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The ATLAS Collaboration

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1

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Keywords Exotics, W' boson, top-tagging, jet substructure

1 Introduction

Several theories beyond the Standard Model (SM) [1–3] involve enhanced symmetries that introduce new charged vector currents carried by new heavy gauge bosons, usually called W' bosons. For instance, Grand Unified Theories [4–7] extend fundamental symmetries of the SM, in which a massive right-handed counterpart to the SM W boson may occur. W' bosons can appear in phenomenological models involving extra space-time dimensions such as Kaluza-Klein excitations of the SM W boson [8] or in technicolor models [9]. Also Little Higgs theories [10] predict several new particles, including a W' boson. In order to interpret a direct

experimental search independently of the details of particular models predicting a W' boson, it is advantageous to rely on an effective model describing the couplings of the W' boson to fermions [11].

The search for a W' boson decaying to a top quark and a b -quark ($W' \rightarrow tb$)¹ explores models potentially inaccessible to $W' \rightarrow \ell\nu$ searches. Also, in the right-handed sector, it is assumed that there is no light right-handed neutrino to which a W' boson could decay, and, hence, only hadronic decays are allowed [11, 12]. In some theories beyond the SM, new physics couples more strongly to the third generation than to the first and second [9]. Searches for W' bosons decaying to tb have been performed at the Tevatron [13–15] and at the LHC [16, 17], in leptonic top-quark decay channels excluding a W' boson with purely right-handed couplings (referred to as W'_R) with mass less than 2.13 TeV at 95% Confidence Level (CL).

This document describes the first search for the $W' \rightarrow tb$ process in the fully hadronic final state of the top-quark decay. For high W' masses, the final state signature consists of one high-momentum b -quark and another b -quark close to the two light-quarks from the W -boson decay. The distinct signature of high-momentum top quarks is exploited to isolate the signal from the copious hadronic multijet background making use of novel jet substructure techniques to identify boosted hadronically decaying top quarks. This allows for particularly good sensitivity at high W' masses. 95% CL exclusion limits are presented on the W' -boson coupling as a function of the W' mass in an effective model.

¹ Decays of W'^+ to a top quark and an anti- b quark and of W'^- to an anti-top quark and a b -quark are equally taken into account. For simplicity, both decays are referred to as $W' \rightarrow tb$ in this document.

2 The ATLAS Detector

Charged particles in the pseudorapidity² range $|\eta| < 2.5$ are reconstructed with the inner detector (ID), which consists of several layers of semiconductor detectors (pixel and strip) and a straw-tube transition-radiation tracker, the latter extending to $|\eta| < 2.0$. The inner tracking system is immersed in a 2 T magnetic field provided by a superconducting solenoid. The solenoid is surrounded by sampling calorimeters, which span the pseudorapidity range up to $|\eta| = 4.9$. High-granularity liquid-argon (LAr) electromagnetic calorimeters are present up to $|\eta| = 3.2$. Hadronic calorimeters with scintillating tiles as active material cover $|\eta| < 1.74$ while LAr technology is used for hadronic calorimetry from $|\eta| = 1.5$ to $|\eta| = 4.9$. Outside the calorimeter system, air-core toroids provide a magnetic field for the muon spectrometer (MS). Three stations of precision drift tubes and cathode strip chambers provide a measurement of the muon track in the region of $|\eta| < 2.7$. Resistive-plate and thin-gap chambers provide muon triggering capability up to $|\eta| < 2.4$.

3 Data and Monte-Carlo Simulation Samples

3.1 Data Samples

The data used for this analysis was collected in pp collisions in 2012 at a centre-of-mass energy of $\sqrt{s} = 8$ TeV. All candidate events must satisfy data-quality requirements that include being recorded during the LHC stable-beam periods and proper functioning of the detector and trigger subsystems. After the trigger and data-quality requirements, the amount of data used by this analysis corresponds to an integrated luminosity of 20.3 fb^{-1} with an average number of interactions per bunch-crossing of 20.7.

3.2 Signal Modelling

The right- and left-handed W' boson (denoted as W'_R and W'_L , respectively) models are implemented in MADGRAPH 5 [18] using FeynRules [19, 20], which is used to generate events at leading-order (LO) in α_s through Drell-Yan like production. MADGRAPH also simulates the

² The ATLAS experiment 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 line. 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 line. Observables labelled “transverse” are projected into the x - y plane. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan \theta/2$. The transverse momentum is defined as $p_T = p \sin \theta = p/\cosh \eta$, and the transverse energy E_T has an analogous definition.

Table 1: NLO cross sections times branching ratio to tb for different W' masses for the left-handed and for the right-handed model [11, 23].

Mass [TeV]	$\sigma \times \text{BR}(W'_L \rightarrow tb)$	$\sigma \times \text{BR}(W'_R \rightarrow tb)$
1.5	0.40 pb	0.52 pb
2.0	0.067 pb	0.086 pb
2.5	0.014 pb	0.017 pb
3.0	0.0035 pb	0.0039 pb

decay of the top quark taking spin correlations into account. PYTHIA 8.165 [21] is used for parton showering and hadronisation. CTEQ6L1 [22] parton distribution functions (PDFs) are used for the event generation.

The W'_R and W'_L cross sections times branching ratios to the tb final state are obtained from next-to-leading order (NLO) QCD calculations [11, 23] and are shown for different W' masses in Table 1. The mass of a possible right-handed neutrino is assumed to be larger than the mass of the W'_R boson, allowing only hadronic decays of the W'_R . In the case of a W'_L boson, leptonic decays are allowed. Dedicated Monte-Carlo (MC) simulation samples with interference effects between W'_L and SM W included have been used to estimate the change in the number of expected signal events. In the high mass signal region the change in event yield is less than 1% after kinematic requirements. Interference effects with the SM s -channel single-top quark process are ignored. All simulated samples are normalised to these NLO calculations using NLO/LO k -factors ranging from 1.15 to 1.35 depending on the mass and the chirality of the W' boson. The models assume that the W' -boson coupling strength to quarks is the same as for the SM W boson: $g'_R = g_{\text{SM}}$ and $g'_L = 0$ ($g'_R = 0$ and $g'_L = g_{\text{SM}}$) for W'_R (W'_L) bosons, where g_{SM} is the SM $SU(2)$ coupling.

3.3 Background Samples

The background estimate in this analysis is derived from a fit to data. However, an initial background estimate is introduced in Section 5.2, which uses a data-driven technique based on sideband regions for the multijet process and MC simulation samples for top-quark pair production ($t\bar{t}$). For this purpose, $t\bar{t}$ production is simulated using the POWHEG-BOX generator [24, 25] coupled to PYTHIA 6.426 [26, 27] for parton showering and hadronisation. This sample uses the CTEQ6L1 PDF set. The $t\bar{t}$ samples are normalised to the next-to-next-to-leading order (NNLO) calculations in α_s including resummation of next-to-next-to-leading logarithmic soft gluon terms with TOP++2.0 [28–33]: $\sigma_{t\bar{t}} = 253^{+14}_{-16}$ pb. PDF and α_s uncertainties are calculated using the PDF4LHC prescription [34] with the MSTW2008 68% CL NNLO [35, 36], CT10 NNLO [37, 38] and

NNPDF2.3 [39] PDF sets, added in quadrature to the scale uncertainty. An uncertainty on the top-quark mass of 1 GeV is also considered.

For the optimisation of the W' top-tagger (Section 4.1), MC samples are generated with PYTHIA 8.160 using the AU2 tune [40] and the CT10 [37] PDF set.

After event generation, all signal and background MC samples are passed through a full simulation of the ATLAS detector [41] based on GEANT4 [42] and then reconstructed using the same algorithms as for collision data. All MC processes are simulated with pile-up interactions included and re-weighted to match the conditions of the data sample.

4 Physics Objects and Boosted Top Identification

This analysis relies on the reconstruction and identification of jets. Jets are built from energy depositions in the calorimeters with the anti- k_T algorithm [43] using locally-calibrated topological clusters as inputs. Jets are further calibrated using energy and η -dependent correction factors derived from simulation and with residual corrections from *in-situ* measurements [44]. Events with jets built from noisy calorimeter cells or non-collision backgrounds are removed [45]. In this analysis two radius parameters are used for jet reconstruction: a small- R radius of 0.4 and a large- R radius of 1.0. Small- R jets are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. To minimise the impact of energy depositions from pile-up interactions the large- R jets are trimmed [46]. The trimming algorithm reconstructs jets using the k_T jet algorithm with $R = 0.3$ built out of the constituents of the original large- R jet. Constituent jets contributing less than 5% of the large- R jet p_T are removed. The remaining energy depositions are used to calculate the jet kinematics and substructure properties. Large- R jets are required to have $p_T > 350$ GeV and $|\eta| < 2.0$.

In order to identify small- R jets which originate from b -quarks, this analysis uses a neural-network based b -tagging algorithm [47]. Different observables based on the long lifetime of B hadrons are used as inputs and are able to discriminate between b -jets, c -jets and light-quark jets.

Events with reconstructed high-quality electrons [48] or muons [49] are vetoed in order to ensure orthogonality to analyses using the leptonic decay of the top quark [17]. Electrons and muons with transverse momenta above 30 GeV are considered for this veto.

4.1 The W' Top-tagger

This analysis searches for W' bosons in the high mass ($m_{W'} > 1.5$ TeV) region, where the top quark and bottom

quark have high transverse momentum. The average distance between the decay products of the top quark falls with increasing top-quark p_T , and their hadronic showers begin to overlap. This high- p_T topology, where the decay products of a massive particle can be captured in one single large- R jet, is referred to as “boosted” [50–53].

The discrimination of large- R jets originating from hadronic top-quark decays from large- R jets originating from other sources using calorimeter information is termed top-tagging. The W' top-tagging algorithm is a cut-based algorithm using different large- R jet substructure properties developed to efficiently select large- R jets from W' signal events over the dominant background from multijet production featuring light-quark, b -quark and gluon-initiated jets. The procedure uses three substructure variables: the one-to-two k_T -splitting scale $\sqrt{d_{12}}$ [54] and two ratios of N -subjettiness (τ_N) variables [55, 56] $\tau_{32} = \tau_3/\tau_2$ and $\tau_{21} = \tau_2/\tau_1$.

The splitting scale $\sqrt{d_{12}}$ distinguishes jets containing top-quark decays, which are relatively p_T -symmetric in the top-quark rest frame, from p_T -asymmetric light jets. It is calculated by reclustering the constituents of the large- R jet using the k_T algorithm, where the reclustering procedure is stopped at the last merging step. Since the k_T algorithm clusters the hardest objects last, the last clustering step corresponds to the merging of the two hardest subjets, and $\sqrt{d_{12}}$ is defined as the corresponding scale:

$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \times \sqrt{(\Delta\eta_{12})^2 + (\Delta\phi_{12})^2},$$

where $p_{T,1}$ and $p_{T,2}$ are the transverse momenta of the two remaining subjets, and $\Delta\eta_{12}$ and $\Delta\phi_{12}$ are the distances in η and ϕ between these two subjets. For jets from hadronic top-quark decays the $\sqrt{d_{12}}$ distribution is expected to peak at approximately half the top-quark mass. For jets initiated by light quarks, b -quarks and gluons, the $\sqrt{d_{12}}$ distribution is expected to peak near zero.

N -subjettiness is a measure of the compatibility of a large- R jet with a given number of subjets. The τ_N are calculated by reclustering the large- R jet constituents with the k_T algorithm requiring exactly N subjets to be found. The τ_N are then defined by:

$$\tau_N = \frac{1}{d_0} \sum_k p_{Tk} \times \min(\delta R_{1k}, \dots, \delta R_{Nk}),$$

with $d_0 = \sum_k p_{Tk} \times R$, where the sum runs over all constituents of the jet, p_{Tk} is the p_T of the k^{th} constituent, R is the radius parameter of the original jet, and the variable δR_{ik} is the distance in η - ϕ space from the i^{th} subjet to the k^{th} constituent. Ratios of the τ_N ($\tau_{ij} = \tau_i/\tau_j$) are then defined to discriminate if a jet is more i - or j -subjet-like. The τ_{ij} distributions peak closer to 0 for i -subjet-like jets and closer to 1 for j -subjet-like jets.

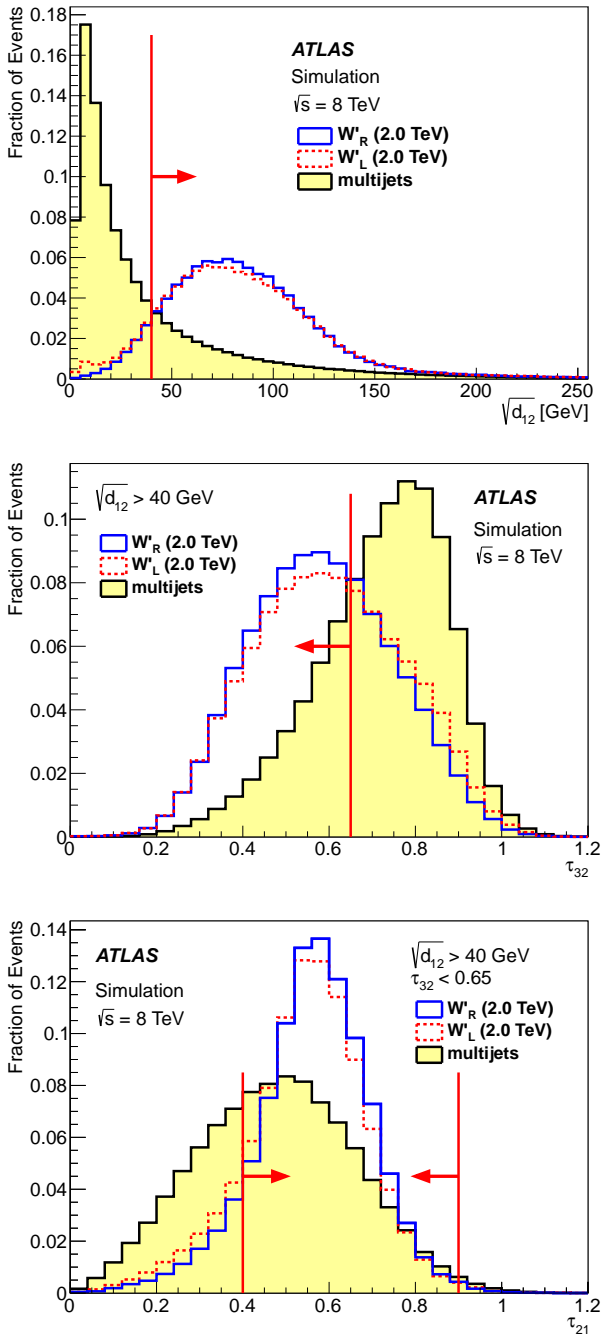


Fig. 1: Distributions in simulated samples of the substructure observables used for the W' top-tagger for trimmed large- R jets originating from QCD-multijet production and originating from hadronic decays of top quarks from 2 TeV W'_L and W'_R boson decays. The top figure shows the $\sqrt{d_{12}}$ distributions and the middle (bottom) figures show the τ_{32} (τ_{21}) distribution after requiring $\sqrt{d_{12}} > 40$ GeV ($\sqrt{d_{12}} > 40$ GeV and $\tau_{32} < 0.65$). All distributions are normalised to unity. The arrows indicate the cut values used in the W' top-tagger.

The optimisation procedure for the W' top-tagger aims for an optimal compromise between the efficiency for jets originating from hadronically decaying top quarks and the rejection of jets originating from QCD-multijet production. First, an optimal requirement on $\sqrt{d_{12}}$ is applied and then, selection criteria on the N -subjettiness variables are determined. The MC samples used are the 2 TeV $W'_L \rightarrow tb$ signal sample and a high- p_T QCD-multijet sample with a similar range in transverse momentum. It has been checked that changing the order in which $\sqrt{d_{12}}$, τ_{32} and τ_{21} are optimised yields very similar results.

Figure 1 shows distributions of $\sqrt{d_{12}}$ (top), τ_{32} with the $\sqrt{d_{12}}$ requirement applied (centre), and τ_{21} with both $\sqrt{d_{12}}$ and τ_{32} requirements applied (bottom) for jets originating from hadronically decaying top quarks in 2 TeV W'_L and W'_R MC simulations. These are compared to the distributions for jets originating from light-quark, b -quark and gluon jets from QCD-multijet MC simulations. The optimised top-tagging requirements are $\sqrt{d_{12}} > 40$ GeV, $\tau_{32} < 0.65$ and $0.4 < \tau_{21} < 0.9$. While τ_N is an infrared- and collinear-safe observable [55], infrared-safety of τ_{32} is ensured by the requirements on τ_{21} . The selection efficiency for jets originating from hadronic top-quark decays is estimated in MC simulations to be larger than 50% for jet p_T above 500 GeV, while the probability to falsely tag a light-quark, b -quark or gluon jet is below 10% [51]. For jet p_T below 800 GeV, where the sample size is sufficient, the top-tagging efficiency is cross-checked in data using single lepton $t\bar{t}$ events, and the top-tagging efficiency is found to be consistent between data and MC.

