⁹⁹, E. Meoni¹⁶¹, K.M. Mercurio⁵⁷, P. Mermod⁴⁹, L. Merola^{102a,102b}, C. Meroni^{89a}, F.S. Merritt³¹, H. Merritt¹⁰⁹, A. Messina^{30,y}, J. Metcalfe²⁵, A.S. Mete¹⁶³, C. Meyer⁸¹, C. Meyer³¹, J-P. Meyer¹³⁶, J. Meyer¹⁷⁴, J. Meyer⁵⁴, S. Michal³⁰, L. Micu^{26a}, R.P. Middleton¹²⁹, S. Migas⁷³, L. Mijović¹³⁶, G. Mikenberg¹⁷², M. Mikestikova¹²⁵, M. Mikuž⁷⁴, D.W. Miller³¹, R.J. Miller⁸⁸, W.J. Mills¹⁶⁸, C. Mills⁵⁷, A. Milov¹⁷², D.A. Milstead^{146a,146b}, D. Milstein¹⁷², G. Milutinovic-Dumbelovic^{13a}, A.A. Minaenko¹²⁸, M. Miñano Moya¹⁶⁷, I.A. Minashvili⁶⁴, A.I. Mincer¹⁰⁸, B. Mindur³⁸, M. Mineev⁶⁴, Y. Ming¹⁷³, L.M. Mir¹², G. Mirabelli^{132a}, J. Mitrevski¹³⁷, V.A. Mitsou¹⁶⁷, S. Mitsui⁶⁵, P.S. Miyagawa¹³⁹, J.U. Mjörnmark⁷⁹, T. Moe^{146a,146b}, V. Moeller²⁸, K. Mönig⁴², N. Möser²¹, S. Mohapatra¹⁴⁸, W. Mohr⁴⁸, R. Moles-Valls¹⁶⁷, A. Molfetas³⁰, J. Monk⁷⁷, E. Monnier⁸³, J. Montejo Berlingen¹², F. Monticelli⁷⁰, S. Monzani^{20a,20b}, R.W. Moore³, G.F. Moorhead⁸⁶, C. Mora Herrera⁴⁹, A. Moraes⁵³, N. Morange¹³⁶, J. Morel⁵⁴, G. Morello^{37a,37b}, D. Moreno⁸¹, M. Moreno Llácer¹⁶⁷, P. Morettini^{50a}, M. Morgenstern⁴⁴, M. Morii⁵⁷, A.K. Morley³⁰, G. Mornacchi³⁰, J.D. Morris⁷⁵, L. Morvaj¹⁰¹, H.G. Moser⁹⁹, M. Mosidze^{51b}, J. Moss¹⁰⁹, R. Mount¹⁴³, E. Mountricha^{10,z}, S.V. Mouraviev^{94,*}, E.J.W. Moyses⁸⁴, F. Mueller^{58a}, J. Mueller¹²³, K. Mueller²¹, T.A. Müller⁹⁸, T. Mueller⁸¹, D. Muenstermann³⁰, Y. Munwes¹⁵³, W.J. Murray¹²⁹, I. Mussche¹⁰⁵, E. Musto¹⁵², A.G. Myagkov¹²⁸, M. Myska¹²⁵, O. Nackenhorst⁵⁴, J. Nadal¹², K. Nagai¹⁶⁰, R. Nagai¹⁵⁷,