5 Analysis

5.1 Event Selection

Candidate events are triggered by requiring the scalar sum of the E_T of the energy deposits in the calorimeters at trigger level to be at least 700 GeV. In order to perform the offline analysis in the fully efficient regime of this trigger, the scalar sum of the transverse momenta of reconstructed small- R jets with $p_T > 25$ GeV and $|\eta| < 2.5$ is required to be at least 850 GeV. Candidate events must have at least one primary vertex with at least five tracks associated to it and have exactly one large- R W' top-tagged jet (top candidate) and one small- R b -tagged jet (b -candidate) each with $p_T > 350$ GeV and an angular separation $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ larger than 2.0 between the flight direction of the top candidate and the b -candidate. The invariant mass of the dijet system must be at least 1.1 TeV in order to avoid turn-on effects from the kinematic selection. The events are divided into two categories: the one b -tag category and the two b -tag category. For the two b -tag category, an additional b -tagged small- R

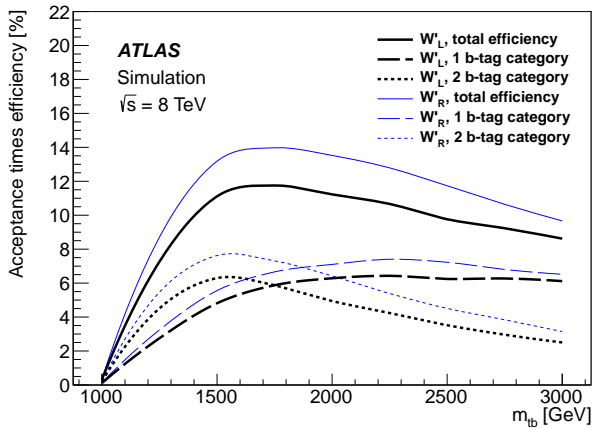


Fig. 2: Selection acceptance times efficiency as a function of tb invariant mass at truth level for left- and right-handed W' MC. The total efficiency curves correspond to the sum of the efficiencies of the one b -tag and two b -tag categories.

jet with $p_T > 25$ GeV has to be present close to the top candidate by requiring ΔR between the small- R b -jet and the top candidate to be less than the large- R jet radius parameter 1.0. Figure 2 shows the acceptance times selection efficiency as a function of tb invariant mass at truth level in the one and two b -tag categories and the total signal efficiency corresponding to their sum. The difference in the efficiencies observed in the W'_L and W'_R models originates from the different top-tagging efficiencies, which is due to the preferred flight directions of the top-quark decay products in the top-quark rest frame for the two chiralities.

5.2 Initial Background Estimate

An initial background estimate is performed to choose the fit function which is used to estimate the background from data. It is also used to derive the associated systematic uncertainties on the background modelling.

Multijet events are the dominant background comprising 99% (88%) of the events in the one (two) b -tag category. The estimate of the contribution of multijet events is based on a data-driven method which categorises events based on top- and b -tagging. Requiring the high- p_T small- R jet to fail the b -tagging requirement or the large- R jet to fail the top-tagging requirement provides three orthogonal control regions in each b -tag category that are dominated by multijet events. These control regions are then used to make an estimate of the multijet contribution in the signal region, as defined by the event selection.

The other significant background is top-quark pairs, contributing 11% in the two b -tag category as estimated using MC simulations. Other backgrounds, such as single-top, W -

boson+jets, and Z -boson+jets production are found to have a very small contribution.

Table 2 reports the number of data and expected background events in the signal region for the one b -tag and two b -tag categories.

Table 2: Event yields in the signal region for SM processes using the initial background estimate compared to the yield observed in data. The uncertainties quoted for multijet and for $t\bar{t}$ production contain statistical as well as systematic uncertainties (Section 6). The contributions from other background sources (single-top, W -boson+jets and Z -boson+jets production) have only been estimated approximately, but were found to be smaller than 0.4% of the expectation for multijet production. An uncertainty of 100% is quoted here in order to reflect the approximations made.

Process	One b -tag	Two b -tag
Multijet	16100 ± 800	2600 ± 300
Hadronic $t\bar{t}$	130 ± 30	210 ± 60
Leptonic $t\bar{t}$	60 ± 20	90 ± 30
Other	60 ± 60	8 ± 8
Total SM prediction	16400 ± 800	2900 ± 300
Data	16601	2925

5.3 Statistical Analysis

An unbinned likelihood fit to the m_{tb} distributions combining the one b -tag category and the two b -category is performed, where the range considered is 1.1 – 4 TeV. The lower bound of m_{tb} is due to turn-on effects of the m_{tb} distribution originating in the kinematic selection. This allows W' signals of $m_{W'} \geq 1.5$ TeV to be tested, because for lower values of $m_{W'}$, the peak of the signal shape is only partially contained in the m_{tb} range considered. The upper bound of m_{tb} is motivated by the low expected number of events in the two b -tag category at such high values. Hence, W' signals of $m_{W'} \leq 3.0$ TeV can be tested, in order to constrain the background function parameters also for high m_{tb} values. A profile likelihood-based test statistic is used for the evaluation of p -values for observations as well as a CL_s test statistic for setting 95% CL exclusion limits, where asymptotic formulas [57] are used. The expected and observed limits are corrected for small differences observed using toy experiments.

The reconstructed m_{tb} spectrum for the W' signal is parametrised using the sum of a skew-normal [58] and a Gaussian function. The skew-normal accounts for the asymmetric shape of the resonant W' signal and is the product of a Gaussian and a Gaussian error function. Non-resonant

off-shell W' production is accounted for with the additional Gaussian distribution. This allows the signal shape to be fully parametrised. In order to search for a W' signal over the full mass range, the signal shape parameters, as well as the signal acceptance and the expected cross sections are interpolated between the generated mass points. Figure 3 shows the parametric fits to the W' signal distributions in the two b -tag category for W'_L masses between 1.5 and 3 TeV overlaid to the corresponding MC distributions.

Additional contributions from $W' \rightarrow tb \rightarrow \ell\nu bb$ are between 3.5 and 10%. The leptonic contribution is taken into account by fitting the reconstructed m_{tb} distribution with a double-Gaussian function and interpolating between generated masses analogously to the treatment of the $W' \rightarrow tb \rightarrow qqbb$ signal. Large- R jets can falsely be top-tagged in events with leptonic top-quark decays due to several effects including hard gluon radiation, calorimeter activity from non-identified electrons and hadronically decaying tau leptons.

The sum of all backgrounds is fitted with an analytic function. For each of the two categories, a function is chosen among several tested functions following a procedure based on the m_{tb} distribution obtained from the initial background estimate (Section 5.2). For each function under study the corresponding fake signal bias is quantified by fitting the m_{tb} distribution from the initial background estimate with a background-plus-signal model. The maximal extracted fake signal observed over the full range of W' masses is chosen as systematic uncertainty on the background modelling (Section 6). The function with the least number of free parameters is chosen out of all tested functions giving similarly small bias. This procedure yields an exponential function with a polynomial of order n as its argument:

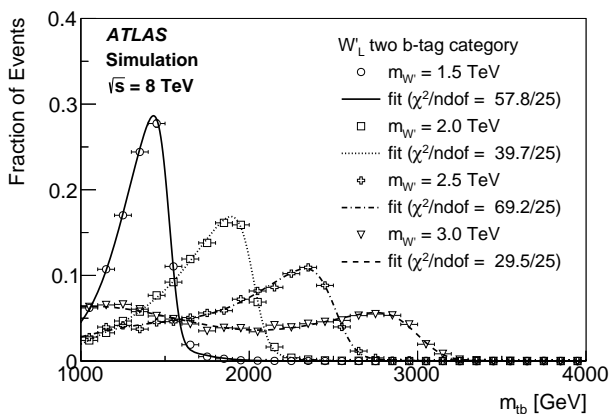


Fig. 3: Parametric fits to the $W' \rightarrow tb \rightarrow qqbb$ signal distributions in the two b -tag category for W'_L masses between 1.5 and 3 TeV overlaid to the corresponding MC distributions. While unbinned fits are performed, the events from MC simulation are shown as a histogram for presentational purposes.

$\exp(\sum_{k=1}^n c_k m_{tb}^k)$, with $n = 4$ ($n = 2$) in the one (two) b -tag category. Figure 4 shows background-only fits to the initial background estimate in the one and two b -tag categories using the chosen functions. The ratio of the distribution and the fit is also shown, where the uncertainties are the control-region and MC statistical uncertainties and the grey shaded band shows the statistical uncertainty in each bin as expected for 20.3 fb^{-1} . Deviations from 1 in the ratio plot are much smaller than the expected statistical uncertainty and the chosen background functions are hence shown to be flexible enough to describe the background distribution in the signal region.

6 Systematic Uncertainties

Systematic uncertainties may change the acceptance and shape of the potential W' signal, and are included as nuisance parameters in the likelihood function. Table 3 shows the impact of the systematic uncertainties on the event yield of a 2 TeV W' boson in the one and two b -tag categories. The largest sources of uncertainty come from the uncertainties associated with b -tagging, top-tagging and background modelling.

Uncertainties on the b -tagging efficiency and mistag rates are estimated from data using $t\bar{t}$ di-lepton decays [47, 59]. The b -tagging (mistagging) uncertainties are increased for high p_T and reach up to 34% (60%) per jet. Uncertainties on the W' top-tagger performance are evaluated based on the data-MC agreement as shown in Refs. [52, 53]. They are derived comparing the ratio of each variable from jets built from calorimeter clusters and the corresponding jet built from tracks in the ID. The observed differences between data and MC are taken as variations on the substructure variables and are translated into an uncertainty on the efficiency of the W' top-tagger. Within the kinematic reach, it has been shown with $t\bar{t}$ events in the single-lepton channel that these uncertainties cover any possible disagreement between the efficiency observed in data and MC simulations. The jet energy scale (JES) uncertainty [44] depends on the p_T and η of the reconstructed jet and includes the uncertainty on the b -jet energy scale. The JES of the two jet types are assumed to be correlated. The impact of the jet energy resolution uncertainty is evaluated by smearing the jet energy in the simulation to increase the nominal resolution. The uncertainty on the integrated luminosity is 2.8% as derived from beam-separated scans [60]. Theoretical uncertainties are included by evaluating the change in the expected number of signal events. The deviations from varying the CTEQ6L1 PDF eigenvectors are summed in quadrature with the uncertainty from α_s , the renormalisation scale, and the change in acceptance at LO and NLO. In addition, the uncertainty on the beam energy [61] is included.

Table 3: Systematic uncertainties on the event yields of a 2 TeV W' boson in both categories in percent and on the background modelling in numbers of expected W' boson events.

Systematic Uncertainties [%]	W'_L		W'_R	
	One b -tag	Two b -tag	One b -tag	Two b -tag
b -tagging	+13, -20	+45, -37	+15, -21	+40, -34
W' Top-tagging	± 13	± 10	± 11	± 9
Jet Energy Scale	± 1.3	± 1.9	± 0.8	± 1.9
Jet Energy Resolution	< 0.1	± 0.2	± 0.1	± 0.5
Theoretical		± 10		+8, -10
Luminosity			± 2.8	
Background Modelling	± 44 events	± 28 events	± 45 events	± 24 events

Uncertainties due to background mismodelling are quantified as discussed in Section 5.3. This uncertainty amounts to 28 (24) events in the two b -tag category and 44 (45) events in the one b -tag category for the W'_L (W'_R) model.

7 Results

Figure 5 shows the observed m_{tb} spectra in the two categories. The highest mass event in the two (one) b -tag category is at 3.25 TeV (4.68 TeV). A background-only fit to the spectra is also shown and good agreement is observed between the fit and the data.

Figure 6 shows the observed p -values for background plus left-handed or right-handed W' model as a function of the W' mass allowing the background parameters to float. The p -value from both categories combined is shown taking into account all systematic uncertainties. The maximum local significance is 1.4σ . Hence, no significant excess over the background-only hypothesis is observed and 95% CL limits are derived on the cross section times branching ratio to tb as shown in Figure 7. The observed limits agree with the expected limits roughly within 1σ over the whole range for both W' models and range from 0.16 pb to 0.33 pb for left-handed W' bosons and from 0.10 pb to 0.21 pb for W' bosons with purely right-handed couplings. The relative mass independence of the expected sensitivity and observed limits is a unique feature of this search arising from the flat signal efficiency when combining the one and two b -tag categories.

For $g' = g_{SM}$, the limits on the cross section times branching ratio translate to observed (expected) limits on the mass to be above 1.68 TeV (1.63 TeV) and 1.76 TeV (1.85 TeV) in the left- and right-handed models, respectively. The observed cross-section limits are also interpreted as limits on other values of the couplings $g'_{L/R}$. For $g'_{L/R}/g_{SM} < 2$, the reconstructed m_{tb} distributions are dominated by the experimental width. The results obtained for $g'_{L/R} = g_{SM}$ can hence be interpreted as limits in the g'_L - W'_L mass (g'_R - W'_R mass) plane, making use of the approximately

quadratic dependence of the W' production cross section on g' . The observed and expected limits on the ratio of couplings g'_L/g_{SM} (g'_R/g_{SM}) of the W'_L (W'_R) model as a function of W' mass are shown in Figure 8 and amount to $g' < 0.70$ ($g' < 0.55$) for a 1.5 TeV W'_L (W'_R) and to $g' < 2$ for a 2.18 (2.29) TeV W'_L (W'_R) boson.

8 Summary and Conclusion

A search for $W' \rightarrow tb \rightarrow qqbb$ was presented using 20.3 fb $^{-1}$ of 8 TeV proton-proton collisions data taken with the ATLAS detector. The analysis makes use of jet substructure tagging optimised to select large- R jets coming from hadronically decaying top quarks and b -tagging of small- R jets. The observed m_{tb} spectrum from data is consistent with the background-only prediction and exclusion limits at 95% CL are set on the W' boson production cross section times branching ratio to tb . The use of novel jet substructure techniques allows cross-section limits to be set at high W' masses, which are similar to the limits at lower masses and range from 0.16 pb to 0.33 pb for left-handed W' bosons, and from 0.10 pb to 0.21 pb for W' bosons with purely right-handed couplings. In addition, limits are set at 95% CL on the W' -boson effective couplings as a function of the W' mass.

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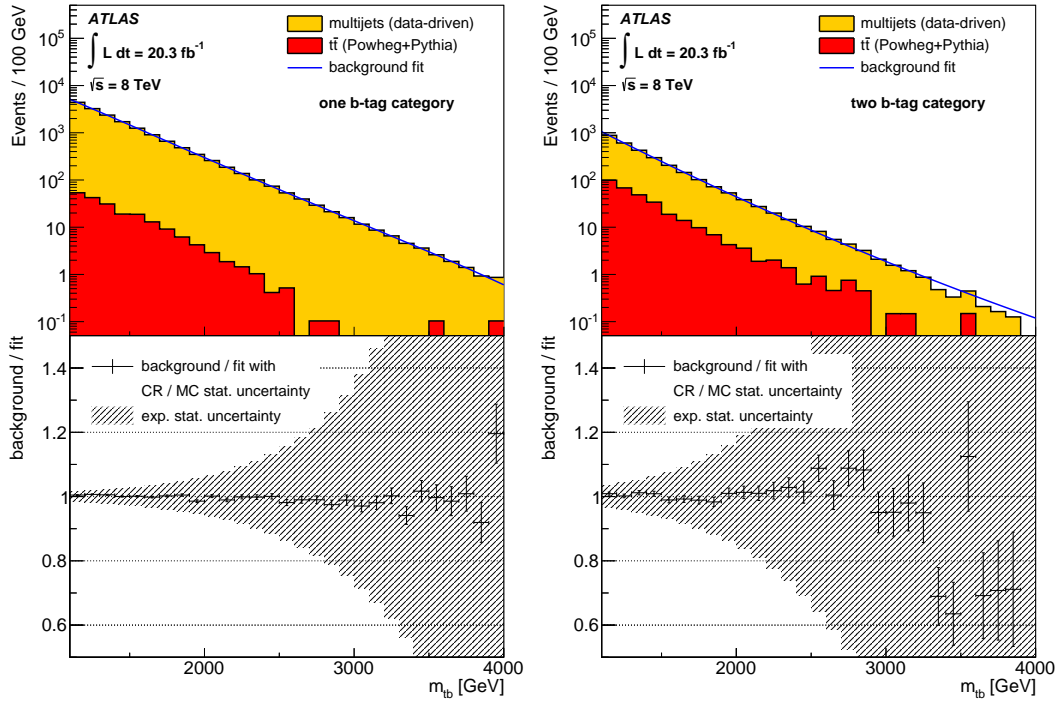


Fig. 4: Fit to the m_{tb} distribution from the initial background estimate in the one b -tag category (left) and in the two b -tag category (right). The ratio background/fit is also shown, where the uncertainties are the control-region and MC statistical uncertainties and the grey shaded band shows the statistical uncertainty in each bin as expected for 20.3 fb^{-1} .

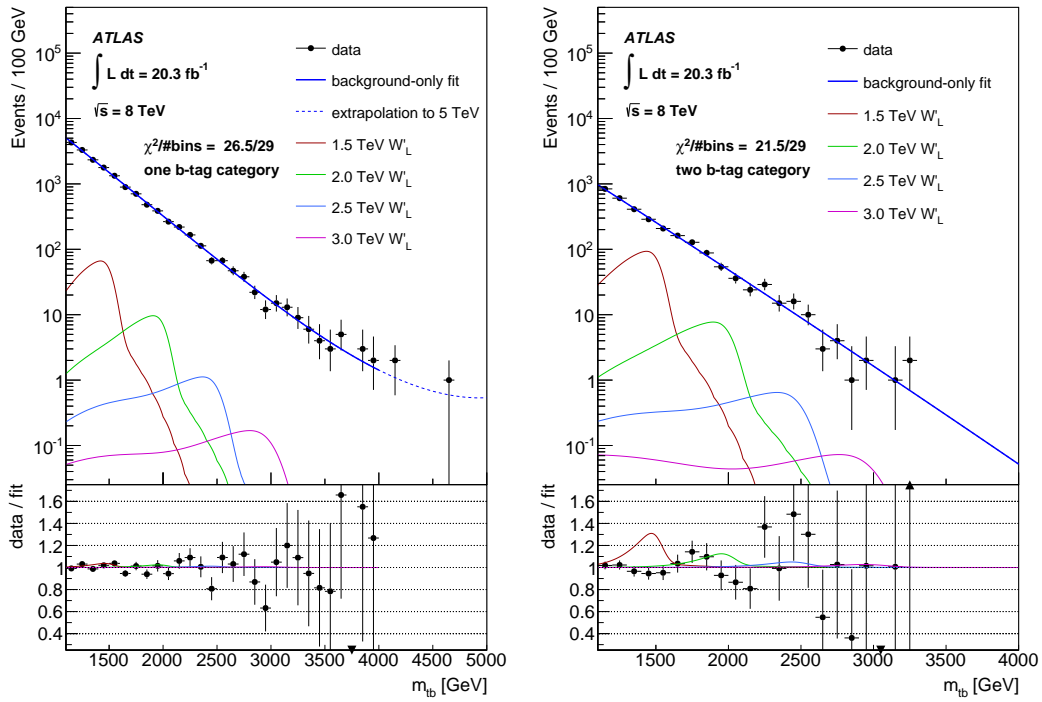


Fig. 5: m_{tb} distributions in data in the one b -tag (left) and the two b -tag category (right). Background-only fits are shown, and the bottom plots show the ratio of the data and the fit. The left plot shows an extrapolation of the background fit into the region 4 – 5 TeV. The ratio plot, however does not show the three data points in this range, because they are beyond the range considered for this analysis. Potential W'_L signal shapes in the hadronic top-quark decay channel with $g' = g_{SM}$ are also overlaid for resonance masses of 1.5, 2.0, 2.5 and 3.0 TeV.

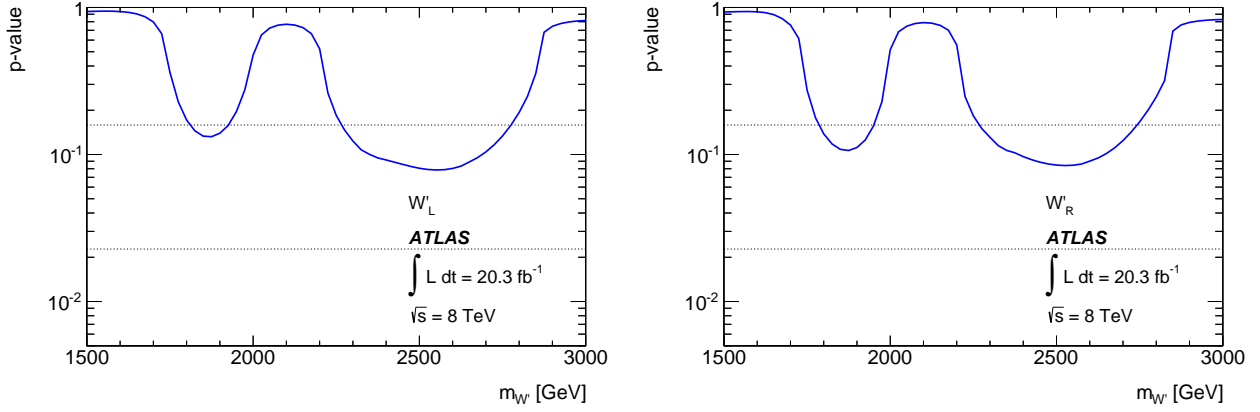


Fig. 6: Observed p -values for a left-handed (left) and right-handed (right) W' model as a function of the W' mass.

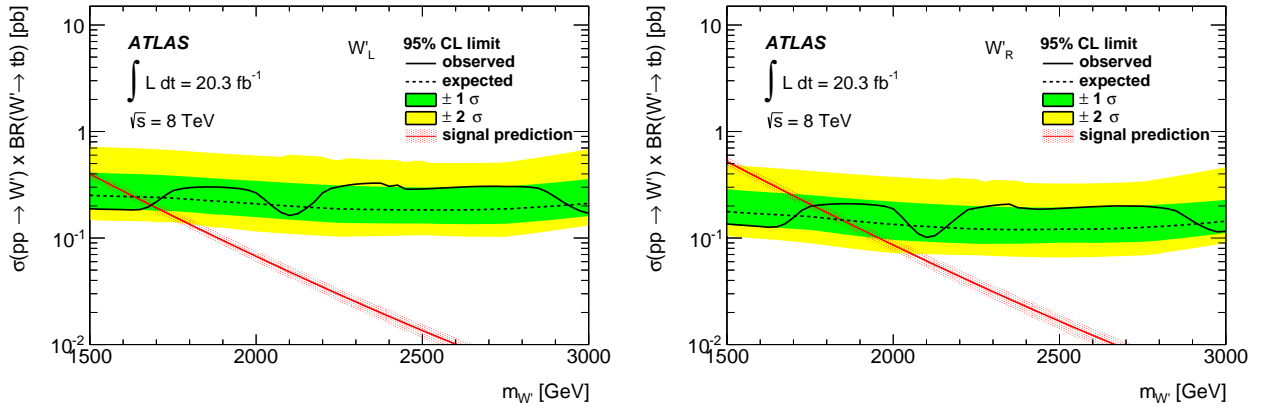


Fig. 7: Limits at 95% CL on the cross section times branching ratio to tb for the left-handed (left) and for the right-handed (right) W' model. The expected cross section for W' production with $g' = g_{\text{SM}}$ is also shown.

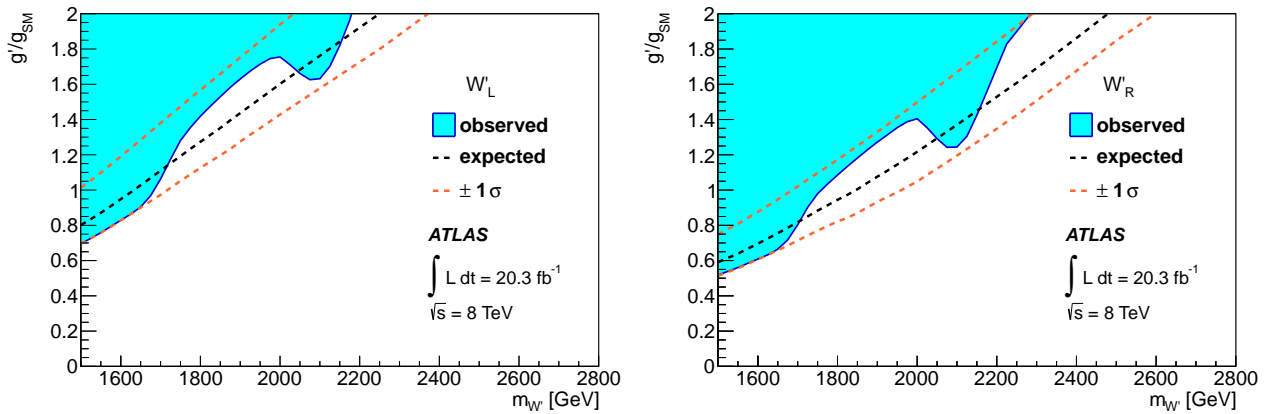


Fig. 8: Observed and expected 95% CL limits on the ratio of coupling g'_L/g_{SM} (g'_R/g_{SM}) of the W'_L (W'_R) model as a function of the W' mass.

Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; RGC, Hong Kong SAR, China; ISF, MINERVA, GIF, I-CORE and Benozziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

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The ATLAS Collaboration

G. Aad⁸⁴, B. Abbott¹¹², J. Abdallah¹⁵², S. Abdel Khalek¹¹⁶, O. Abidinov¹¹, R. Aben¹⁰⁶, B. Abi¹¹³, M. Abolins⁸⁹,
O.S. AbouZeid¹⁵⁹, H. Abramowicz¹⁵⁴, H. Abreu¹⁵³, R. Abreu³⁰, Y. Abulaiti^{147a,147b}, B.S. Acharya^{165a,165b,a},
L. Adamczyk^{38a}, D.L. Adams²⁵, J. Adelman¹⁷⁷, S. Adomeit⁹⁹, T. Adye¹³⁰, T. Agatonovic-Jovin^{13a},
J.A. Aguilar-Saavedra^{125a,125f}, M. Agustoni¹⁷, S.P. Ahlen²², F. Ahmadov^{64,b}, G. Aielli^{134a,134b}, H. Akerstedt^{147a,147b},
T.P.A. Åkesson⁸⁰, G. Akimoto¹⁵⁶, A.V. Akimov⁹⁵, G.L. Alberghi^{20a,20b}, J. Albert¹⁷⁰, S. Albrand⁵⁵,
M.J. Alconada Verzini⁷⁰, M. Aleksa³⁰, I.N. Aleksandrov⁶⁴, C. Alexa^{26a}, G. Alexander¹⁵⁴, G. Alexandre⁴⁹,
T. Alexopoulos¹⁰, M. Alhroob^{165a,165c}, G. Alimonti^{103a,103b}, A. Alonso³⁶, F. Alonso⁷⁰, C. Alpigiani⁷⁵, A. Althaiser³⁵,
B. Alvarez Gonzalez⁸⁹, M.G. Alviggi^{103a,103b}, K. Amako⁶⁵, Y. Amaral Coutinho^{24a}, C. Amelung²³, D. Amidei⁸⁸,
S.P. Amor Dos Santos^{125a,125c}, A. Amorim^{125a,125b}, S. Amoroso⁴⁸, N. Amram¹⁵⁴, G. Amundsen²³, C. Anastopoulos¹⁴⁰,
L.S. Ancu⁴⁹, N. Andari³⁰, T. Andeen³⁵, C.F. Anders^{58b}, G. Anders³⁰, K.J. Anderson³¹, A. Andreazza^{90a,90b}, V. Andrei^{58a},
X.S. Anduaga⁷⁰, S. Angelidakis⁹, I. Angelozzi¹⁰⁶, P. Anger⁴⁴, A. Angerami³⁵, F. Anghinolfi³⁰, A.V. Anisenkov¹⁰⁸,
N. Anjos^{125a}, A. Annovi⁴⁷, A. Antonaki⁹, M. Antonelli⁴⁷, A. Antonov⁹⁷, J. Antos^{145b}, F. Anulli^{133a}, M. Aoki⁶⁵,
L. Aperio Bella¹⁸, R. Apolle^{119,c}, G. Arabidze⁸⁹, I. Aracena¹⁴⁴, Y. Arai⁶⁵, J.P. Araque^{125a}, A.T.H. Arce⁴⁵, J-F. Arguin⁹⁴,
S. Argyropoulos⁴², M. Arik^{19a}, A.J. Armbruster³⁰, O. Arnaez³⁰, V. Arnal⁸¹, H. Arnold⁴⁸, M. Arratia²⁸, O. Arslan²¹,
A. Artamonov⁹⁶, G. Artoni²³, S. Asai¹⁵⁶, N. Asbah⁴², A. Ashkenazi¹⁵⁴, B. Åsman^{147a,147b}, L. Asquith⁶, K. Assamagan²⁵,
R. Astalos^{145a}, M. Atkinson¹⁶⁶, N.B. Atlay¹⁴², B. Auerbach⁶, K. Augsten¹²⁷, M. Auresseau^{146b}, G. Avolio³⁰,
G. Azuelos^{94,d}, Y. Azuma¹⁵⁶, M.A. Baak³⁰, A. Baas^{58a}, C. Bacci^{135a,135b}, H. Bachacou¹³⁷, K. Bachas¹⁵⁵, M. Backes³⁰,
M. Backhaus³⁰, J. Backus Mayes¹⁴⁴, E. Badescu^{26a}, P. Bagiacci^{133a,133b}, P. Bagnaia^{133a,133b}, Y. Bai^{33a}, T. Bain³⁵,
J.T. Baines¹³⁰, O.K. Baker¹⁷⁷, P. Balek¹²⁸, F. Balli¹³⁷, E. Banas³⁹, Sw. Banerjee¹⁷⁴, A.A.E. Bannoura¹⁷⁶, V. Bansal¹⁷⁰,
H.S. Bansil¹⁸, L. Barak¹⁷³, S.P. Baranov⁹⁵, E.L. Barberio⁸⁷, D. Barberis^{50a,50b}, M. Barbero⁸⁴, T. Barillari¹⁰⁰,
M. Barisonzi¹⁷⁶, T. Barklow¹⁴⁴, N. Barlow²⁸, B.M. Barnett¹³⁰, R.M. Barnett¹⁵, Z. Barnovska⁵, A. Baroncelli^{135a},
G. Barone⁴⁹, A.J. Barr¹¹⁹, F. Barreiro⁸¹, J. Barreiro Guimarães da Costa⁵⁷, R. Bartoldus¹⁴⁴, A.E. Barton⁷¹, P. Bartos^{145a},
V. Bartsch¹⁵⁰, A. Bassalat¹¹⁶, A. Basye¹⁶⁶, R.L. Bates⁵³, J.R. Batley²⁸, M. Battaglia¹³⁸, M. Battistin³⁰, F. Bauer¹³⁷,
H.S. Bawa^{144,e}, M.D. Beattie⁷¹, T. Beau⁷⁹, P.H. Beauchemin¹⁶², R. Beccherle^{123a,123b}, P. Bechtel²¹, H.P. Beck¹⁷,
K. Becker¹⁷⁶, S. Becker⁹⁹, M. Beckingham¹⁷¹, C. Becot¹¹⁶, A.J. Beddall^{19c}, A. Beddall^{19c}, S. Bedikian¹⁷⁷,
V.A. Bednyakov⁶⁴, C.P. Bee¹⁴⁹, L.J. Beemster¹⁰⁶, T.A. Beermann¹⁷⁶, M. Begel²⁵, K. Behr¹¹⁹, C. Belanger-Champagne⁸⁶,
P.J. Bell⁴⁹, W.H. Bell⁴⁹, G. Bella¹⁵⁴, L. Bellagamba^{20a}, A. Bellerive²⁹, M. Bellomo⁸⁵, K. Belotskiy⁹⁷, O. Beltramello³⁰,
O. Benary¹⁵⁴, D. Bencheikroun^{136a}, K. Bendtz^{147a,147b}, N. Benekos¹⁶⁶, Y. Benhammou¹⁵⁴, E. Benhar Noccioli⁴⁹,
J.A. Benitez Garcia^{160b}, D.P. Benjamin⁴⁵, J.R. Bensinger²³, K. Benslama¹³¹, S. Bentvelsen¹⁰⁶, D. Berge¹⁰⁶,
E. Bergeas Kuutmann¹⁶, N. Berger⁵, F. Berghaus¹⁷⁰, J. Beringer¹⁵, C. Bernard²², P. Bernat⁷⁷, C. Bernius⁷⁸,
F.U. Bernlochner¹⁷⁰, T. Berry⁷⁶, P. Berta¹²⁸, C. Bertella⁸⁴, G. Bertoli^{147a,147b}, F. Bertolucci^{123a,123b}, C. Bertsche¹¹²,
D. Bertsche¹¹², M.I. Besana^{90a}, G.J. Besjes¹⁰⁵, O. Bessidskaia Bylund^{147a,147b}, M. Bessner⁴², N. Besson¹³⁷,
C. Betancourt⁴⁸, S. Bethke¹⁰⁰, W. Bhimji⁴⁶, R.M. Bianchi¹²⁴, L. Bianchini²³, M. Bianco³⁰, O. Biebel⁹⁹, S.P. Bieniek⁷⁷,
K. Bierwagen⁵⁴, J. Biesiada¹⁵, M. Biglietti^{135a}, J. Bilbao De Mendizabal⁴⁹, H. Bilokon⁴⁷, M. Bindi⁵⁴, S. Binet¹¹⁶,
A. Bingul^{19c}, C. Bini^{133a,133b}, C.W. Black¹⁵¹, J.E. Black¹⁴⁴, K.M. Black²², D. Blackburn¹³⁹, R.E. Blair⁶,
J.-B. Blanchard¹³⁷, T. Blazek^{145a}, I. Bloch⁴², C. Blocker²³, W. Blum^{82,*}, U. Blumenschein⁵⁴, G.J. Bobbink¹⁰⁶,
V.S. Bobrovnikov¹⁰⁸, S.S. Bocchetta⁸⁰, A. Bocchi⁴⁵, C. Bock⁹⁹, C.R. Boddy¹¹⁹, M. Boehler⁴⁸, T.T. Boek¹⁷⁶,
J.A. Bogaerts³⁰, A.G. Bogdanchikov¹⁰⁸, A. Bogouch^{91,*}, C. Bohm^{147a}, J. Bohm¹²⁶, V. Boisvert⁷⁶, T. Bold^{38a}, V. Boldea^{26a},
A.S. Boldyrev⁹⁸, M. Bomben⁷⁹, M. Bona⁷⁵, M. Boonekamp¹³⁷, A. Borisov¹²⁹, G. Borissov⁷¹, M. Borri⁸³, S. Borroni⁴²,
J. Bortfeldt⁹⁹, V. Bortolotto^{135a,135b}, K. Bos¹⁰⁶, D. Boscherini^{20a}, M. Bosman¹², H. Boterenbrood¹⁰⁶, J. Boudreau¹²⁴,
J. Bouffard², E.V. Bouhova-Thacker⁷¹, D. Boumediene³⁴, C. Bourdarios¹¹⁶, N. Bousson¹¹³, S. Boutouil^{136d}, A. Boveia³¹,
J. Boyd³⁰, I.R. Boyko⁶⁴, J. Bracinik¹⁸, A. Brandt⁸, G. Brandt¹⁵, O. Brandt^{58a}, U. Bratzler¹⁵⁷, B. Brau⁸⁵, J.E. Brau¹¹⁵,
H.M. Braun^{176,*}, S.F. Brazzale^{165a,165c}, B. Brelier¹⁵⁹, K. Brendlinger¹²¹, A.J. Brennan⁸⁷, R. Brenner¹⁶⁷, S. Bressler¹⁷³,
K. Bristow^{146c}, T.M. Bristow⁴⁶, D. Britton⁵³, F.M. Brochu²⁸, I. Brock²¹, R. Brock⁸⁹, C. Bromberg⁸⁹, J. Bronner¹⁰⁰,
G. Brooijmans³⁵, T. Brooks⁷⁶, W.K. Brooks^{32b}, J. Brosamer¹⁵, E. Brost¹¹⁵, J. Brown⁵⁵, P.A. Bruckman de Renstrom³⁹,
D. Bruncko^{145b}, R. Bruneliere⁴⁸, S. Brunet⁶⁰, A. Bruni^{20a}, G. Bruni^{20a}, M. Bruschi^{20a}, L. Bryngemark⁸⁰, T. Buanes¹⁴,
Q. Buat¹⁴³, F. Bucci⁴⁹, P. Buchholz¹⁴², R.M. Buckingham¹¹⁹, A.G. Buckley⁵³, S.I. Buda^{26a}, I.A. Budagov⁶⁴, F. Buehrer⁴⁸,
L. Bugge¹¹⁸, M.K. Bugge¹¹⁸, O. Bulekov⁹⁷, A.C. Bundock⁷³, H. Burckhart³⁰, S. Burdin⁷³, B. Burghgrave¹⁰⁷, S. Burke¹³⁰,
I. Burmeister⁴³, E. Busato³⁴, D. Büscher⁴⁸, V. Büscher⁸², P. Bussey⁵³, C.P. Buszello¹⁶⁷, B. Butler⁵⁷, J.M. Butler²²,
A.I. Butt³, C.M. Buttar⁵³, J.M. Butterworth⁷⁷, P. Butti¹⁰⁶, W. Buttinger²⁸, A. Buzatu⁵³, M. Byszewski¹⁰,