K. Nagano⁶⁵, A. Nagarkar¹⁰⁹, Y. Nagasaka⁵⁹, M. Nagel⁹⁹, A.M. Nairz³⁰, Y. Nakahama³⁰,
 K. Nakamura¹⁵⁵, T. Nakamura¹⁵⁵, I. Nakano¹¹⁰, G. Nanava²¹, A. Napier¹⁶¹, R. Narayan^{58b},
 M. Nash^{77,d}, T. Nattermann²¹, T. Naumann⁴², G. Navarro¹⁶², H.A. Neal⁸⁷, P.Yu. Nechaeva⁹⁴,
 T.J. Neep⁸², A. Negri^{119a,119b}, G. Negri³⁰, M. Negrini^{20a}, S. Nektarijevic⁴⁹, A. Nelson¹⁶³,
 T.K. Nelson¹⁴³, S. Nemecek¹²⁵, P. Nemethy¹⁰⁸, A.A. Nepomuceno^{24a}, M. Nessi^{30,aa},
 M.S. Neubauer¹⁶⁵, M. Neumann¹⁷⁵, A. Neusiedl⁸¹, R.M. Neves¹⁰⁸, P. Nevski²⁵,
 F.M. Newcomer¹²⁰, P.R. Newman¹⁸, V. Nguyen Thi Hong¹³⁶, R.B. Nickerson¹¹⁸,
 R. Nicolaidou¹³⁶, B. Nicquevert³⁰, F. Niedercorn¹¹⁵, J. Nielsen¹³⁷, N. Nikiforou³⁵, A. Nikiforov¹⁶,
 V. Nikolaenko¹²⁸, I. Nikolic-Audit⁷⁸, K. Nikolics⁴⁹, K. Nikolopoulos¹⁸, H. Nilsen⁴⁸, P. Nilsson⁸,
 Y. Ninomiya¹⁵⁵, A. Nisati^{132a}, R. Nisius⁹⁹, T. Nobe¹⁵⁷, L. Nodulman⁶, M. Nomachi¹¹⁶,
 I. Nomidis¹⁵⁴, S. Norberg¹¹¹, M. Nordberg³⁰, J. Novakova¹²⁷, M. Nozaki⁶⁵, L. Nozka¹¹³,
 I.M. Nugent^{159a}, A.-E. Nuncio-Quiroz²¹, G. Nunes Hanninger⁸⁶, T. Nunnemann⁹⁸, E. Nurse⁷⁷,
 B.J. O'Brien⁴⁶, D.C. O'Neil¹⁴², V. O'Shea⁵³, L.B. Oakes⁹⁸, F.G. Oakham^{29,f}, H. Oberlack⁹⁹,
 J. Ocariz⁷⁸, A. Ochi⁶⁶, S. Oda⁶⁹, S. Odaka⁶⁵, J. Odier⁸³, H. Ogren⁶⁰, A. Oh⁸², S.H. Oh⁴⁵,
 C.C. Ohm³⁰, T. Ohshima¹⁰¹, W. Okamura¹¹⁶, H. Okawa²⁵, Y. Okumura³¹, T. Okuyama¹⁵⁵,
 A. Olariu^{26a}, A.G. Olchevski⁶⁴, S.A. Olivares Pino^{32a}, M. Oliveira^{124a,i}, D. Oliveira Damazio²⁵,
 E. Oliver Garcia¹⁶⁷, D. Olivito¹²⁰, A. Olszewski³⁹, J. Olszowska³⁹, A. Onofre^{124a,ab},
 P.U.E. Onyisi^{31,ac}, C.J. Oram^{159a}, M.J. Oreglia³¹, Y. Oren¹⁵³, D. Orestano^{134a,134b},
 N. Orlando^{72a,72b}, I. Orlov¹⁰⁷, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁸, B. Osculati^{50a,50b},
 R. Ospanov¹²⁰, C. Osuna¹², G. Otero y Garzon²⁷, J.P. Ottersbach¹⁰⁵, M. Ouchrif^{135d},
 E.A. Ouellette¹⁶⁹, F. Ould-Saada¹¹⁷, A. Ouraou¹³⁶, Q. Ouyang^{33a}, A. Ovcharova¹⁵, M. Owen⁸²,
 S. Owen¹³⁹, V.E. Ozcan^{19a}, N. Ozturk⁸, A. Pacheco Pages¹², C. Padilla Aranda¹²,
 S. Pagan Griso¹⁵, E. Paganis¹³⁹, C. Pahl⁹⁹, F. Paige²⁵, P. Pais⁸⁴, K. Pajchel¹¹⁷, G. Palacino^{159b},
 C.P. Paleari⁷, S. Palestini³⁰, D. Pallin³⁴, A. Palma^{124a}, J.D. Palmer¹⁸, Y.B. Pan¹⁷³,
 E. Panagiotopoulou¹⁰, J.G. Panduro Vazquez⁷⁶, P. Pani¹⁰⁵, N. Panikashvili⁸⁷, S. Panitkin²⁵,
 D. Pantea^{26a}, A. Papadelis^{146a}, Th.D. Papadopoulou¹⁰, A. Paramonov⁶, D. Paredes Hernandez³⁴,
 W. Park^{25,ad}, M.A. Parker²⁸, F. Parodi^{50a,50b}, J.A. Parsons³⁵, U. Parzefall⁴⁸, S. Pashapour⁵⁴,
 E. Pasqualucci^{132a}, S. Passaggio^{50a}, A. Passeri^{134a}, F. Pastore^{134a,134b,*}, Fr. Pastore⁷⁶,
 G. Pásztor^{49,ae}, S. Patariaia¹⁷⁵, N.D. Patel¹⁵⁰, J.R. Pater⁸², S. Patricelli^{102a,102b}, T. Pauly³⁰,
 M. Pecsny^{144a}, S. Pedraza Lopez¹⁶⁷, M.I. Pedraza Morales¹⁷³, S.V. Peleganchuk¹⁰⁷, D. Pelikan¹⁶⁶,
 H. Peng^{33b}, B. Penning³¹, A. Penson³⁵, J. Penwell⁶⁰, M. Perantoni^{24a}, K. Perez^{35,af},
 T. Perez Cavalcanti⁴², E. Perez Codina^{159a}, M.T. Pérez García-Estañ¹⁶⁷, V. Perez Reale³⁵,
 L. Perini^{89a,89b}, H. Pernegger³⁰, R. Perrino^{72a}, P. Perrodo⁵, V.D. Peshekhonov⁶⁴, K. Peters³⁰,
 B.A. Petersen³⁰, J. Petersen³⁰, T.C. Petersen³⁶, E. Petit⁵, A. Petridis¹⁵⁴, C. Petridou¹⁵⁴,
 E. Petrolu^{132a}, F. Petrucci^{134a,134b}, D. Petschull⁴², M. Petteni¹⁴², R. Pezoa^{32b}, A. Phan⁸⁶,
 P.W. Phillips¹²⁹, G. Piacquadio³⁰, A. Picazio⁴⁹, E. Piccaro⁷⁵, M. Piccinini^{20a,20b}, S.M. Piec⁴²,
 R. Piegai²⁷, D.T. Pignotti¹⁰⁹, J.E. Pilcher³¹, A.D. Pilkington⁸², J. Pina^{124a,c},
 M. Pinamonti^{164a,164c,ag}, A. Pinder¹¹⁸, J.L. Pinfold³, A. Pingel³⁶, B. Pinto^{124a}, C. Pizio^{89a,89b},
 M.-A. Pleier²⁵, E. Plotnikova⁶⁴, A. Poblaguev²⁵, S. Poddar^{58a}, F. Podlyski³⁴, L. Poggioli¹¹⁵,
 D. Pohl²¹, M. Pohl⁴⁹, G. Polesello^{119a}, A. Policicchio^{37a,37b}, A. Polini^{20a}, J. Poll⁷⁵,
 V. Polychronakos²⁵, D. Pomeroy²³, K. Pommès³⁰, L. Pontecorvo^{132a}, B.G. Pope⁸⁸,
 G.A. Popeneciu^{26a}, D.S. Popovic^{13a}, A. Poppleton³⁰, X. Portell Bueso³⁰, G.E. Pospelov⁹⁹,
 S. Pospisil¹²⁶, I.N. Potrap⁹⁹, C.J. Potter¹⁴⁹, C.T. Potter¹¹⁴, G. Poulard³⁰, J. Poveda⁶⁰,
 V. Pozdnyakov⁶⁴, R. Prabhu⁷⁷, P. Pralavorio⁸³, A. Pranko¹⁵, S. Prasad³⁰, R. Pravahan²⁵,
 S. Prell⁶³, K. Pretzl¹⁷, D. Price⁶⁰, J. Price⁷³, L.E. Price⁶, D. Prieur¹²³, M. Primavera^{72a},
 K. Prokofiev¹⁰⁸, F. Prokoshin^{32b}, S. Protopopescu²⁵, J. Proudfoot⁶, X. Prudent⁴⁴,
 M. Przybycien³⁸, H. Przysiezniak⁵, S. Psoroulas²¹, E. Ptacek¹¹⁴, E. Pueschel⁸⁴, D. Pudlon¹⁴⁸,
 J. Purdham⁸⁷, M. Purohit^{25,ad}, P. Puzo¹¹⁵, Y. Pylypchenko⁶², J. Qian⁸⁷, A. Quadt⁵⁴,
 D.R. Quarrie¹⁵, W.B. Quayle¹⁷³, M. Raas¹⁰⁴, V. Radeka²⁵, V. Radescu⁴², P. Radloff¹¹⁴,
 F. Ragusa^{89a,89b}, G. Rahal¹⁷⁸, A.M. Rahimi¹⁰⁹, D. Rahm²⁵, S. Rajagopalan²⁵, M. Rammensee⁴⁸,
 M. Rammes¹⁴¹, A.S. Randle-Conde⁴⁰, K. Randrianarivony²⁹, K. Rao¹⁶³, F. Rauscher⁹⁸,
 T.C. Rave⁴⁸, M. Raymond³⁰, A.L. Read¹¹⁷, D.M. Rebuzzi^{119a,119b}, A. Redelbach¹⁷⁴,