S. Cabrera Urbán¹⁶⁸, D. Caforio^{20a,20b}, O. Cakir^{4a}, P. Calafiura¹⁵, A. Calandri¹³⁷, G. Calderini⁷⁹, P. Calfayan⁹⁹, R. Calkins¹⁰⁷, L.P. Caloba^{24a}, D. Calvet³⁴, S. Calvet³⁴, R. Camacho Toro⁴⁹, S. Camarda⁴², D. Cameron¹¹⁸, L.M. Caminada¹⁵, R. Caminal Armadans¹², S. Campana³⁰, M. Campanelli⁷⁷, A. Campoverde¹⁴⁹, V. Canale^{103a,103b}, A. Canepa^{160a}, M. Cano Bret⁷⁵, J. Cantero⁸¹, R. Cantrill^{125a}, T. Cao⁴⁰, M.D.M. Capeans Garrido³⁰, I. Caprini^{26a}, M. Caprini^{26a}, M. Capua^{37a,37b}, R. Caputo⁸², R. Cardarelli^{134a}, T. Carli³⁰, G. Carlino^{103a}, L. Carminati^{90a,90b}, S. Caron¹⁰⁵, E. Carquin^{32a}, G.D. Carrillo-Montoya^{146c}, J.R. Carter²⁸, J. Carvalho^{125a,125c}, D. Casadei⁷⁷, M.P. Casado¹², M. Casolino¹², E. Castaneda-Miranda^{146b}, A. Castelli¹⁰⁶, V. Castillo Gimenez¹⁶⁸, N.F. Castro^{125a}, P. Catastini⁵⁷, A. Catinaccio³⁰, J.R. Catmore¹¹⁸, A. Cattai³⁰, G. Cattani^{134a,134b}, S. Caughron⁸⁹, V. Cavaliere¹⁶⁶, D. Cavalli^{90a}, M. Cavalli-Sforza¹², V. Cavasinni^{123a,123b}, F. Ceradini^{135a,135b}, B. Cerio⁴⁵, K. Cerny¹²⁸, A.S. Cerqueira^{24b}, A. Cerri¹⁵⁰, L. Cerrito⁷⁵, F. Cerutti¹⁵, M. Cerv³⁰, A. Cervelli¹⁷, S.A. Cetin^{19b}, A. Chafaq^{136a}, D. Chakraborty¹⁰⁷, I. Chalupkova¹²⁸, P. Chang¹⁶⁶, B. Chapleau⁸⁶, J.D. Chapman²⁸, D. Charfeddine¹¹⁶, D.G. Charlton¹⁸, C.C. Chau¹⁵⁹, C.A. Chavez Barajas¹⁵⁰, S. Cheatham⁸⁶, A. Chegwidan⁸⁹, S. Chekanov⁶, S.V. Chekulaev^{160a}, G.A. Chelkov^{64,f}, M.A. Chelstowska⁸⁸, C. Chen⁶³, H. Chen²⁵, K. Chen¹⁴⁹, L. Chen^{33d,g}, S. Chen^{33c}, X. Chen^{146c}, Y. Chen⁶⁶, Y. Chen³⁵, H.C. Cheng⁸⁸, Y. Cheng³¹, A. Cheplakov⁶⁴, R. Cherkaoui El Moursli^{136e}, V. Chernyatin^{25,*}, E. Cheu⁷, L. Chevalier¹³⁷, V. Chiarella⁴⁷, G. Chiefari^{103a,103b}, J.T. Childers⁶, A. Chilingarov⁷¹, G. Chiodini^{72a}, A.S. Chisholm¹⁸, R.T. Chislett⁷⁷, A. Chitan^{26a}, M.V. Chizhov⁶⁴, S. Chouridou⁹, B.K.B. Chow⁹⁹, D. Chromek-Burckhart³⁰, M.L. Chu¹⁵², J. Chudoba¹²⁶, J.J. Chwastowski³⁹, L. Chytka¹¹⁴, G. Ciapetti^{133a,133b}, A.K. Ciftci^{4a}, R. Ciftci^{4a}, D. Cinca⁵³, V. Cindro⁷⁴, A. Ciocio¹⁵, P. Cirkovic^{13b}, Z.H. Citron¹⁷³, M. Citterio^{90a}, M. Ciubancan^{26a}, A. Clark⁴⁹, P.J. Clark⁴⁶, R.N. Clarke¹⁵, W. Cleland¹²⁴, J.C. Clemens⁸⁴, C. Clement^{147a,147b}, Y. Coadou⁸⁴, M. Cobal^{165a,165c}, A. Cocco¹³⁹, J. Cochran⁶³, L. Coffey²³, J.G. Cogan¹⁴⁴, J. Coggeshall¹⁶⁶, B. Cole³⁵, S. Cole¹⁰⁷, A.P. Colijn¹⁰⁶, J. Collot⁵⁵, T. Colombo^{58c}, G. Colon⁸⁵, G. Compostella¹⁰⁰, P. Conde Muiño^{125a,125b}, E. Coniavitis⁴⁸, M.C. Conidi¹², S.H. Connell^{146b}, I.A. Connelly⁷⁶, S.M. Consonni^{90a,90b}, V. Consorti⁴⁸, S. Constantinescu^{26a}, C. Conta^{120a,120b}, G. Conti⁵⁷, F. Conventi^{103a,h}, M. Cooke¹⁵, B.D. Cooper⁷⁷, A.M. Cooper-Sarkar¹¹⁹, N.J. Cooper-Smith⁷⁶, K. Copic¹⁵, T. Cornelissen¹⁷⁶, M. Corradi^{20a}, F. Corriveau^{86,i}, A. Corso-Radu¹⁶⁴, A. Cortes-Gonzalez¹², G. Cortiana¹⁰⁰, G. Costa^{90a}, M.J. Costa¹⁶⁸, D. Costanzo¹⁴⁰, D. Côté⁸, G. Cottin²⁸, G. Cowan⁷⁶, B.E. Cox⁸³, K. Cranmer¹⁰⁹, G. Cree²⁹, S. Crépe-Renaudin⁵⁵, F. Crescioli⁷⁹, W.A. Cribbs^{147a,147b}, M. Crispin Ortuzar¹¹⁹, M. Cristinziani²¹, V. Croft¹⁰⁵, G. Crosetti^{37a,37b}, C.-M. Cucuc^{26a}, T. Cuhadar Donszelmann¹⁴⁰, J. Cummings¹⁷⁷, M. Curatolo⁴⁷, C. Cuthbert¹⁵¹, H. Cziri¹⁴², P. Czodrowski³, Z. Czyczula¹⁷⁷, S. D'Auria⁵³, M. D'Onofrio⁷³, M.J. Da Cunha Sargedas De Sousa^{125a,125b}, C. Da Via⁸³, W. Dabrowski^{38a}, A. Dafinca¹¹⁹, T. Dai⁸⁸, O. Dale¹⁴, F. Dallaire⁹⁴, C. Dallapiccola⁸⁵, M. Dam³⁶, A.C. Daniells¹⁸, M. Dano Hoffmann¹³⁷, V. Dao⁴⁸, G. Darbo^{50a}, S. Darmora⁸, J.A. Dassoulas⁴², A. Dattagupta⁶⁰, W. Davey²¹, C. David¹⁷⁰, T. Davidek¹²⁸, E. Davies^{119,c}, M. Davies¹⁵⁴, O. Davignon⁷⁹, A.R. Davison⁷⁷, P. Davison⁷⁷, Y. Davygora^{58a}, E. Dawe¹⁴³, I. Dawson¹⁴⁰, R.K. Daya-Ishmukhametova⁸⁵, K. De⁸, R. de Asmundis^{103a}, S. De Castro^{20a,20b}, S. De Cecco⁷⁹, N. De Groot¹⁰⁵, P. de Jong¹⁰⁶, H. De la Torre⁸¹, F. De Lorenzi⁶³, L. De Nooij¹⁰⁶, D. De Pedis^{133a}, A. De Salvo^{133a}, U. De Sanctis^{165a,165b}, A. De Santo¹⁵⁰, J.B. De Vivie De Regie¹¹⁶, W.J. Dearnaley⁷¹, R. Debbe²⁵, C. Debenedetti¹³⁸, B. Dechenaux⁵⁵, D.V. Dedovich⁶⁴, I. Deigaard¹⁰⁶, J. Del Peso⁸¹, T. Del Prete^{123a,123b}, F. Deliot¹³⁷, C.M. Delitzsch⁴⁹, M. Deliyergiyev⁷⁴, A. Dell'Acqua³⁰, L. Dell'Asta²², M. Dell'Orso^{123a,123b}, M. Della Pietra^{103a,h}, D. della Volpe⁴⁹, M. Delmastro⁵, P.A. Delsart⁵⁵, C. Deluca¹⁰⁶, S. Demers¹⁷⁷, M. Demichev⁶⁴, A. Demilly⁷⁹, S.P. Denisov¹²⁹, D. Derendarz³⁹, J.E. Derkaoui^{136d}, F. Derue⁷⁹, P. Dervan⁷³, K. Desch²¹, C. Deterre⁴², P.O. Deviveiros¹⁰⁶, A. Dewhurst¹³⁰, S. Dhaliwal¹⁰⁶, A. Di Ciaccio^{134a,134b}, L. Di Ciaccio⁵, A. Di Domenico^{133a,133b}, C. Di Donato^{103a,103b}, A. Di Girolamo³⁰, B. Di Girolamo³⁰, A. Di Mattia¹⁵³, B. Di Micco^{135a,135b}, R. Di Nardo⁴⁷, A. Di Simone⁴⁸, R. Di Sipio^{20a,20b}, D. Di Valentino²⁹, F.A. Dias⁴⁶, M.A. Diaz^{32a}, E.B. Diehl⁸⁸, J. Dietrich⁴², T.A. Dietzsch^{58a}, S. Diglio⁸⁴, A. Dimitrievska^{13a}, J. Dingfelder²¹, C. Dionisi^{133a,133b}, P. Dita^{26a}, S. Dita^{26a}, F. Dittus³⁰, F. Djama⁸⁴, T. Djobava^{51b}, M.A.B. do Vale^{24c}, A. Do Valle Wemans^{125a,125g}, T.K.O. Doan⁵, D. Dobos³⁰, C. Doglioni⁴⁹, T. Doherty⁵³, T. Dohmae¹⁵⁶, J. Dolejsi¹²⁸, Z. Dolezal¹²⁸, B.A. Dolgoshein^{97,*}, M. Donadelli^{24d}, S. Donati^{123a,123b}, P. Dondero^{120a,120b}, J. Donini³⁴, J. Dopke¹³⁰, A. Doria^{103a}, M.T. Dova⁷⁰, A.T. Doyle⁵³, M. Dris¹⁰, J. Dubbert⁸⁸, S. Dube¹⁵, E. Dubreuil³⁴, E. Duchovni¹⁷³, G. Duckeck⁹⁹, O.A. Ducu^{26a}, D. Duda¹⁷⁶, A. Dudarev³⁰, F. Dudziak⁶³, L. Duflo¹¹⁶, L. Duguid⁷⁶, M. Dührssen³⁰, M. Dunford^{58a}, H. Duran Yildiz^{4a}, M. Düren⁵², A. Durglishvili^{51b}, M. Dwuznik^{38a}, M. Dyndal^{38a}, J. Ebke⁹⁹, W. Edson², N.C. Edwards⁴⁶, W. Ehrenfeld²¹, T. Eifert¹⁴⁴, G. Eigen¹⁴, K. Einsweiler¹⁵, T. Ekelof¹⁶⁷, M. El Kacimi^{136c}, M. Ellert¹⁶⁷, S. Elles⁵, F. Ellinghaus⁸², N. Ellis³⁰, J. Elmsheuser⁹⁹, M. Elsing³⁰, D. Emelianov¹³⁰, Y. Enari¹⁵⁶, O.C. Endner⁸², M. Endo¹¹⁷, R. Engelmann¹⁴⁹, J. Erdmann¹⁷⁷, A. Ereditato¹⁷, D. Eriksson^{147a}, G. Ernis¹⁷⁶, J. Ernst², M. Ernst²⁵, J. Ernwein¹³⁷, D. Errede¹⁶⁶, S. Errede¹⁶⁶, E. Ertel⁸², M. Escalier¹¹⁶, H. Esch⁴³, C. Escobar¹²⁴, B. Esposito⁴⁷, A.I. Etienne¹³⁷, E. Etzion¹⁵⁴, H. Evans⁶⁰, A. Ezhilov¹²², L. Fabbri^{20a,20b}, G. Facini³¹, R.M. Fakhruddinov¹²⁹, S. Falciano^{133a}, R.J. Falla⁷⁷, J. Faltova¹²⁸, Y. Fang^{33a}, M. Fanti^{90a,90b}, A. Farbin⁸, A. Farilla^{135a}, T. Farooque¹², S. Farrell¹⁵, S.M. Farrington¹⁷¹, P. Farthouat³⁰, F. Fassi^{136e}, P. Fassnacht³⁰, D. Fassouliotis⁹,

A. Favareto^{50a,50b}, L. Fayard¹¹⁶, P. Federic^{145a}, O.L. Fedin^{122,j}, W. Fedorko¹⁶⁹, M. Fehling-Kaschek⁴⁸, S. Feigl³⁰, L. Feligioni⁸⁴, C. Feng^{33d}, E.J. Feng⁶, H. Feng⁸⁸, A.B. Fenyuk¹²⁹, S. Fernandez Perez³⁰, S. Ferrag⁵³, J. Ferrando⁵³, A. Ferrari¹⁶⁷, P. Ferrari¹⁰⁶, R. Ferrari^{120a}, D.E. Ferreira de Lima⁵³, A. Ferrer¹⁶⁸, D. Ferrere⁴⁹, C. Ferretti⁸⁸, A. Ferretto Parodi^{50a,50b}, M. Fiassaric³¹, F. Fiedler⁸², A. Filipčič⁷⁴, M. Filipuzzi⁴², F. Filthaut¹⁰⁵, M. Fincke-Keeler¹⁷⁰, K.D. Finelli¹⁵¹, M.C.N. Fiolhais^{125a,125c}, L. Fiorini¹⁶⁸, A. Firan⁴⁰, A. Fischer², J. Fischer¹⁷⁶, W.C. Fisher⁸⁹, E.A. Fitzgerald²³, M. Flechl⁴⁸, I. Fleck¹⁴², P. Fleischmann⁸⁸, S. Fleischmann¹⁷⁶, G.T. Fletcher¹⁴⁰, G. Fletcher⁷⁵, T. Flick¹⁷⁶, A. Floderus⁸⁰, L.R. Flores Castillo^{174,k}, A.C. Florez Bustos^{160b}, M.J. Flowerdew¹⁰⁰, A. Formica¹³⁷, A. Forti⁸³, D. Fortin^{160a}, D. Fournier¹¹⁶, H. Fox⁷¹, S. Fracchia¹², P. Francavilla⁷⁹, M. Franchini^{20a,20b}, S. Franchino³⁰, D. Francis³⁰, L. Franconi¹¹⁸, M. Franklin⁵⁷, S. Franz⁶¹, M. Fraternali^{120a,120b}, S.T. French²⁸, C. Friedrich⁴², F. Friedrich⁴⁴, D. Froidevaux³⁰, J.A. Frost²⁸, C. Fukunaga¹⁵⁷, E. Fullana Torregrosa⁸², B.G. Fulsom¹⁴⁴, J. Fuster¹⁶⁸, C. Gabaldon⁵⁵, O. Gabizon¹⁷³, A. Gabrielli^{20a,20b}, A. Gabrielli^{133a,133b}, S. Gadatsch¹⁰⁶, S. Gadowski⁴⁹, G. Gagliardi^{50a,50b}, P. Gagnon⁶⁰, C. Galea¹⁰⁵, B. Galhardo^{125a,125c}, E.J. Gallas¹¹⁹, V. Gallo¹⁷, B.J. Gallop¹³⁰, P. Gallus¹²⁷, G. Galster³⁶, K.K. Gan¹¹⁰, J. Gao^{33b,g}, Y.S. Gao^{144,e}, F.M. Garay Walls⁴⁶, F. Garberson¹⁷⁷, C. García¹⁶⁸, J.E. García Navarro¹⁶⁸, M. Garcia-Sciveres¹⁵, R.W. Gardner³¹, N. Garelli¹⁴⁴, V. Garonne³⁰, C. Gatti⁴⁷, G. Gaudio^{120a}, B. Gaur¹⁴², L. Gauthier⁹⁴, P. Gauzzi^{133a,133b}, I.L. Gavrilenko⁹⁵, C. Gay¹⁶⁹, G. Gaycken²¹, E.N. Gazis¹⁰, P. Ge^{33d}, Z. Gece¹⁶⁹, C.N.P. Gee¹³⁰, D.A.A. Geerts¹⁰⁶, Ch. Geich-Gimbel²¹, K. Gellerstedt^{147a,147b}, C. Gemme^{50a}, A. Gemmell⁵³, M.H. Genest⁵⁵, S. Gentile^{133a,133b}, M. George⁵⁴, S. George⁷⁶, D. Gerbaudo¹⁶⁴, A. Gershon¹⁵⁴, H. Ghazlane^{136b}, N. Ghodbane³⁴, B. Giacobbe^{20a}, S. Giagu^{133a,133b}, V. Giangiobbe¹², P. Giannetti^{123a,123b}, F. Gianotti³⁰, B. Gibbard²⁵, S.M. Gibson⁷⁶, M. Gilchriese¹⁵, T.P.S. Gillam²⁸, D. Gillberg³⁰, G. Gilles³⁴, D.M. Gingrich^{3,d}, N. Giokaris⁹, M.P. Giordani^{165a,165c}, R. Giordano^{103a,103b}, F.M. Giorgi^{20a}, F.M. Giorgi¹⁶, P.F. Giraud¹³⁷, D. Giugni^{90a}, C. Giuliani⁴⁸, M. Giulini^{58b}, B.K. Gjelsten¹¹⁸, S. Gkaitatzis¹⁵⁵, I. Gkialas^{155,l}, L.K. Gladilin⁹⁸, C. Glasman⁸¹, J. Glatzer³⁰, P.C.F. Glaysher⁴⁶, A. Glazov⁴², G.L. Glonti⁶⁴, M. Goblirsch-Kolb¹⁰⁰, J.R. Goddard⁷⁵, J. Godfrey¹⁴³, J. Godlewski³⁰, C. Goeringer⁸², S. Goldfarb⁸⁸, T. Golling¹⁷⁷, D. Golubkov¹²⁹, A. Gomes^{125a,125b,125d}, L.S. Gomez Fajardo⁴², R. Gonçalo^{125a}, J. Goncalves Pinto Firmino Da Costa¹³⁷, L. Gonella²¹, S. González de la Hoz¹⁶⁸, G. Gonzalez Parra¹², S. Gonzalez-Sevilla⁴⁹, L. Goossens³⁰, P.A. Gorbounov⁹⁶, H.A. Gordon²⁵, I. Gorelov¹⁰⁴, B. Gorini³⁰, E. Gorini^{72a,72b}, A. Gorišek⁷⁴, E. Gornicki³⁹, A.T. Goshaw⁶, C. Gössling⁴³, M.I. Gostkin⁶⁴, M. Gouighri^{136a}, D. Goujdami^{136c}, M.P. Goulette⁴⁹, A.G. Goussiou¹³⁹, C. Goy⁵, S. Gozpinar²³, H.M.X. Grabas¹³⁷, L. Graber⁵⁴, I. Grabowska-Bold^{38a}, P. Grafström^{20a,20b}, K.-J. Grahm⁴², J. Gramling⁴⁹, E. Gramstad¹¹⁸, S. Grancagnolo¹⁶, V. Grassi¹⁴⁹, V. Gratchev¹²², H.M. Gray³⁰, E. Graziani^{135a}, O.G. Grebenyuk¹²², Z.D. Greenwood^{78,m}, K. Gregersen⁷⁷, I.M. Gregor⁴², P. Grenier¹⁴⁴, J. Griffiths⁸, A.A. Grillo¹³⁸, K. Grimm⁷¹, S. Grinstein^{12,n}, Ph. Gris³⁴, Y.V. Grishkevich⁹⁸, J.-F. Grivaz¹¹⁶, J.P. Grohs⁴⁴, A. Grohsjean⁴², E. Gross¹⁷³, J. Grosse-Knetter⁵⁴, G.C. Grossi^{134a,134b}, J. Groth-Jensen¹⁷³, Z.J. Grout¹⁵⁰, L. Guan^{33b}, F. Guescini⁴⁹, D. Guest¹⁷⁷, O. Gueta¹⁵⁴, C. Guicheney³⁴, E. Guido^{50a,50b}, T. Guillemin¹¹⁶, S. Guindon², U. Gul⁵³, C. Gumpert⁴⁴, J. Gunther¹²⁷, J. Guo³⁵, S. Gupta¹¹⁹, P. Gutierrez¹¹², N.G. Gutierrez Ortiz⁵³, C. Gutsche⁷⁷, N. Guttman¹⁵⁴, C. Guyot¹³⁷, C. Gwenlan¹¹⁹, C.B. Gwilliam⁷³, A. Haas¹⁰⁹, C. Haber¹⁵, H.K. Hadavand⁸, N. Haddad^{136e}, P. Haefner²¹, S. Hageböck²¹, Z. Hajduk³⁹, H. Hakobyan¹⁷⁸, M. Haleem⁴², D. Hall¹¹⁹, G. Halladjian⁸⁹, K. Hamacher¹⁷⁶, P. Hamal¹¹⁴, K. Hamano¹⁷⁰, M. Hamer⁵⁴, A. Hamilton^{146a}, S. Hamilton¹⁶², G.N. Hamity^{146c}, P.G. Hamnett⁴², L. Han^{33b}, K. Hanagaki¹¹⁷, K. Hanawa¹⁵⁶, M. Hance¹⁵, P. Hanke^{58a}, R. Hanna¹³⁷, J.B. Hansen³⁶, J.D. Hansen³⁶, P.H. Hansen³⁶, K. Hara¹⁶¹, A.S. Hard¹⁷⁴, T. Harenberg¹⁷⁶, F. Hariri¹¹⁶, S. Harkusha⁹¹, D. Harper⁸⁸, R.D. Harrington⁴⁶, O.M. Harris¹³⁹, P.F. Harrison¹⁷¹, F. Hartjes¹⁰⁶, M. Hasegawa⁶⁶, S. Hasegawa¹⁰², Y. Hasegawa¹⁴¹, A. Hasib¹¹², S. Hassani¹³⁷, S. Haug¹⁷, M. Hauschild³⁰, R. Hauser⁸⁹, M. Havranek¹²⁶, C.M. Hawkes¹⁸, R.J. Hawkins³⁰, A.D. Hawkins⁸⁰, T. Hayashi¹⁶¹, D. Hayden⁸⁹, C.P. Hays¹¹⁹, H.S. Hayward⁷³, S.J. Haywood¹³⁰, S.J. Head¹⁸, T. Heck⁸², V. Hedberg⁸⁰, L. Heelan⁸, S. Heim¹²¹, T. Heim¹⁷⁶, B. Heinemann¹⁵, L. Heinrich¹⁰⁹, J. Hejbal¹²⁶, L. Helary²², C. Heller⁹⁹, M. Heller³⁰, S. Hellman^{147a,147b}, D. Hellmich²¹, C. Helsens³⁰, J. Henderson¹¹⁹, R.C.W. Henderson⁷¹, Y. Heng¹⁷⁴, C. Hengler⁴², A. Henrichs¹⁷⁷, A.M. Henriques Correia³⁰, S. Henrot-Versille¹¹⁶, C. Hensel⁵⁴, G.H. Herbert¹⁶, Y. Hernández Jiménez¹⁶⁸, R. Herrberg-Schubert¹⁶, G. Herten⁴⁸, R. Hertenberger⁹⁹, L. Hervas³⁰, G.G. Hesketh⁷⁷, N.P. Hessey¹⁰⁶, R. Hickling⁷⁵, E. Higón-Rodríguez¹⁶⁸, E. Hill¹⁷⁰, J.C. Hill²⁸, K.H. Hiller⁴², S. Hillert²¹, S.J. Hillier¹⁸, I. Hinchliffe¹⁵, E. Hines¹²¹, M. Hirose¹⁵⁸, D. Hirschbuehl¹⁷⁶, J. Hobbs¹⁴⁹, N. Hod¹⁰⁶, M.C. Hodgkinson¹⁴⁰, P. Hodgson¹⁴⁰, A. Hoecker³⁰, M.R. Hoferkamp¹⁰⁴, F. Hoenig⁹⁹, J. Hoffman⁴⁰, D. Hoffmann⁸⁴, J.I. Hofmann^{58a}, M. Hohlfield⁸², T.R. Holmes¹⁵, T.M. Hong¹²¹, L. Hooft van Huysduynen¹⁰⁹, Y. Horii¹⁰², J.-Y. Hostachy⁵⁵, S. Hou¹⁵², A. Hoummada^{136a}, J. Howard¹¹⁹, J. Howarth⁴², M. Hrabovsky¹¹⁴, I. Hristova¹⁶, J. Hrivnac¹¹⁶, T. Hryn'ova⁵, C. Hsu^{146c}, P.J. Hsu⁸², S.-C. Hsu¹³⁹, D. Hu³⁵, X. Hu²⁵, Y. Huang⁴², Z. Hubacek³⁰, F. Hubaut⁸⁴, F. Huegging²¹, T.B. Huffman¹¹⁹, E.W. Hughes³⁵, G. Hughes⁷¹, M. Huhtinen³⁰, T.A. Hülsing⁸², M. Hurwitz¹⁵, N. Huseynov^{64,b}, J. Huston⁸⁹, J. Huth⁵⁷, G. Iacobucci⁴⁹, G. Iakovidis¹⁰, I. Ibragimov¹⁴², L. Iconomidou-Fayard¹¹⁶, E. Ideal¹⁷⁷, P. Iengo^{103a}, O. Igonkina¹⁰⁶, T. Iizawa¹⁷², Y. Ikegami⁶⁵, K. Ikematsu¹⁴², M. Ikeno⁶⁵, Y. Ilchenko^{31,o}, D. Iliadis¹⁵⁵, N. Ilic¹⁵⁹, Y. Inamaru⁶⁶, T. Ince¹⁰⁰, P. Ioannou⁹,