G. Redlinger²⁵, R. Reece¹²⁰, K. Reeves⁴¹, A. Reinsch¹¹⁴, I. Reisinger⁴³, C. Rembser³⁰, Z.L. Ren¹⁵¹, A. Renaud¹¹⁵, M. Rescigno^{132a}, S. Resconi^{89a}, B. Resende¹³⁶, P. Reznicek⁹⁸, R. Rezvani¹⁵⁸, R. Richter⁹⁹, E. Richter-Was^{5,ah}, M. Ridel⁷⁸, M. Rijpstra¹⁰⁵, M. Rijssenbeek¹⁴⁸, A. Rimoldi^{119a,119b}, L. Rinaldi^{20a}, R.R. Rios⁴⁰, I. Riu¹², G. Rivoltella^{89a,89b}, F. Rizatdinova¹¹², E. Rizvi⁷⁵, S.H. Robertson^{85,l}, A. Robichaud-Veronneau¹¹⁸, D. Robinson²⁸, J.E.M. Robinson⁸², A. Robson⁵³, J.G. Rocha de Lima¹⁰⁶, C. Roda^{122a,122b}, D. Roda Dos Santos³⁰, A. Roe⁵⁴, S. Roe³⁰, O. Røhne¹¹⁷, S. Rolli¹⁶¹, A. Romaniouk⁹⁶, M. Romano^{20a,20b}, G. Romeo²⁷, E. Romero Adam¹⁶⁷, N. Rompotis¹³⁸, L. Roos⁷⁸, E. Ros¹⁶⁷, S. Rosati^{132a}, K. Rosbach⁴⁹, A. Rose¹⁴⁹, M. Rose⁷⁶, G.A. Rosenbaum¹⁵⁸, P.L. Rosendahl¹⁴, O. Rosenthal¹⁴¹, L. Rosselet⁴⁹, V. Rossetti¹², E. Rossi^{132a,132b}, L.P. Rossi^{50a}, M. Rotaru^{26a}, I. Roth¹⁷², J. Rothberg¹³⁸, D. Rousseau¹¹⁵, C.R. Royon¹³⁶, A. Rozanov⁸³, Y. Rozen¹⁵², X. Ruan^{33a,ai}, F. Rubbo¹², I. Rubinskiy⁴², N. Ruckstuhl¹⁰⁵, V.I. Rud⁹⁷, C. Rudolph⁴⁴, G. Rudolph⁶¹, F. Rühr⁷, A. Ruiz-Martinez⁶³, L. Rumyantsev⁶⁴, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁴, A. Ruschke⁹⁸, J.P. Rutherford⁷, N. Ruthmann⁴⁸, P. Ruzicka¹²⁵, Y.F. Ryabov¹²¹, M. Rybar¹²⁷, G. Rybkin¹¹⁵, N.C. Ryder¹¹⁸, A.F. Saavedra¹⁵⁰, I. Sadeh¹⁵³, H.F.-W. Sadrozinski¹³⁷, R. Sadykov⁶⁴, F. Safai Tehrani^{132a}, H. Sakamoto¹⁵⁵, G. Salamanna⁷⁵, A. Salamon^{133a}, M. Saleem¹¹¹, D. Salek³⁰, D. Salihagic⁹⁹, A. Salnikov¹⁴³, J. Salt¹⁶⁷, B.M. Salvachua Ferrando⁶, D. Salvatore^{37a,37b}, F. Salvatore¹⁴⁹, A. Salvucci¹⁰⁴, A. Salzburger³⁰, D. Sampsonidis¹⁵⁴, B.H. Samset¹¹⁷, A. Sanchez^{102a,102b}, V. Sanchez Martinez¹⁶⁷, H. Sandaker¹⁴, H.G. Sander⁸¹, M.P. Sanders⁹⁸, M. Sandhoff¹⁷⁵, T. Sandoval²⁸, C. Sandoval¹⁶², R. Sandstroem⁹⁹, D.P.C. Sankey¹²⁹, A. Sansoni⁴⁷, C. Santamarina Rios⁸⁵, C. Santoni³⁴, R. Santonico^{133a,133b}, H. Santos^{124a}, I. Santoyo Castillo¹⁴⁹, J.G. Saraiva^{124a}, T. Sarangi¹⁷³, E. Sarkisyan-Grinbaum⁸, B. Sarrazin²¹, F. Sarri^{122a,122b}, G. Sartisohn¹⁷⁵, O. Sasaki⁶⁵, Y. Sasaki¹⁵⁵, N. Sasao⁶⁷, I. Satsounkevitch⁹⁰, G. Sauvage^{5,*}, E. Sauvan⁵, J.B. Sauvan¹¹⁵, P. Savard^{158,f}, V. Savinov¹²³, D.O. Savu³⁰, L. Sawyer^{25,n}, D.H. Saxon⁵³, J. Saxon¹²⁰, C. Sbarra^{20a}, A. Sbrizzi^{20a,20b}, D.A. Scannicchio¹⁶³, M. Scarcella¹⁵⁰, J. Schaarschmidt¹¹⁵, P. Schacht⁹⁹, D. Schaefer¹²⁰, U. Schäfer⁸¹, A. Schaelicke⁴⁶, S. Schaepe²¹, S. Schaetzel^{58b}, A.C. Schaffer¹¹⁵, D. Schaile⁹⁸, R.D. Schamberger¹⁴⁸, A.G. Schamov¹⁰⁷, V. Scharf^{58a}, V.A. Schegelsky¹²¹, D. Scheirich⁸⁷, M. Schernau¹⁶³, M.I. Scherzer³⁵, C. Schiavi^{50a,50b}, J. Schieck⁹⁸, M. Schioppa^{37a,37b}, S. Schlenker³⁰, E. Schmidt⁴⁸, K. Schmieden²¹, C. Schmitt⁸¹, S. Schmitt^{58b}, B. Schneider¹⁷, U. Schnoor⁴⁴, L. Schoeffel¹³⁶, A. Schoening^{58b}, A.L.S. Schorlemmer⁵⁴, M. Schott⁸¹, D. Schouten^{159a}, J. Schovancova¹²⁵, M. Schram⁸⁵, C. Schroeder⁸¹, N. Schroer^{58c}, M.J. Schultens²¹, J. Schultes¹⁷⁵, H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁶, M. Schumacher⁴⁸, B.A. Schumm¹³⁷, Ph. Schune¹³⁶, A. Schwartzman¹⁴³, Ph. Schwegler⁹⁹, Ph. Schwemling⁷⁸, R. Schwienhorst⁸⁸, R. Schwierz⁴⁴, J. Schwindling¹³⁶, T. Schwindt²¹, M. Schwoerer⁵, F.G. Sciacca¹⁷, G. Sciolla²³, W.G. Scott¹²⁹, J. Searcy¹¹⁴, G. Sedov⁴², E. Sedykh¹²¹, S.C. Seidel¹⁰³, A. Seiden¹³⁷, F. Seifert⁴⁴, J.M. Seixas^{24a}, G. Sekhniadze^{102a}, S.J. Sekula⁴⁰, K.E. Selbach⁴⁶, D.M. Seliverstov¹²¹, B. Sellden^{146a}, G. Sellers⁷³, M. Seman^{144b}, N. Semprini-Cesari^{20a,20b}, C. Serfon⁹⁸, L. Serin¹¹⁵, L. Serkin⁵⁴, R. Seuster^{159a}, H. Severini¹¹¹, A. Sfyrila³⁰, E. Shabalina⁵⁴, M. Shamim¹¹⁴, L.Y. Shan^{33a}, J.T. Shank²², Q.T. Shao⁸⁶, M. Shapiro¹⁵, P.B. Shatalov⁹⁵, K. Shaw^{164a,164c}, D. Sherman¹⁷⁶, P. Sherwood⁷⁷, S. Shimizu¹⁰¹, M. Shimojima¹⁰⁰, T. Shin⁵⁶, M. Shiyakova⁶⁴, A. Shmeleva⁹⁴, M.J. Shochet³¹, D. Short¹¹⁸, S. Shrestha⁶³, E. Shulga⁹⁶, M.A. Shupe⁷, P. Sicho¹²⁵, A. Sidoti^{132a}, F. Siegert⁴⁸, Dj. Sijacki^{13a}, O. Silbert¹⁷², J. Silva^{124a}, Y. Silver¹⁵³, D. Silverstein¹⁴³, S.B. Silverstein^{146a}, V. Simak¹²⁶, O. Simard¹³⁶, Lj. Simic^{13a}, S. Simion¹¹⁵, E. Simioni⁸¹, B. Simmons⁷⁷, R. Simoniello^{89a,89b}, M. Simonyan³⁶, P. Sinervo¹⁵⁸, N.B. Sinev¹¹⁴, V. Sipica¹⁴¹, G. Siragusa¹⁷⁴, A. Sircar²⁵, A.N. Sisakyan^{64,*}, S.Yu. Sivoklov⁹⁷, J. Sjölin^{146a,146b}, T.B. Sjursen¹⁴, L.A. Skinnari¹⁵, H.P. Skottowe⁵⁷, K. Skovpen¹⁰⁷, P. Skubic¹¹¹, M. Slater¹⁸, T. Slavicek¹²⁶, K. Sliwa¹⁶¹, V. Smakhtin¹⁷², B.H. Smart⁴⁶, L. Smestad¹¹⁷, S.Yu. Smirnov⁹⁶, Y. Smirnov⁹⁶, L.N. Smirnova^{97,aj}, O. Smirnova⁷⁹, B.C. Smith⁵⁷, D. Smith¹⁴³, K.M. Smith⁵³, M. Smizanska⁷¹, K. Smolek¹²⁶, A.A. Snesarev⁹⁴, S.W. Snow⁸², J. Snow¹¹¹, S. Snyder²⁵, R. Sobie^{169,l}, J. Sodomka¹²⁶, A. Soffer¹⁵³, C.A. Solans¹⁶⁷, M. Solar¹²⁶, J. Solc¹²⁶, E.Yu. Soldatov⁹⁶, U. Soldevila¹⁶⁷, E. Solfaroli Camillocci^{132a,132b}, A.A. Solodkov¹²⁸, O.V. Solovyanov¹²⁸,

V. Solovyev¹²¹, N. Soni¹, A. Sood¹⁵, V. Sopko¹²⁶, B. Sopko¹²⁶, M. Sosebee⁸, R. Soualah^{164a,164c}, P. Soueid⁹³, A. Soukharev¹⁰⁷, S. Spagnolo^{72a,72b}, F. Spanò⁷⁶, R. Spighi^{20a}, G. Spigo³⁰, R. Spiwok³⁰, M. Spousta^{127,ak}, T. Spreitzer¹⁵⁸, B. Spurlock⁸, R.D. St. Denis⁵³, J. Stahlman¹²⁰, R. Stamen^{58a}, E. Stanecka³⁹, R.W. Stanek⁶, C. Stanescu^{134a}, M. Stanescu-Bellu⁴², M.M. Stanitzki⁴², S. Stapnes¹¹⁷, E.A. Starchenko¹²⁸, J. Stark⁵⁵, P. Staroba¹²⁵, P. Starovoitov⁴², R. Staszewski³⁹, A. Staude⁹⁸, P. Stavina^{144a,*}, G. Steele⁵³, P. Steinbach⁴⁴, P. Steinberg²⁵, I. Stekl¹²⁶, B. Stelzer¹⁴², H.J. Stelzer⁸⁸, O. Stelzer-Chilton^{159a}, H. Stenzel⁵², S. Stern⁹⁹, G.A. Stewart³⁰, J.A. Stillings²¹, M.C. Stockton⁸⁵, K. Stoerig⁴⁸, G. Stoicea^{26a}, S. Stonjek⁹⁹, P. Strachota¹²⁷, A.R. Stradling⁸, A. Straessner⁴⁴, J. Strandberg¹⁴⁷, S. Strandberg^{146a,146b}, A. Strandlie¹¹⁷, M. Strang¹⁰⁹, E. Strauss¹⁴³, M. Strauss¹¹¹, P. Strizenec^{144b}, R. Ströhmer¹⁷⁴, D.M. Strom¹¹⁴, J.A. Strong^{76,*}, R. Stroynowski⁴⁰, B. Stugu¹⁴, I. Stumer^{25,*}, J. Stupak¹⁴⁸, P. Sturm¹⁷⁵, N.A. Styles⁴², D.A. Soh^{151,v}, D. Su¹⁴³, HS. Subramania³, R. Subramaniam²⁵, A. Succurro¹², Y. Sugaya¹¹⁶, C. Suhr¹⁰⁶, M. Suk¹²⁷, V.V. Sulin⁹⁴, S. Sultansoy^{4d}, T. Sumida⁶⁷, X. Sun⁵⁵, J.E. Sundermann⁴⁸, K. Suruliz¹³⁹, G. Susinno^{37a,37b}, M.R. Sutton¹⁴⁹, Y. Suzuki⁶⁵, Y. Suzuki⁶⁶, M. Svatos¹²⁵, S. Swedish¹⁶⁸, I. Sykora^{144a}, T. Sykora¹²⁷, J. Sánchez¹⁶⁷, D. Ta¹⁰⁵, K. Tackmann⁴², A. Taffard¹⁶³, R. Tafirout^{159a}, N. Taiblum¹⁵³, Y. Takahashi¹⁰¹, H. Takai²⁵, R. Takashima⁶⁸, H. Takeda⁶⁶, T. Takeshita¹⁴⁰, Y. Takubo⁶⁵, M. Talby⁸³, A. Talyshev^{107,h}, M.C. Tamsett²⁵, K.G. Tan⁸⁶, J. Tanaka¹⁵⁵, R. Tanaka¹¹⁵, S. Tanaka¹³¹, S. Tanaka⁶⁵, A.J. Tanasijczuk¹⁴², K. Tani⁶⁶, N. Tannoury⁸³, S. Tapprogge⁸¹, D. Tardif¹⁵⁸, S. Tarem¹⁵², F. Tarrade²⁹, G.F. Tartarelli^{89a}, P. Tas¹²⁷, M. Tasevsky¹²⁵, E. Tassi^{37a,37b}, Y. Tayalati^{135d}, C. Taylor⁷⁷, F.E. Taylor⁹², G.N. Taylor⁸⁶, W. Taylor^{159b}, M. Teinturier¹¹⁵, F.A. Teischinger³⁰, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸, H. Ten Kate³⁰, P.K. Teng¹⁵¹, S. Terada⁶⁵, K. Terashi¹⁵⁵, J. Terron⁸⁰, M. Testa⁴⁷, R.J. Teuscher^{158,l}, J. Therhaag²¹, T. Theveneaux-Pelzer⁷⁸, S. Thoma⁴⁸, J.P. Thomas¹⁸, E.N. Thompson³⁵, P.D. Thompson¹⁸, P.D. Thompson¹⁵⁸, A.S. Thompson⁵³, L.A. Thomsen³⁶, E. Thomson¹²⁰, M. Thomson²⁸, W.M. Thong⁸⁶, R.P. Thun⁸⁷, F. Tian³⁵, M.J. Tibbetts¹⁵, T. Tic¹²⁵, V.O. Tikhomirov⁹⁴, Y.A. Tikhonov^{107,h}, S. Timoshenko⁹⁶, E. Tiouchichine⁸³, P. Tipton¹⁷⁶, S. Tisserant⁸³, T. Todorov⁵, S. Todorova-Nova¹⁶¹, B. Toggerson¹⁶³, J. Tojo⁶⁹, S. Tokár^{144a}, K. Tokushuku⁶⁵, K. Tollefson⁸⁸, M. Tomoto¹⁰¹, L. Tompkins³¹, K. Toms¹⁰³, A. Tonoyan¹⁴, C. Topfel¹⁷, N.D. Topilin⁶⁴, E. Torrence¹¹⁴, H. Torres⁷⁸, E. Torró Pastor¹⁶⁷, J. Toth^{83,ae}, F. Touchard⁸³, D.R. Tovey¹³⁹, T. Trefzger¹⁷⁴, L. Tremblet³⁰, A. Tricoli³⁰, I.M. Trigger^{159a}, S. Trincaz-Duvold⁷⁸, M.F. Tripiana⁷⁰, N. Triplett²⁵, W. Trischuk¹⁵⁸, B. Trocmé⁵⁵, C. Troncon^{89a}, M. Trottier-McDonald¹⁴², P. True⁸⁸, M. Trzebinski³⁹, A. Trzupek³⁹, C. Tsarouchas³⁰, J.C-L. Tseng¹¹⁸, M. Tsiakiris¹⁰⁵, P.V. Tsiareshka⁹⁰, D. Tsionou^{5,al}, G. Tsipolitis¹⁰, S. Tsiskaridze¹², V. Tsiskaridze⁴⁸, E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁵, V. Tsulaia¹⁵, J.-W. Tsung²¹, S. Tsuno⁶⁵, D. Tsybychev¹⁴⁸, A. Tua¹³⁹, A. Tudorache^{26a}, V. Tudorache^{26a}, J.M. Tuggle³¹, M. Turala³⁹, D. Turecek¹²⁶, I. Turk Cakir^{4e}, E. Turlay¹⁰⁵, R. Turra^{89a,89b}, P.M. Tuts³⁵, A. Tykhonov⁷⁴, M. Tylmad^{146a,146b}, M. Tyndel¹²⁹, G. Tzanakos⁹, K. Uchida²¹, I. Ueda¹⁵⁵, R. Ueno²⁹, M. Ughetto⁸³, M. Uglund¹⁴, M. Uhlenbrock²¹, M. Uhrmacher⁵⁴, F. Ukegawa¹⁶⁰, G. Unal³⁰, A. Undrus²⁵, G. Unel¹⁶³, F.C. Ungaro⁴⁸, Y. Unno⁶⁵, D. Urbaniec³⁵, P. Urquijo²¹, G. Usai⁸, M. Uslenghi^{119a,119b}, L. Vacavant⁸³, V. Vacek¹²⁶, B. Vachon⁸⁵, S. Vahsen¹⁵, S. Valentineti^{20a,20b}, A. Valero¹⁶⁷, S. Valkar¹²⁷, E. Valladolid Gallego¹⁶⁷, S. Vallecorsa¹⁵², J.A. Valls Ferrer¹⁶⁷, R. Van Berg¹²⁰, P.C. Van Der Deijl¹⁰⁵, R. van der Geer¹⁰⁵, H. van der Graaf¹⁰⁵, R. Van Der Leeuw¹⁰⁵, E. van der Poel¹⁰⁵, D. van der Ster³⁰, N. van Eldik³⁰, P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴², I. van Vulpen¹⁰⁵, M. Vanadia⁹⁹, W. Vandelli³⁰, A. Vaniachine⁶, P. Vankov⁴², F. Vannucci⁷⁸, R. Vari^{132a}, E.W. Varnes⁷, T. Varol⁸⁴, D. Varouchas¹⁵, A. Vartapetian⁸, K.E. Varvell¹⁵⁰, V.I. Vassilakopoulos⁵⁶, F. Vazeille³⁴, T. Vazquez Schroeder⁵⁴, G. Vegni^{89a,89b}, J.J. Veillet¹¹⁵, F. Veloso^{124a}, R. Veness³⁰, S. Veneziano^{132a}, A. Ventura^{72a,72b}, D. Ventura⁸⁴, M. Venturi⁴⁸, N. Venturi¹⁵⁸, V. Vercesi^{119a}, M. Verducci¹³⁸, W. Verkerke¹⁰⁵, J.C. Vermeulen¹⁰⁵, A. Vest⁴⁴, M.C. Vetterli^{142,f}, I. Vichou¹⁶⁵, T. Vickey^{145b,am}, O.E. Vickey Boeriu^{145b}, G.H.A. Viehhauser¹¹⁸, S. Viel¹⁶⁸, M. Villa^{20a,20b}, M. Villaplana Perez¹⁶⁷, E. Vilucchi⁴⁷, M.G. Vincter²⁹, E. Vinek³⁰, V.B. Vinogradov⁶⁴,