M. Iodice^{135a}, K. Iordanidou⁹, V. Ippolito⁵⁷, A. Irlles Quiles¹⁶⁸, C. Isaksson¹⁶⁷, M. Ishino⁶⁷, M. Ishitsuka¹⁵⁸, R. Ishmukhametov¹¹⁰, C. Issever¹¹⁹, S. Istin^{19a}, J.M. Iturbe Ponce⁸³, R. Iuppa^{134a,134b}, J. Ivarsson⁸⁰, W. Iwanski³⁹, H. Iwasaki⁶⁵, J.M. Izen⁴¹, V. Izzo^{103a}, B. Jackson¹²¹, M. Jackson⁷³, P. Jackson¹, M.R. Jaekel³⁰, V. Jain², K. Jakobs⁴⁸, S. Jakobsen³⁰, T. Jakoubek¹²⁶, J. Jakubek¹²⁷, D.O. Jamin¹⁵², D.K. Jana⁷⁸, E. Jansen⁷⁷, H. Jansen³⁰, J. Janssen²¹, M. Janus¹⁷¹, G. Jarlskog⁸⁰, N. Javadov^{64,b}, T. Javůrek⁴⁸, L. Jeanty¹⁵, J. Jejelava^{51a,p}, G.-Y. Jeng¹⁵¹, D. Jennens⁸⁷, P. Jenni^{48,q}, J. Jentzsch⁴³, C. Jeske¹⁷¹, S. Jézéquel⁵, H. Ji¹⁷⁴, J. Jia¹⁴⁹, Y. Jiang^{33b}, M. Jimenez Belenguer⁴², S. Jin^{33a}, A. Jinaru^{26a}, O. Jinnouchi¹⁵⁸, M.D. Joergensen³⁶, K.E. Johansson^{147a,147b}, P. Johansson¹⁴⁰, K.A. Johns⁷, K. Jon-And^{147a,147b}, G. Jones¹⁷¹, R.W.L. Jones⁷¹, T.J. Jones⁷³, J. Jongmanns^{58a}, P.M. Jorge^{125a,125b}, K.D. Joshi⁸³, J. Jovicevic¹⁴⁸, X. Ju¹⁷⁴, C.A. Jung⁴³, R.M. Jungst³⁰, P. Jussel⁶¹, A. Juste Rozas^{12,n}, M. Kaci¹⁶⁸, A. Kaczmarzka³⁹, M. Kado¹¹⁶, H. Kagan¹¹⁰, M. Kagan¹⁴⁴, E. Kajomovitz⁴⁵, C.W. Kalderon¹¹⁹, S. Kama⁴⁰, A. Kamenshchikov¹²⁹, N. Kanaya¹⁵⁶, M. Kaneda³⁰, S. Kaneti²⁸, V.A. Kantserov⁹⁷, J. Kanzaki⁶⁵, B. Kaplan¹⁰⁹, A. Kapliy³¹, D. Kar⁵³, K. Karakostas¹⁰, N. Karastathis¹⁰, M. Karnevskiy⁸², S.N. Karpov⁶⁴, Z.M. Karpova⁶⁴, K. Karthik¹⁰⁹, V. Kartvelishvili⁷¹, A.N. Karyukhin¹²⁹, L. Kashif¹⁷⁴, G. Kasieczka^{58b}, R.D. Kass¹¹⁰, A. Kastanas¹⁴, Y. Kataoka¹⁵⁶, A. Katre⁴⁹, J. Katzy⁴², V. Kaushik⁷, K. Kawagoe⁶⁹, T. Kawamoto¹⁵⁶, G. Kawamura⁵⁴, S. Kazama¹⁵⁶, V.F. Kazanin¹⁰⁸, M.Y. Kazarinov⁶⁴, R. Keeler¹⁷⁰, R. Kehoe⁴⁰, M. Keil⁵⁴, J.S. Keller⁴², J.J. Kempster⁷⁶, H. Keoshkerian⁵, O. Kepka¹²⁶, B.P. Kerševan⁷⁴, S. Kersten¹⁷⁶, K. Kessoku¹⁵⁶, J. Keung¹⁵⁹, F. Khalil-zada¹¹, H. Khandanyan^{147a,147b}, A. Khanov¹¹³, A. Khodinov⁹⁷, A. Khomich^{58a}, T.J. Khoo²⁸, G. Khoriali²¹, A. Khoroshilov¹⁷⁶, V. Khovanskij⁹⁶, E. Khranov⁶⁴, J. Khubua^{51b}, H.Y. Kim⁸, H. Kim^{147a,147b}, S.H. Kim¹⁶¹, N. Kimura¹⁷², O. Kind¹⁶, B.T. King⁷³, M. King¹⁶⁸, R.S.B. King¹¹⁹, S.B. King¹⁶⁹, J. Kirk¹³⁰, A.E. Kiryunin¹⁰⁰, T. Kishimoto⁶⁶, D. Kisiulewska^{38a}, F. Kiss⁴⁸, T. Kittelmann¹²⁴, K. Kiuchi¹⁶¹, E. Kladiva^{145b}, M. Klein⁷³, U. Klein⁷³, K. Kleinknecht⁸², P. Klimek^{147a,147b}, A. Klimentov²⁵, R. Klingenberg⁴³, J.A. Klinger⁸³, T. Klioutchnikova³⁰, P.F. Klok¹⁰⁵, E.-E. Kluge^{58a}, P. Kluit¹⁰⁶, S. Kluth¹⁰⁰, E. Kneringer⁶¹, E.B.F.G. Knoops⁸⁴, A. Knue⁵³, D. Kobayashi¹⁵⁸, T. Kobayashi¹⁵⁶, M. Kobel⁴⁴, M. Kocian¹⁴⁴, P. Kodys¹²⁸, P. Koevesarki²¹, T. Koffas²⁹, E. Koffeman¹⁰⁶, L.A. Kogan¹¹⁹, S. Kohlmann¹⁷⁶, Z. Kohout¹²⁷, T. Kohriki⁶⁵, T. Koi¹⁴⁴, H. Kolanoski¹⁶, I. Koletsou⁵, J. Koll⁸⁹, A.A. Komar^{95,*}, Y. Komori¹⁵⁶, T. Kondo⁶⁵, N. Kondrashova⁴², K. Köneke⁴⁸, A.C. König¹⁰⁵, S. König⁸², T. Kono^{65,r}, R. Konoplich^{109,s}, N. Konstantinidis⁷⁷, R. Kopeliandy¹⁵³, S. Koperny^{38a}, L. Köpke⁸², A.K. Kopp⁴⁸, K. Korcyl³⁹, K. Kordas¹⁵⁵, A. Korn⁷⁷, A.A. Korol^{108,t}, I. Korolkov¹², E.V. Korolkova¹⁴⁰, V.A. Korotkov¹²⁹, O. Kortner¹⁰⁰, S. Kortner¹⁰⁰, V.V. Kostyukhin²¹, V.M. Kotov⁶⁴, A. Kotwal⁴⁵, C. Kourkouvelis⁹, V. Kouskoura¹⁵⁵, A. Koutsman^{160a}, R. Kowalewski¹⁷⁰, T.Z. Kowalski^{38a}, W. Kozanecki¹³⁷, A.S. Kozhin¹²⁹, V. Kral¹²⁷, V.A. Kramarenko⁹⁸, G. Kramberger⁷⁴, D. Krasnopevtsev⁹⁷, M.W. Krasny⁷⁹, A. Krasznahorkay³⁰, J.K. Kraus²¹, A. Kravchenko²⁵, S. Kreiss¹⁰⁹, M. Kretz^{58c}, J. Kretzschmar⁷³, K. Kreutzfeldt⁵², P. Krieger¹⁵⁹, K. Kroeninger⁵⁴, H. Kroha¹⁰⁰, J. Kroll¹²¹, J. Kroseberg²¹, J. Krstic^{13a}, U. Kruchonak⁶⁴, H. Krüger²¹, T. Kruker¹⁷, N. Krumnack⁶³, Z.V. Krumshteyn⁶⁴, A. Kruse¹⁷⁴, M.C. Kruse⁴⁵, M. Kruskal²², T. Kubota⁸⁷, S. Kудay^{4a}, S. Kuehn⁴⁸, A. Kugel^{58c}, A. Kuhl¹³⁸, T. Kuhl⁴², V. Kukhtin⁶⁴, Y. Kulchitsky⁹¹, S. Kuleshov^{32b}, M. Kuna^{133a,133b}, J. Kunkle¹²¹, A. Kupco¹²⁶, H. Kurashige⁶⁶, Y.A. Kurochkin⁹¹, R. Kurumida⁶⁶, V. Kus¹²⁶, E.S. Kuwertz¹⁴⁸, M. Kuze¹⁵⁸, J. Kvita¹¹⁴, A. La Rosa⁴⁹, L. La Rotonda^{37a,37b}, C. Lacasta¹⁶⁸, F. Lacava^{133a,133b}, J. Lacey²⁹, H. Lacker¹⁶, D. Lacour⁷⁹, V.R. Lacuesta¹⁶⁸, E. Ladygin⁶⁴, R. Lafaye⁵, B. Laforge⁷⁹, T. Lagouri¹⁷⁷, S. Lai⁴⁸, H. Laier^{58a}, L. Lambourne⁷⁷, S. Lammers⁶⁰, C.L. Lampen⁷, W. Lampl⁷, E. Lançon¹³⁷, U. Landgraf⁴⁸, M.P.J. Landon⁷⁵, V.S. Lang^{58a}, A.J. Lankford¹⁶⁴, F. Lanni²⁵, K. Lantzsch³⁰, S. Laplace⁷⁹, C. Lapoire²¹, J.F. Laporte¹³⁷, T. Lari^{90a}, M. Lassnig³⁰, P. Laurelli⁴⁷, W. Lavrijsen¹⁵, A.T. Law¹³⁸, P. Laycock⁷³, O. Le Dortz⁷⁹, E. Le Guirriec⁸⁴, E. Le Menedeu¹², T. LeCompte⁶, F. Ledroit-Guillon⁵⁵, C.A. Lee¹⁵², H. Lee¹⁰⁶, J.S.H. Lee¹¹⁷, S.C. Lee¹⁵², L. Lee¹, G. Lefebvre⁷⁹, M. Lefebvre¹⁷⁰, F. Legger⁹⁹, C. Leggett¹⁵, A. Lehan⁷³, M. Lehmacher²¹, G. Lehmann Miotto³⁰, X. Lei⁷, W.A. Leight²⁹, A. Leisos¹⁵⁵, A.G. Leister¹⁷⁷, M.A.L. Leite^{24d}, R. Leitner¹²⁸, D. Lellouch¹⁷³, B. Lemmer⁵⁴, K.J.C. Leney⁷⁷, T. Lenz²¹, G. Lenzen¹⁷⁶, B. Lenzi³⁰, R. Leone⁷, S. Leone^{123a,123b}, K. Leonhardt⁴⁴, C. Leonidopoulos⁴⁶, S. Leontsinis¹⁰, C. Leroy⁹⁴, C.G. Lester²⁸, C.M. Lester¹²¹, M. Levchenko¹²², J. Levêque⁵, D. Levin⁸⁸, L.J. Levinson¹⁷³, M. Levy¹⁸, A. Lewis¹¹⁹, G.H. Lewis¹⁰⁹, A.M. Leyko²¹, M. Leyton⁴¹, B. Li^{33b,u}, B. Li⁸⁴, H. Li¹⁴⁹, H.L. Li³¹, L. Li⁴⁵, L. Li^{33e}, S. Li⁴⁵, Y. Li^{33c,v}, Z. Liang¹³⁸, H. Liao³⁴, B. Liberti^{134a}, P. Lichard³⁰, K. Lie¹⁶⁶, J. Liebal²¹, W. Liebig¹⁴, C. Limbach²¹, A. Limosani⁸⁷, S.C. Lin^{152,w}, T.H. Lin⁸², F. Linde¹⁰⁶, B.E. Lindquist¹⁴⁹, J.T. Linnemann⁸⁹, E. Lipeles¹²¹, A. Lipniacka¹⁴, M. Lisovsky⁴², T.M. Liss¹⁶⁶, D. Lissauer²⁵, A. Lister¹⁶⁹, A.M. Litke¹³⁸, B. Liu¹⁵², D. Liu¹⁵², J.B. Liu^{33b}, K. Liu^{33b,x}, L. Liu⁸⁸, M. Liu⁴⁵, M. Liu^{33b}, Y. Liu^{33b}, M. Livan^{120a,120b}, S.S.A. Livermore¹¹⁹, A. Lleres⁵⁵, J. Llorente Merino⁸¹, S.L. Lloyd⁷⁵, F. Lo Sterzo¹⁵², E. Lobodzinska⁴², P. Loch⁷, W.S. Lockman¹³⁸, T. Loddenkoetter²¹, F.K. Loebinger⁸³, A.E. Loevschall-Jensen³⁶, A. Loginov¹⁷⁷, T. Lohse¹⁶, K. Lohwasser⁴², M. Lokajicek¹²⁶, V.P. Lombardo⁵, B.A. Long²², J.D. Long⁸⁸, R.E. Long⁷¹, L. Lopes^{125a}, D. Lopez Mateos⁵⁷, B. Lopez Paredes¹⁴⁰, I. Lopez Paz¹², J. Lorenz⁹⁹, N. Lorenzo Martinez⁶⁰, M. Losada¹⁶³, P. Loscuttoff¹⁵, X. Lou⁴¹, A. Lounis¹¹⁶, J. Love⁶, P.A. Love⁷¹, A.J. Lowe^{144,e}, F. Lu^{33a}, N. Lu⁸⁸, H.J. Lubatti¹³⁹, C. Luci^{133a,133b}, A. Lucotte⁵⁵, F. Luehring⁶⁰, W. Lukas⁶¹, L. Luminari^{133a}, O. Lundberg^{147a,147b}, B. Lund-Jensen¹⁴⁸,

M. Lungwitz⁸², D. Lynn²⁵, R. Lysak¹²⁶, E. Lytken⁸⁰, H. Ma²⁵, L.L. Ma^{33d}, G. Maccarrone⁴⁷, A. Macchiolo¹⁰⁰, J. Machado Miguens^{125a,125b}, D. Macina³⁰, D. Madaffari⁸⁴, R. Madar⁴⁸, H.J. Maddocks⁷¹, W.F. Mader⁴⁴, A. Madsen¹⁶⁷, M. Maeno⁸, T. Maeno²⁵, E. Magradze⁵⁴, K. Mahboubi⁴⁸, J. Mahlstedt¹⁰⁶, S. Mahmoud⁷³, C. Maiani¹³⁷, C. Maidantchik^{24a}, A.A. Maier¹⁰⁰, A. Maio^{125a,125b,125d}, S. Majewski¹¹⁵, Y. Makida⁶⁵, N. Makovec¹¹⁶, P. Mal^{137,y}, B. Malaescu⁷⁹, Pa. Malecki³⁹, V.P. Maleev¹²², F. Malek⁵⁵, U. Mallik⁶², D. Malon⁶, C. Malone¹⁴⁴, S. Maltezos¹⁰, V.M. Malyshev¹⁰⁸, S. Malyukov³⁰, J. Mamuzic^{13b}, B. Mandelli³⁰, L. Mandelli^{90a}, I. Mandić⁷⁴, R. Mandrysch⁶², J. Maneira^{125a,125b}, A. Manfredini¹⁰⁰, L. Manhaes de Andrade Filho^{24b}, J.A. Manjarres Ramos^{160b}, A. Mann⁹⁹, P.M. Manning¹³⁸, A. Manousakis-Katsikakis⁹, B. Mansoulie¹³⁷, R. Mantifel⁸⁶, L. Mapelli³⁰, L. March¹⁶⁸, J.F. Marchand²⁹, G. Marchiori⁷⁹, M. Marcisovsky¹²⁶, C.P. Marino¹⁷⁰, M. Marjanovic^{13a}, C.N. Marques^{125a}, F. Marroquin^{24a}, S.P. Marsden⁸³, Z. Marshall¹⁵, L.F. Marti¹⁷, S. Marti-Garcia¹⁶⁸, B. Martin³⁰, B. Martin⁸⁹, T.A. Martin¹⁷¹, V.J. Martin⁴⁶, B. Martin dit Latour¹⁴, H. Martinez¹³⁷, M. Martinez^{12,n}, S. Martin-Haugh¹³⁰, A.C. Martyniuk⁷⁷, M. Marx¹³⁹, F. Marzano^{133a}, A. Marzin³⁰, L. Masetti⁸², T. Mashimo¹⁵⁶, R. Mashinistov⁹⁵, J. Masik⁸³, A.L. Maslennikov¹⁰⁸, I. Massa^{20a,20b}, L. Massa^{20a,20b}, N. Massol⁵, P. Mastrandrea¹⁴⁹, A. Mastroberardino^{37a,37b}, T. Masubuchi¹⁵⁶, P. Mättig¹⁷⁶, J. Mattmann⁸², J. Maurer^{26a}, S.J. Maxfield⁷³, D.A. Maximov^{108,t}, R. Mazini¹⁵², L. Mazzaferro^{134a,134b}, G. Mc Goldrick¹⁵⁹, S.P. Mc Kee⁸⁸, A. McCarn⁸⁸, R.L. McCarthy¹⁴⁹, T.G. McCarthy²⁹, N.A. McCubbin¹³⁰, K.W. McFarlane^{56,*}, J.A. MCFayden⁷⁷, G. Mchedlidze⁵⁴, S.J. McMahon¹³⁰, R.A. McPherson^{170,i}, A. Meade⁸⁵, J. Mechnich¹⁰⁶, M. Medinnis⁴², S. Meehan³¹, S. Mehlhase⁹⁹, A. Mehta⁷³, K. Meier^{58a}, C. Meineck⁹⁹, B. Meirose⁸⁰, C. Melachrinou³¹, B.R. Mellado Garcia^{146c}, F. Meloni¹⁷, A. Mengarelli^{20a,20b}, S. Menke¹⁰⁰, E. Meoni¹⁶², K.M. Mercurio⁵⁷, S. Mergelmeyer²¹, N. Meric¹³⁷, P. Mermod⁴⁹, L. Merola^{103a,103b}, C. Meroni^{90a}, F.S. Merritt³¹, H. Merritt¹¹⁰, A. Messina^{30,z}, J. Metcalfe²⁵, A.S. Mete¹⁶⁴, C. Meyer⁸², C. Meyer¹²¹, J-P. Meyer¹³⁷, J. Meyer³⁰, R.P. Middleton¹³⁰, S. Migas⁷³, L. Mijović²¹, G. Mikenberg¹⁷³, M. Mikesstikova¹²⁶, M. Mikuž⁷⁴, A. Milic³⁰, D.W. Miller³¹, C. Mills⁴⁶, A. Milov¹⁷³, D.A. Milstead^{147a,147b}, D. Milstein¹⁷³, A.A. Minaenko¹²⁹, I.A. Minashvili⁶⁴, A.I. Mincer¹⁰⁹, B. Mindur^{38a}, M. Mineev⁶⁴, Y. Ming¹⁷⁴, L.M. Mir¹², G. Mirabelli^{133a}, T. Mitani¹⁷², J. Mitrevski⁹⁹, V.A. Mitsou¹⁶⁸, S. Mitsui⁶⁵, A. Miucci⁴⁹, P.S. Miyagawa¹⁴⁰, J.U. Mjörnmark⁸⁰, T. Moa^{147a,147b}, K. Mochizuki⁸⁴, S. Mohapatra³⁵, W. Mohr⁴⁸, S. Molander^{147a,147b}, R. Moles-Valls¹⁶⁸, K. Mönig⁴², C. Monini⁵⁵, J. Monk³⁶, E. Monnier⁸⁴, J. Montejo Berlingen¹², F. Monticelli⁷⁰, S. Monzani^{133a,133b}, R.W. Moore³, N. Morange⁶², D. Moreno⁸², M. Moreno Llácer⁵⁴, P. Moretini^{50a}, M. Morgenstern⁴⁴, M. Morii⁵⁷, S. Moritz⁸², A.K. Morley¹⁴⁸, G. Mornacchi³⁰, J.D. Morris⁷⁵, L. Morvaj¹⁰², H.G. Moser¹⁰⁰, M. Mosidze^{51b}, J. Moss¹¹⁰, K. Motohashi¹⁵⁸, R. Mount¹⁴⁴, E. Mountricha²⁵, S.V. Mouraviev^{95,*}, E.J.W. Moyse⁸⁵, S. Muanza⁸⁴, R.D. Mudd¹⁸, F. Mueller^{58a}, J. Mueller¹²⁴, K. Mueller²¹, T. Mueller²⁸, T. Mueller⁸², D. Muenstermann⁴⁹, Y. Munwes¹⁵⁴, J.A. Murillo Quijada¹⁸, W.J. Murray^{171,130}, H. Musheghyan⁵⁴, E. Musto¹⁵³, A.G. Myagkov^{129,aa}, M. Myska¹²⁷, O. Nackenhorst⁵⁴, J. Nadal⁵⁴, K. Nagai⁶¹, R. Nagai¹⁵⁸, Y. Nagai⁸⁴, K. Nagano⁶⁵, A. Nagarkar¹¹⁰, Y. Nagasaka⁵⁹, M. Nagel¹⁰⁰, A.M. Nairz³⁰, Y. Nakahama³⁰, K. Nakamura⁶⁵, T. Nakamura¹⁵⁶, I. Nakano¹¹¹, H. Namasivayam⁴¹, G. Nanava²¹, R. Narayan^{58b}, T. Nattermann²¹, T. Naumann⁴², G. Navarro¹⁶³, R. Nayyar⁷, H.A. Neal⁸⁸, P.Yu. Nechaeva⁹⁵, T.J. Neep⁸³, P.D. Nef¹⁴⁴, A. Negri^{120a,120b}, G. Negri³⁰, M. Negrini^{20a}, S. Nektarijevic⁴⁹, A. Nelson¹⁶⁴, T.K. Nelson¹⁴⁴, S. Nemecek¹²⁶, P. Nemethy¹⁰⁹, A.A. Nepomuceno^{24a}, M. Nessi^{30,ab}, M.S. Neubauer¹⁶⁶, M. Neumann¹⁷⁶, R.M. Neves¹⁰⁹, P. Nevski²⁵, P.R. Newman¹⁸, D.H. Nguyen⁶, R.B. Nickerson¹¹⁹, R. Nicolaidou¹³⁷, B. Nicquevert³⁰, J. Nielsen¹³⁸, N. Nikiforou³⁵, A. Nikiforov¹⁶, V. Nikolaenko^{129,aa}, I. Nikolic-Audit⁷⁹, K. Nikolics⁴⁹, K. Nikolopoulos¹⁸, P. Nilsson⁸, Y. Ninomiya¹⁵⁶, A. Nisati^{133a}, R. Nisius¹⁰⁰, T. Nobe¹⁵⁸, L. Nodulman⁶, M. Nomachi¹¹⁷, I. Nomidis²⁹, S. Norberg¹¹², M. Nordberg³⁰, O. Novgorodova⁴⁴, S. Nowak¹⁰⁰, M. Nozaki⁶⁵, L. Nozka¹¹⁴, K. Ntekas¹⁰, G. Nunes Hanninger⁸⁷, T. Nunnemann⁹⁹, E. Nurse⁷⁷, F. Nuti⁸⁷, B.J. O'Brien⁴⁶, F. O'grady⁷, D.C. O'Neil¹⁴³, V. O'Shea⁵³, F.G. Oakham^{29,d}, H. Oberlack¹⁰⁰, T. Obermann²¹, J. Ocariz⁷⁹, A. Ochi⁶⁶, M.I. Ochoa⁷⁷, S. Oda⁶⁹, S. Odaka⁶⁵, H. Ogren⁶⁰, A. Oh⁸³, S.H. Oh⁴⁵, C.C. Ohm¹⁵, H. Ohman¹⁶⁷, W. Okamura¹¹⁷, H. Okawa²⁵, Y. Okumura³¹, T. Okuyama¹⁵⁶, A. Olariu^{26a}, A.G. Olchevski⁶⁴, S.A. Olivares Pino⁴⁶, D. Oliveira Damazio²⁵, E. Oliver Garcia¹⁶⁸, A. Olszewski³⁹, J. Olszowska³⁹, A. Onofre^{125a,125e}, P.U.E. Onyisi^{31,o}, C.J. Oram^{160a}, M.J. Oreglia³¹, Y. Oren¹⁵⁴, D. Orestano^{135a,135b}, N. Orlando^{72a,72b}, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁹, B. Osculati^{50a,50b}, R. Ospanov¹²¹, G. Otero y Garzon²⁷, H. Otono⁶⁹, M. Ouchrif^{136d}, E.A. Ouellette¹⁷⁰, F. Ould-Saada¹¹⁸, A. Ouraou¹³⁷, K.P. Oussoren¹⁰⁶, Q. Ouyang^{33a}, A. Ovcharova¹⁵, M. Owen⁸³, V.E. Ozcan^{19a}, N. Ozturk⁸, K. Pachal¹¹⁹, A. Pacheco Pages¹², C. Padilla Aranda¹², M. Pagáčová⁴⁸, S. Pagan Griso¹⁵, E. Paganis¹⁴⁰, C. Pahl¹⁰⁰, F. Paige²⁵, P. Pais⁸⁵, K. Pajchel¹¹⁸, G. Palacino^{160b}, S. Palestini³⁰, M. Palka^{38b}, D. Pallin³⁴, A. Palma^{125a,125b}, J.D. Palmer¹⁸, Y.B. Pan¹⁷⁴, E. Panagiotopoulou¹⁰, J.G. Panduro Vazquez⁷⁶, P. Pani¹⁰⁶, N. Panikashvili⁸⁸, S. Panitkin²⁵, D. Pantea^{26a}, L. Paolozzi^{134a,134b}, Th.D. Papadopoulou¹⁰, K. Papageorgiou^{155,l}, A. Paramonov⁶, D. Paredes Hernandez³⁴, M.A. Parker²⁸, F. Parodi^{50a,50b}, J.A. Parsons³⁵, U. Parzefall⁴⁸, E. Pasqualucci^{133a}, S. Passaggio^{50a}, A. Passeri^{135a}, F. Pastore^{135a,135b,*}, Fr. Pastore⁷⁶, G. Pásztor²⁹, S. Patariaia¹⁷⁶, N.D. Patel¹⁵¹, J.R. Pater⁸³, S. Patricelli^{103a,103b}, T. Pauly³⁰, J. Pearce¹⁷⁰, L.E. Pedersen³⁶, M. Pedersen¹¹⁸, S. Pedraza Lopez¹⁶⁸, R. Pedro^{125a,125b}, S.V. Peleganchuk¹⁰⁸, D. Pelikan¹⁶⁷, H. Peng^{33b}, B. Penning³¹, J. Penwell⁶⁰, D.V. Perepelitsa²⁵, E. Perez Codina^{160a},