M. Virchaux^{136,*}, J. Virzi¹⁵, O. Vitells¹⁷², M. Viti⁴², I. Vivarelli⁴⁸, F. Vives Vaque³, S. Vlachos¹⁰, D. Vladoiu⁹⁸, M. Vlasak¹²⁶, A. Vogel²¹, P. Vokac¹²⁶, G. Volpi⁴⁷, M. Volpi⁸⁶, G. Volpini^{89a}, H. von der Schmitt⁹⁹, H. von Radziewski⁴⁸, E. von Toerne²¹, V. Vorobel¹²⁷, V. Vorwerk¹², M. Vos¹⁶⁷, R. Voss³⁰, J.H. Vosseveld⁷³, N. Vranjes¹³⁶, M. Vranjes Milosavljevic¹⁰⁵, V. Vrba¹²⁵, M. Vreeswijk¹⁰⁵, T. Vu Anh⁴⁸, R. Vuillermet³⁰, I. Vukotic³¹, W. Wagner¹⁷⁵, P. Wagner²¹, H. Wahlen¹⁷⁵, S. Wahrmund⁴⁴, J. Wakabayashi¹⁰¹, S. Walch⁸⁷, J. Walder⁷¹, R. Walker⁹⁸, W. Walkowiak¹⁴¹, R. Wall¹⁷⁶, P. Waller⁷³, B. Walsh¹⁷⁶, C. Wang⁴⁵, H. Wang¹⁷³, H. Wang⁴⁰, J. Wang¹⁵¹, J. Wang^{33a}, R. Wang¹⁰³, S.M. Wang¹⁵¹, T. Wang²¹, A. Warburton⁸⁵, C.P. Ward²⁸, D.R. Wardrope⁷⁷, M. Warsinsky⁴⁸, A. Washbrook⁴⁶, C. Wasicki⁴², I. Watanabe⁶⁶, P.M. Watkins¹⁸, A.T. Watson¹⁸, I.J. Watson¹⁵⁰, M.F. Watson¹⁸, G. Watts¹³⁸, S. Watts⁸², A.T. Waugh¹⁵⁰, B.M. Waugh⁷⁷, M.S. Weber¹⁷, J.S. Webster³¹, A.R. Weidberg¹¹⁸, P. Weigell⁹⁹, J. Weingarten⁵⁴, C. Weiser⁴⁸, P.S. Wells³⁰, T. Wenaus²⁵, D. Wendland¹⁶, Z. Weng^{151,v}, T. Wengler³⁰, S. Wenig³⁰, N. Vermes²¹, M. Werner⁴⁸, P. Werner³⁰, M. Werth¹⁶³, M. Wessels^{58a}, J. Wetter¹⁶¹, C. Weydert⁵⁵, K. Whalen²⁹, A. White⁸, M.J. White⁸⁶, S. White^{122a,122b}, S.R. Whitehead¹¹⁸, D. Whiteson¹⁶³, D. Whittington⁶⁰, D. Wicke¹⁷⁵, F.J. Wickens¹²⁹, W. Wiedenmann¹⁷³, M. Wielers¹²⁹, P. Wienemann²¹, C. Wiglesworth⁷⁵, L.A.M. Wiik-Fuchs²¹, P.A. Wijeratne⁷⁷, A. Wildauer⁹⁹, M.A. Wildt^{42,s}, I. Wilhelm¹²⁷, H.G. Wilkens³⁰, J.Z. Will⁹⁸, E. Williams³⁵, H.H. Williams¹²⁰, S. Williams²⁸, W. Willis³⁵, S. Willocq⁸⁴, J.A. Wilson¹⁸, M.G. Wilson¹⁴³, A. Wilson⁸⁷, I. Wingerter-Seez⁵, S. Winkelmann⁴⁸, F. Winklmeier³⁰, M. Wittgen¹⁴³, S.J. Wollstadt⁸¹, M.W. Wolter³⁹, H. Wolters^{124a,i}, W.C. Wong⁴¹, G. Wooden⁸⁷, B.K. Wosiek³⁹, J. Wotschack³⁰, M.J. Woudstra⁸², K.W. Wozniak³⁹, K. Wraight⁵³, M. Wright⁵³, B. Wrona⁷³, S.L. Wu¹⁷³, X. Wu⁴⁹, Y. Wu^{33b,an}, E. Wulf³⁵, B.M. Wynne⁴⁶, S. Xella³⁶, M. Xiao¹³⁶, S. Xie⁴⁸, C. Xu^{33b,z}, D. Xu^{33a}, L. Xu^{33b}, B. Yabsley¹⁵⁰, S. Yacoub^{145a,ao}, M. Yamada⁶⁵, H. Yamaguchi¹⁵⁵, A. Yamamoto⁶⁵, K. Yamamoto⁶³, S. Yamamoto¹⁵⁵, T. Yamamura¹⁵⁵, T. Yamanaka¹⁵⁵, T. Yamazaki¹⁵⁵, Y. Yamazaki⁶⁶, Z. Yan²², H. Yang⁸⁷, U.K. Yang⁸², Y. Yang¹⁰⁹, Z. Yang^{146a,146b}, S. Yanush⁹¹, L. Yao^{33a}, Y. Yasu⁶⁵, E. Yatsenko⁴², J. Ye⁴⁰, S. Ye²⁵, A.L. Yen⁵⁷, M. Yilmaz^{4c}, R. Yoosoofmiya¹²³, K. Yorita¹⁷¹, R. Yoshida⁶, K. Yoshihara¹⁵⁵, C. Young¹⁴³, C.J. Young¹¹⁸, S. Youssef²², D. Yu²⁵, D.R. Yu¹⁵, J. Yu⁸, J. Yu¹¹², L. Yuan⁶⁶, A. Yurkewicz¹⁰⁶, B. Zabinski³⁹, R. Zaidan⁶², A.M. Zaitsev¹²⁸, L. Zanello^{132a,132b}, D. Zanzi⁹⁹, A. Zaytsev²⁵, C. Zeitnitz¹⁷⁵, M. Zeman¹²⁶, A. Zemla³⁹, O. Zenin¹²⁸, T. Ženis^{144a}, Z. Zinonos^{122a,122b}, D. Zerwas¹¹⁵, G. Zevi della Porta⁵⁷, D. Zhang⁸⁷, H. Zhang⁸⁸, J. Zhang⁶, X. Zhang^{33d}, Z. Zhang¹¹⁵, L. Zhao¹⁰⁸, Z. Zhao^{33b}, A. Zhemchugov⁶⁴, J. Zhong¹¹⁸, B. Zhou⁸⁷, N. Zhou¹⁶³, Y. Zhou¹⁵¹, C.G. Zhu^{33d}, H. Zhu⁴², J. Zhu⁸⁷, Y. Zhu^{33b}, X. Zhuang⁹⁸, V. Zhuravlov⁹⁹, A. Zibell⁹⁸, D. Zieminska⁶⁰, N.I. Zimin⁶⁴, R. Zimmermann²¹, S. Zimmermann²¹, S. Zimmermann⁴⁸, M. Ziolkowski¹⁴¹, R. Zitoun⁵, L. Živković³⁵, V.V. Zmouchko^{128,*}, G. Zobernig¹⁷³, A. Zoccoli^{20a,20b}, M. zur Nedden¹⁶, V. Zutshi¹⁰⁶, L. Zwalinski³⁰

¹ School of Chemistry and Physics, University of Adelaide, Adelaide, Australia

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

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

⁴ ^(a) Department of Physics, Ankara University, Ankara; ^(b) Department of Physics, Dumlupinar University, Kutahya; ^(c) Department of Physics, Gazi University, Ankara; ^(d) Division of Physics, TOBB University of Economics and Technology, Ankara; ^(e) Turkish Atomic Energy Authority, Ankara, Turkey

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

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

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

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

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 and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
- ¹³ ^(a) Institute of Physics, University of Belgrade, Belgrade; ^(b) Vinca Institute of Nuclear Sciences, 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 of America
- 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) Division of Physics, Dogus University, Istanbul; ^(c) Department of Physics Engineering, Gaziantep University, Gaziantep; ^(d) Department of Physics, Istanbul Technical University, Istanbul, Turkey
- ²⁰ ^(a) INFN Sezione di Bologna; ^(b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy
- ²¹ Physikalisches Institut, University of Bonn, Bonn, Germany
- ²² Department of Physics, Boston University, Boston MA, United States of America
- ²³ Department of Physics, Brandeis University, Waltham MA, United States of America
- ²⁴ ^(a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; ^(c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; ^(d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
- ²⁵ Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- ²⁶ ^(a) National Institute of Physics and Nuclear Engineering, Bucharest; ^(b) University Politehnica Bucharest, Bucharest; ^(c) West University in Timisoara, Timisoara, Romania
- ²⁷ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- ²⁸ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ²⁹ Department of Physics, Carleton University, Ottawa ON, Canada
- ³⁰ CERN, Geneva, Switzerland
- ³¹ Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- ³² ^(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; ^(b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ³³ ^(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) Physics Department, Shanghai Jiao Tong University, Shanghai, China
- ³⁴ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- ³⁵ Nevis Laboratory, Columbia University, Irvington NY, United States of America
- ³⁶ Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- ³⁷ ^(a) INFN Gruppo Collegato di Cosenza; ^(b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
- ³⁸ AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
- ³⁹ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- ⁴⁰ Physics Department, Southern Methodist University, Dallas TX, United States of America
- ⁴¹ Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- ⁴² DESY, Hamburg and Zeuthen, Germany
- ⁴³ Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁴ Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
- ⁴⁵ Department of Physics, Duke University, Durham NC, United States of America
- ⁴⁶ SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

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

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

- 132 (a) INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
 133 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
 134 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
 135 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
 136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat 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 of America
 138 Department of Physics, University of Washington, Seattle WA, United States of America
 139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
 140 Department of Physics, Shinshu University, Nagano, Japan
 141 Fachbereich Physik, Universität Siegen, Siegen, Germany
 142 Department of Physics, Simon Fraser University, Burnaby BC, Canada
 143 SLAC National Accelerator Laboratory, Stanford CA, United States of America
 144 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
 145 (a) Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
 146 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
 147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
 148 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
 149 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
 150 School of Physics, University of Sydney, Sydney, Australia
 151 Institute of Physics, Academia Sinica, Taipei, Taiwan
 152 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
 153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
 154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
 155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
 156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
 157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
 158 Department of Physics, University of Toronto, Toronto ON, Canada
 159 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
 160 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
 161 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
 162 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
 163 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
 164 (a) INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
 165 Department of Physics, University of Illinois, Urbana IL, United States of America
 166 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
 167 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear

- and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
- ¹⁶⁸ Department of Physics, University of British Columbia, Vancouver BC, Canada
- ¹⁶⁹ Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- ¹⁷⁰ Department of Physics, University of Warwick, Coventry, United Kingdom
- ¹⁷¹ Waseda University, Tokyo, Japan
- ¹⁷² Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- ¹⁷³ Department of Physics, University of Wisconsin, Madison WI, United States of America
- ¹⁷⁴ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- ¹⁷⁵ Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- ¹⁷⁶ Department of Physics, Yale University, New Haven CT, United States of America
- ¹⁷⁷ Yerevan Physics Institute, Yerevan, Armenia
- ¹⁷⁸ 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 Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
- ^c Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal
- ^d Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ^e Also at Department of Physics, University of Johannesburg, Johannesburg, South Africa
- ^f Also at TRIUMF, Vancouver BC, Canada
- ^g Also at Department of Physics, California State University, Fresno CA, United States of America
- ^h Also at Novosibirsk State University, Novosibirsk, Russia
- ⁱ Also at Department of Physics, University of Coimbra, Coimbra, Portugal
- ^j Also at Department of Physics, UASLP, San Luis Potosi, Mexico
- ^k Also at Università di Napoli Parthenope, Napoli, Italy
- ^l Also at Institute of Particle Physics (IPP), Canada
- ^m Also at Department of Physics, Middle East Technical University, Ankara, Turkey
- ⁿ Also at Louisiana Tech University, Ruston LA, United States of America
- ^o Also at Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- ^p Also at Department of Physics and Astronomy, University College London, London, United Kingdom
- ^q Also at Department of Physics, University of Cape Town, Cape Town, South Africa
- ^r Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ^s Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
- ^t Also at Manhattan College, New York NY, United States of America
- ^u Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ^v Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
- ^w Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^x Also at School of Physics, Shandong University, Shandong, China
- ^y Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy
- ^z Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- ^{aa} Also at Section de Physique, Université de Genève, Geneva, Switzerland
- ^{ab} Also at Departamento de Física, Universidade de Minho, Braga, Portugal
- ^{ac} Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
- ^{ad} Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
- ^{ae} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary

- ^{af} Also at California Institute of Technology, Pasadena CA, United States of America
- ^{ag} Also at International School for Advanced Studies (SISSA), Trieste, Italy
- ^{ah} Also at Institute of Physics, Jagiellonian University, Krakow, Poland
- ^{ai} Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- ^{aj} Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- ^{ak} Also at Nevis Laboratory, Columbia University, Irvington NY, United States of America
- ^{al} Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- ^{am} Also at Department of Physics, Oxford University, Oxford, United Kingdom
- ^{an} Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- ^{ao} Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
- * Deceased