M.T. Pérez García-Estañ¹⁶⁸, V. Perez Reale³⁵, L. Perini^{90a,90b}, H. Pernegger³⁰, R. Perrino^{72a}, R. Peschke⁴², V.D. Peshekhonov⁶⁴, K. Peters³⁰, R.F.Y. Peters⁸³, B.A. Petersen³⁰, T.C. Petersen³⁶, E. Petit⁴², A. Petridis^{147a,147b}, C. Petridou¹⁵⁵, E. Petrolo^{133a}, F. Petrucci^{135a,135b}, N.E. Pettersson¹⁵⁸, R. Pezosa^{32b}, P.W. Phillips¹³⁰, G. Piacquadio¹⁴⁴, E. Pianori¹⁷¹, A. Picazio⁴⁹, E. Piccaro⁷⁵, M. Piccinini^{20a,20b}, R. Piegaia²⁷, D.T. Pignotti¹¹⁰, J.E. Pilcher³¹, A.D. Pilkington⁷⁷, J. Pina^{125a,125b,125d}, M. Pinamonti^{165a,165c.ac}, A. Pinder¹¹⁹, J.L. Pinfeld³, A. Pingel³⁶, B. Pinto^{125a}, S. Pires⁷⁹, M. Pitt¹⁷³, C. Pizio^{90a,90b}, L. Plazak^{145a}, M.-A. Pleier²⁵, V. Pleskot¹²⁸, E. Plotnikova⁶⁴, P. Plucinski^{147a,147b}, S. Poddar^{58a}, F. Podlyski³⁴, R. Poettgen⁸², L. Poggioli¹¹⁶, D. Pohl²¹, M. Pohl⁴⁹, G. Polesello^{120a}, A. Policicchio^{37a,37b}, R. Polifka¹⁵⁹, A. Polini^{20a}, C.S. Pollard⁴⁵, V. Polychronakos²⁵, K. Pommès³⁰, L. Pontecorvo^{133a}, B.G. Pope⁸⁹, G.A. Popeneciu^{26b}, D.S. Popovic^{13a}, A. Poppleton³⁰, X. Portell Bueso¹², S. Pospisil¹²⁷, K. Potamianos¹⁵, I.N. Potrap⁶⁴, C.J. Potter¹⁵⁰, C.T. Potter¹¹⁵, G. Poulard³⁰, J. Poveda⁶⁰, V. Pozdnyakov⁶⁴, P. Pralavorio⁸⁴, A. Pranko¹⁵, S. Prasad³⁰, R. Pravahan⁸, S. Prell⁶³, D. Price⁸³, J. Price⁷³, L.E. Price⁶, D. Prieur¹²⁴, M. Primavera^{72a}, M. Proissl¹⁴⁶, K. Prokofiev⁴⁷, F. Prokoshin^{32b}, E. Protopapadaki¹³⁷, S. Protopopescu²⁵, J. Proudfoot⁶, M. Przybycien^{38a}, H. Przysiezniak⁵, E. Ptacek¹¹⁵, D. Puddu^{135a,135b}, E. Pueschel⁸⁵, D. Puldon¹⁴⁹, M. Purohit^{25.ad}, P. Puza¹¹⁶, J. Qian⁸⁸, G. Qin⁵³, Y. Qin⁸³, A. Quadt⁵⁴, D.R. Quarrie¹⁵, W.B. Quayle^{165a,165b}, M. Queitsch-Maitland⁸³, D. Quilty⁵³, A. Qureshi^{160b}, V. Radeka²⁵, V. Radescu⁴², S.K. Radhakrishnan¹⁴⁹, P. Radloff¹¹⁵, P. Rados⁸⁷, F. Ragusa^{90a,90b}, G. Rahal¹⁷⁹, S. Rajagopalan²⁵, M. Rammensee³⁰, A.S. Randle-Conde⁴⁰, C. Rangel-Smith¹⁶⁷, K. Rao¹⁶⁴, F. Rauscher⁹⁹, T.C. Rave⁴⁸, T. Ravenscroft⁵³, M. Raymond³⁰, A.L. Read¹¹⁸, N.P. Readioff⁷³, D.M. Rebuffi^{120a,120b}, A. Redelbach¹⁷⁵, G. Redlinger²⁵, R. Reece¹³⁸, K. Reeves⁴¹, L. Rehnisch¹⁶, H. Reisin²⁷, M. Relich¹⁶⁴, C. Rembser³⁰, H. Ren^{33a}, Z.L. Ren¹⁵², A. Renaud¹¹⁶, M. Rescigno^{133a}, S. Resconi^{90a}, O.L. Rezanova^{108.t}, P. Reznicek¹²⁸, R. Rezvani⁹⁴, R. Richter¹⁰⁰, M. Ridel⁷⁹, P. Rieck¹⁶, J. Rieger⁵⁴, M. Rijssenbeek¹⁴⁹, A. Rimoldi^{120a,120b}, L. Rinaldi^{20a}, E. Ritsch⁶¹, I. Riu¹², F. Rizatdinova¹¹³, E. Rizvi⁷⁵, S.H. Robertson^{86.i}, A. Robichaud-Veronneau⁸⁶, D. Robinson²⁸, J.E.M. Robinson⁸³, A. Robson⁵³, C. Roda^{123a,123b}, L. Rodrigues³⁰, S. Roe³⁰, O. Røhne¹¹⁸, S. Rolli¹⁶², A. Romaniouk⁹⁷, M. Romano^{20a,20b}, E. Romero Adam¹⁶⁸, N. Rompotis¹³⁹, M. Ronzani⁴⁸, L. Roos⁷⁹, E. Ros¹⁶⁸, S. Rosati^{133a}, K. Rosbach⁴⁹, M. Rose⁷⁶, P. Rose¹³⁸, P.L. Rosendahl¹⁴, O. Rosenthal¹⁴², V. Rossetti^{147a,147b}, E. Rossi^{103a,103b}, L.P. Rossi^{50a}, R. Rosten¹³⁹, M. Rotaru^{26a}, I. Roth¹⁷³, J. Rothberg¹³⁹, D. Rousseau¹¹⁶, C.R. Royon¹³⁷, A. Rozanov⁸⁴, Y. Rozen¹⁵³, X. Ruan^{146c}, F. Rubbo¹², I. Rubinsky⁴², V.I. Rud⁹⁸, C. Rudolph⁴⁴, M.S. Rudolph¹⁵⁹, F. Rühr⁴⁸, A. Ruiz-Martinez³⁰, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁴, A. Ruschke⁹⁹, J.P. Rutherford⁷, N. Ruthmann⁴⁸, Y.F. Ryabov¹²², M. Rybar¹²⁸, G. Rybkin¹¹⁶, N.C. Ryder¹¹⁹, A.F. Saavedra¹⁵¹, S. Sacerdoti²⁷, A. Saddique³, I. Sadeh¹⁵⁴, H.F.-W. Sadrozinski¹³⁸, R. Sadykov⁶⁴, F. Safai Tehrani^{133a}, H. Sakamoto¹⁵⁶, Y. Sakurai¹⁷², G. Salamanna^{135a,135b}, A. Salamon^{134a}, M. Saleem¹¹², D. Salek¹⁰⁶, P.H. Sales De Bruin¹³⁹, D. Salihagic¹⁰⁰, A. Salnikov¹⁴⁴, J. Salt¹⁶⁸, D. Salvatore^{37a,37b}, F. Salvatore¹⁵⁰, A. Salvucci¹⁰⁵, A. Salzburger³⁰, D. Sampsonidis¹⁵⁵, A. Sanchez^{103a,103b}, J. Sánchez¹⁶⁸, V. Sanchez Martinez¹⁶⁸, H. Sandaker¹⁴, R.L. Sandbach⁷⁵, H.G. Sander⁸², M.P. Sanders⁹⁹, M. Sandhoff¹⁷⁶, T. Sandoval²⁸, C. Sandoval¹⁶³, R. Sandstroem¹⁰⁰, D.P.C. Sankey¹³⁰, A. Sansoni⁴⁷, C. Santoni³⁴, R. Santonico^{134a,134b}, H. Santos^{125a}, I. Santoyo Castillo¹⁵⁰, K. Sapp¹²⁴, A. Saponov⁶⁴, J.G. Saraiva^{125a,125d}, B. Sarrazin²¹, G. Sartisohn¹⁷⁶, O. Sasaki⁶⁵, Y. Sasaki¹⁵⁶, G. Sauvage^{5,*}, E. Sauvan⁵, P. Savard^{159.d}, D.O. Savu³⁰, C. Sawyer¹¹⁹, L. Sawyer^{78.m}, D.H. Saxon⁵³, J. Saxon¹²¹, C. Sbarra^{20a}, A. Sbrizzi³, T. Scanlon⁷⁷, D.A. Scannicchio¹⁶⁴, M. Scarcella¹⁵¹, V. Scarfone^{37a,37b}, J. Schaarschmidt¹⁷³, P. Schacht¹⁰⁰, D. Schaefer³⁰, R. Schaefer⁴², S. Schaepe²¹, S. Schatzel^{58b}, U. Schäfer⁸², A.C. Schaffer¹¹⁶, D. Schaile⁹⁹, R.D. Schamberger¹⁴⁹, V. Scharf^{58a}, V.A. Schegelsky¹²², D. Scheirich¹²⁸, M. Schernau¹⁶⁴, M.I. Scherzer³⁵, C. Schiavi^{50a,50b}, J. Schieck⁹⁹, C. Schillo⁴⁸, M. Schioppa^{37a,37b}, S. Schlenker³⁰, E. Schmidt⁴⁸, K. Schmieden³⁰, C. Schmitt⁸², S. Schmitt^{58b}, B. Schneider¹⁷, Y.J. Schnellbach⁷³, U. Schnoor⁴⁴, L. Schoeffel¹³⁷, A. Schoening^{58b}, B.D. Schoenrock⁸⁹, A.L.S. Schorlemmer⁵⁴, M. Schott⁸², D. Schouten^{160a}, J. Schovancova²⁵, S. Schramm¹⁵⁹, M. Schreyer¹⁷⁵, C. Schroeder⁸², N. Schuh⁸², M.J. Schultens²¹, H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁶, M. Schumacher⁴⁸, B.A. Schumm¹³⁸, Ph. Schune¹³⁷, C. Schwanenberger⁸³, A. Schwartzman¹⁴⁴, Ph. Schwegler¹⁰⁰, Ph. Schwemling¹³⁷, R. Schwienhorst⁸⁹, J. Schwindling¹³⁷, T. Schwindt²¹, M. Schwoerer⁵, F.G. Sciacca¹⁷, E. Scifo¹¹⁶, G. Sciolla²³, W.G. Scott¹³⁰, F. Scuri^{123a,123b}, F. Scutti²¹, J. Searcy⁸⁸, G. Sedov⁴², E. Sedykh¹²², S.C. Seidel¹⁰⁴, A. Seiden¹³⁸, F. Seifert¹²⁷, J.M. Seixas^{24a}, G. Sekhniaidze^{103a}, S.J. Sekula⁴⁰, K.E. Selbach⁴⁶, D.M. Seliverstov^{122.*}, G. Sellers⁷³, N. Semprini-Cesari^{20a,20b}, C. Serfon³⁰, L. Serin¹¹⁶, L. Serkin⁵⁴, T. Serre⁸⁴, R. Seuster^{160a}, H. Severini¹¹², T. Sfiligoj⁷⁴, F. Sforza¹⁰⁰, A. Sfyrla³⁰, E. Shabalina⁵⁴, M. Shamim¹¹⁵, L.Y. Shan^{33a}, R. Shang¹⁶⁶, J.T. Shank²², M. Shapiro¹⁵, P.B. Shatalov⁹⁶, K. Shaw^{165a,165b}, C.Y. Shehu¹⁵⁰, P. Sherwood⁷⁷, L. Shi^{152.ae}, S. Shimizu⁶⁶, C.O. Shimmin¹⁶⁴, M. Shimojima¹⁰¹, M. Shiyakova⁶⁴, A. Shmeleva⁹⁵, M.J. Shochet³¹, D. Short¹¹⁹, S. Shrestha⁶³, E. Shulga⁹⁷, M.A. Shupe⁷, S. Shushkevich⁴², P. Sicho¹²⁶, O. Sidiropoulou¹⁵⁵, D. Sidorov¹¹³, A. Sidoti^{133a}, F. Siegert⁴⁴, Dj. Sijacki^{13a}, J. Silva^{125a,125d}, Y. Silver¹⁵⁴, D. Silverstein¹⁴⁴, S.B. Silverstein^{147a}, V. Simak¹²⁷, O. Simard⁵, Lj. Simic^{13a}, S. Simion¹¹⁶, E. Simioni⁸², B. Simmons⁷⁷, R. Simoniello^{90a,90b}, M. Simonyan³⁶, P. Sinervo¹⁵⁹, N.B. Sinev¹¹⁵, V. Sipica¹⁴², G. Siragusa¹⁷⁵, A. Sircar⁷⁸, A.N. Sisakyan^{64,*}, S.Yu. Sivoklokov⁹⁸, J. Sjölin^{147a,147b}, T.B. Sjurson¹⁴,

H.P. Skottowe⁵⁷, K.Yu. Skovpen¹⁰⁸, P. Skubic¹¹², M. Slater¹⁸, T. Slavicek¹²⁷, K. Sliwa¹⁶², V. Smakhtin¹⁷³, B.H. Smart⁴⁶, L. Smestad¹⁴, S.Yu. Smirnov⁹⁷, Y. Smirnov⁹⁷, L.N. Smirnova^{98.af}, O. Smirnova⁸⁰, K.M. Smith⁵³, M. Smizanska⁷¹, K. Smolek¹²⁷, A.A. Snesarev⁹⁵, G. Snidero⁷⁵, S. Snyder²⁵, R. Sobie^{170.i}, F. Socher⁴⁴, A. Soffer¹⁵⁴, D.A. Soh^{152.ae}, C.A. Solans³⁰, M. Solar¹²⁷, J. Solc¹²⁷, E.Yu. Soldatov⁹⁷, U. Soldevila¹⁶⁸, A.A. Solodkov¹²⁹, A. Soloshenko⁶⁴, O.V. Solovyanov¹²⁹, V. Solovyev¹²², P. Sommer⁴⁸, H.Y. Song^{33b}, N. Soni¹, A. Sood¹⁵, A. Sopczak¹²⁷, B. Sopko¹²⁷, V. Sopko¹²⁷, V. Sorin¹², M. Sosebee⁸, R. Soualah^{165a,165c}, P. Soueid⁹⁴, A.M. Soukharev¹⁰⁸, D. South⁴², S. Spagnolo^{72a,72b}, F. Spanò⁷⁶, W.R. Spearman⁵⁷, F. Spettel¹⁰⁰, R. Spighi^{20a}, G. Spigo³⁰, L.A. Spiller⁸⁷, M. Spousta¹²⁸, T. Spreitzer¹⁵⁹, B. Spurlock⁸, R.D. St. Denis^{53,*}, S. Staerz⁴⁴, J. Stahlman¹²¹, R. Stamen^{58a}, S. Stamm¹⁶, E. Stanecka³⁹, R.W. Stanek⁶, C. Stanescu^{135a}, M. Stanescu-Bellu⁴², M.M. Stanitzki⁴², S. Stapnes¹¹⁸, E.A. Starchenko¹²⁹, J. Stark⁵⁵, P. Staroba¹²⁶, P. Starovoitov⁴², R. Staszewski³⁹, P. Stavina^{145a,*}, P. Steinberg²⁵, B. Stelzer¹⁴³, H.J. Stelzer³⁰, O. Stelzer-Chilton^{160a}, H. Stenzel⁵², S. Stern¹⁰⁰, G.A. Stewart⁵³, J.A. Stillings²¹, M.C. Stockton⁸⁶, M. Stoebe⁸⁶, G. Stoicica^{26a}, P. Stolte⁵⁴, S. Stonjek¹⁰⁰, A.R. Stradling⁸, A. Straessner⁴⁴, M.E. Stramaglia¹⁷, J. Strandberg¹⁴⁸, S. Strandberg^{147a,147b}, A. Strandlie¹¹⁸, E. Strauss¹⁴⁴, M. Strauss¹¹², P. Strizenc^{145b}, R. Ströhmer¹⁷⁵, D.M. Strom¹¹⁵, R. Stroynowski⁴⁰, A. Struebig¹⁰⁵, S.A. Stucci¹⁷, B. Stugu¹⁴, N.A. Styles⁴², D. Su¹⁴⁴, J. Su¹²⁴, R. Subramaniam⁷⁸, A. Succurro¹², Y. Sugaya¹¹⁷, C. Suhr¹⁰⁷, M. Suk¹²⁷, V.V. Sulin⁹⁵, S. Sultansoy^{4c}, T. Sumida⁶⁷, S. Sun⁵⁷, X. Sun^{33a}, J.E. Sundermann⁴⁸, K. Suruliz¹⁴⁰, G. Susinno^{37a,37b}, M.R. Sutton¹⁵⁰, Y. Suzuki⁶⁵, M. Svatos¹²⁶, S. Swedish¹⁶⁹, M. Swiatlowski¹⁴⁴, I. Sykora^{145a}, T. Sykora¹²⁸, D. Ta⁸⁹, C. Taccini^{135a,135b}, K. Tackmann⁴², J. Taenzer¹⁵⁹, A. Taffard¹⁶⁴, R. Tafirout^{160a}, N. Taiblum¹⁵⁴, H. Takai²⁵, R. Takashima⁶⁸, H. Takeda⁶⁶, T. Takeshita¹⁴¹, Y. Takubo⁶⁵, M. Talby⁸⁴, A.A. Talyshev^{108.t}, J.Y.C. Tam¹⁷⁵, K.G. Tan⁸⁷, J. Tanaka¹⁵⁶, R. Tanaka¹¹⁶, S. Tanaka¹³², S. Tanaka⁶⁵, A.J. Tanasijczuk¹⁴³, B.B. Tannenwald¹¹⁰, N. Tannoury²¹, S. Tapprogge⁸², S. Tarem¹⁵³, F. Tarrade²⁹, G.F. Tartarelli^{90a}, P. Tas¹²⁸, M. Tasevsky¹²⁶, T. Tashiro⁶⁷, E. Tassi^{37a,37b}, A. Tavares Delgado^{125a,125b}, Y. Tayalati^{136d}, F.E. Taylor⁹³, G.N. Taylor⁸⁷, W. Taylor^{160b}, F.A. Teischinger³⁰, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸, H. Ten Kate³⁰, P.K. Teng¹⁵², J.J. Teoh¹¹⁷, S. Terada⁶⁵, K. Terashi¹⁵⁶, J. Terron⁸¹, S. Terzo¹⁰⁰, M. Testa⁴⁷, R.J. Teuscher^{159.i}, J. Therhaag²¹, T. Theveneaux-Pelzer³⁴, J.P. Thomas¹⁸, J. Thomas-Wilsker⁷⁶, E.N. Thompson³⁵, P.D. Thompson¹⁸, P.D. Thompson¹⁵⁹, R.J. Thompson⁸³, A.S. Thompson⁵³, L.A. Thomsen³⁶, E. Thomson¹²¹, M. Thomson²⁸, W.M. Thong⁸⁷, R.P. Thun^{88,*}, F. Tian³⁵, M.J. Tibbetts¹⁵, V.O. Tikhomirov^{95.ag}, Yu.A. Tikhonov^{108.t}, S. Timoshenko⁹⁷, E. Tiouchichine⁸⁴, P. Tipton¹⁷⁷, S. Tisserant⁸⁴, T. Todorov⁵, S. Todorova-Nova¹²⁸, B. Toggerson⁷, J. Tojo⁶⁹, S. Tokár^{145a}, K. Tokushuku⁶⁵, K. Tollefson⁸⁹, L. Tomlinson⁸³, M. Tomoto¹⁰², L. Tompkins³¹, K. Toms¹⁰⁴, N.D. Topilin⁶⁴, E. Torrence¹¹⁵, H. Torres¹⁴³, E. Torró Pastor¹⁶⁸, J. Toth^{84.ah}, F. Touchard⁸⁴, D.R. Tovey¹⁴⁰, H.L. Tran¹¹⁶, T. Trefzger¹⁷⁵, L. Tremblet³⁰, A. Tricoli³⁰, I.M. Trigger^{160a}, S. Trincaz-Duvoid⁷⁹, M.F. Tripiana¹², W. Trischuk¹⁵⁹, B. Trocmé⁵⁵, C. Troncon^{90a}, M. Trottier-McDonald¹⁴³, M. Trovatelli^{135a,135b}, P. True⁸⁹, M. Trzebinski³⁹, A. Trzupek³⁹, C. Tsarouchas³⁰, J.C-L. Tseng¹¹⁹, P.V. Tsiarehka⁹¹, D. Tsiou¹³⁷, G. Tsipolitis¹⁰, N. Tsirintanis⁹, S. Tsiskaridze¹², V. Tsiskaridze⁴⁸, E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁶, V. Tsulaia¹⁵, S. Tsuno⁶⁵, D. Tsybychev¹⁴⁹, A. Tudorache^{26a}, V. Tudorache^{26a}, A.N. Tuna¹²¹, S.A. Tuppiti^{20a,20b}, S. Turchikhin^{98.af}, D. Turecek¹²⁷, I. Turk Cakir^{4d}, R. Turra^{90a,90b}, P.M. Tuts³⁵, A. Tykhonov⁴⁹, M. Tylmad^{147a,147b}, M. Tyndel¹³⁰, K. Uchida²¹, I. Ueda¹⁵⁶, R. Ueno²⁹, M. Ughetto⁸⁴, M. Ugland¹⁴, M. Uhlenbrock²¹, F. Ukegawa¹⁶¹, G. Unal³⁰, A. Undrus²⁵, G. Unel¹⁶⁴, F.C. Ungaro⁴⁸, Y. Unno⁶⁵, C. Unverdorben⁹⁹, D. Urbaniec³⁵, P. Urquijo⁸⁷, G. Usai⁸, A. Usanova⁶¹, L. Vacavant⁸⁴, V. Vacek¹²⁷, B. Vachon⁸⁶, N. Valencic¹⁰⁶, S. Valentinetti^{20a,20b}, A. Valero¹⁶⁸, L. Valery³⁴, S. Valkar¹²⁸, E. Valladolid Gallego¹⁶⁸, S. Vallecorsa⁴⁹, J.A. Valls Ferrer¹⁶⁸, W. Van Den Wollenberg¹⁰⁶, P.C. Van Der Deijl¹⁰⁶, R. van der Geer¹⁰⁶, H. van der Graaf¹⁰⁶, R. Van Der Leeuw¹⁰⁶, D. van der Ster³⁰, N. van Eldik³⁰, P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴³, I. van Vulpen¹⁰⁶, M.C. van Woerden³⁰, M. Vanadia^{133a,133b}, W. Vandelli³⁰, R. Vanguri¹²¹, A. Vaniachine⁶, P. Vankov⁴², F. Vannucci⁷⁹, G. Vardanyan¹⁷⁸, R. Vari^{133a}, E.W. Varnes⁷, T. Varol⁸⁵, D. Varouchas⁷⁹, A. Vartapetian⁸, K.E. Varvell¹⁵¹, F. Vazeille³⁴, T. Vazquez Schroeder⁵⁴, J. Veatch⁷, F. Veloso^{125a,125c}, S. Veneziano^{133a}, A. Ventura^{72a,72b}, D. Ventura⁸⁵, M. Venturi¹⁷⁰, N. Venturi¹⁵⁹, A. Venturini²³, V. Vercesi^{120a}, M. Verducci^{133a,133b}, W. Verkerke¹⁰⁶, J.C. Vermeulen¹⁰⁶, A. Vest⁴⁴, M.C. Vetterli^{143.d}, O. Viazlo⁸⁰, I. Vichou¹⁶⁶, T. Vickey^{146c.ai}, O.E. Vickey Boeriu^{146c}, G.H.A. Viehhauser¹¹⁹, S. Viel¹⁶⁹, R. Vigne³⁰, M. Villa^{20a,20b}, M. Villaplana Perez^{90a,90b}, E. Vilucchi⁴⁷, M.G. Vincker²⁹, V.B. Vinogradov⁶⁴, J. Virzi¹⁵, I. Vivarelli¹⁵⁰, F. Vives Vaque³, S. Vlachos¹⁰, D. Vladoiu⁹⁹, M. Vlasak¹²⁷, A. Vogel²¹, M. Vogel^{32a}, P. Vokac¹²⁷, G. Volpi^{123a,123b}, M. Volpi⁸⁷, H. von der Schmitt¹⁰⁰, H. von Radziewski⁴⁸, E. von Toerne²¹, V. Vorobel¹²⁸, K. Vorobev⁹⁷, M. Vos¹⁶⁸, R. Voss³⁰, J.H. Vosseveld⁷³, N. Vranjes¹³⁷, M. Vranjes Milosavljevic^{13a}, V. Vrba¹²⁶, M. Vreeswijk¹⁰⁶, T. Vu Anh⁴⁸, R. Vuillermet³⁰, I. Vukotic³¹, Z. Vykydal¹²⁷, P. Wagner²¹, W. Wagner¹⁷⁶, H. Wahlberg⁷⁰, S. Wahrmund⁴⁴, J. Wakabayashi¹⁰², J. Walder⁷¹, R. Walker⁹⁹, W. Walkowiak¹⁴², R. Wall¹⁷⁷, P. Waller⁷³, B. Walsh¹⁷⁷, C. Wang^{152.aj}, C. Wang⁴⁵, F. Wang¹⁷⁴, H. Wang¹⁵, H. Wang⁴⁰, J. Wang⁴², J. Wang^{33a}, K. Wang⁸⁶, R. Wang¹⁰⁴, S.M. Wang¹⁵², T. Wang²¹, X. Wang¹⁷⁷, C. Wanotayaroj¹¹⁵, A. Warburton⁸⁶, C.P. Ward²⁸, D.R. Wardrope⁷⁷, M. Warsinsky⁴⁸, A. Washbrook⁴⁶, C. Wasicki⁴², P.M. Watkins¹⁸,

A.T. Watson¹⁸, I.J. Watson¹⁵¹, M.F. Watson¹⁸, G. Watts¹³⁹, S. Watts⁸³, B.M. Waugh⁷⁷, S. Webb⁸³, M.S. Weber¹⁷, S.W. Weber¹⁷⁵, J.S. Webster³¹, A.R. Weidberg¹¹⁹, P. Weigell¹⁰⁰, B. Weinert⁶⁰, J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Weits¹⁰⁶, P.S. Wells³⁰, T. Wenaus²⁵, D. Wendland¹⁶, Z. Weng^{152,ae}, T. Wengler³⁰, S. Wenig³⁰, N. Wermes²¹, M. Werner⁴⁸, P. Werner³⁰, M. Wessels^{58a}, J. Wetter¹⁶², K. Whalen²⁹, A. White⁸, M.J. White¹, R. White^{32b}, S. White^{123a,123b}, D. Whiteson¹⁶⁴, D. Wicke¹⁷⁶, F.J. Wickens¹³⁰, W. Wiedenmann¹⁷⁴, M. Wielers¹³⁰, P. Wienemann²¹, C. Wiglesworth³⁶, L.A.M. Wiik-Fuchs²¹, P.A. Wijeratne⁷⁷, A. Wildauer¹⁰⁰, M.A. Wildt^{42,ak}, H.G. Wilkens³⁰, J.Z. Will⁹⁹, H.H. Williams¹²¹, S. Williams²⁸, C. Willis⁸⁹, S. Willocq⁸⁵, A. Wilson⁸⁸, J.A. Wilson¹⁸, I. Wingerter-Seez⁵, F. Winklmeier¹¹⁵, B.T. Winter²¹, M. Wittgen¹⁴⁴, T. Wittig⁴³, J. Wittkowski⁹⁹, S.J. Wollstadt⁸², M.W. Wolter³⁹, H. Wolters^{125a,125c}, B.K. Wosiek³⁹, J. Wotschack³⁰, M.J. Woudstra⁸³, K.W. Wozniak³⁹, M. Wright⁵³, M. Wu⁵⁵, S.L. Wu¹⁷⁴, X. Wu⁴⁹, Y. Wu⁸⁸, E. Wulf³⁵, T.R. Wyatt⁸³, B.M. Wynne⁴⁶, S. Xella³⁶, M. Xiao¹³⁷, D. Xu^{33a}, L. Xu^{33b,al}, B. Yabsley¹⁵¹, S. Yacoub^{146b,am}, R. Yakabe⁶⁶, M. Yamada⁶⁵, H. Yamaguchi¹⁵⁶, Y. Yamaguchi¹¹⁷, A. Yamamoto⁶⁵, K. Yamamoto⁶³, S. Yamamoto¹⁵⁶, T. Yamamura¹⁵⁶, T. Yamanaka¹⁵⁶, K. Yamauchi¹⁰², Y. Yamazaki⁶⁶, Z. Yan²², H. Yang^{33e}, H. Yang¹⁷⁴, U.K. Yang⁸³, Y. Yang¹¹⁰, S. Yanush⁹², L. Yao^{33a}, W.-M. Yao¹⁵, Y. Yasu⁶⁵, E. Yatsenko⁴², K.H. Yau Wong²¹, J. Ye⁴⁰, S. Ye²⁵, I. Yeletsikh⁶⁴, A.L. Yen⁵⁷, E. Yildirim⁴², M. Yilmaz^{4b}, R. Yoosoofmiya¹²⁴, K. Yorita¹⁷², R. Yoshida⁶, K. Yoshihara¹⁵⁶, C. Young¹⁴⁴, C.J.S. Young³⁰, S. Youssef²², D.R. Yu¹⁵, J. Yu⁸, J.M. Yu⁸⁸, J. Yu¹¹³, L. Yuan⁶⁶, A. Yurkewicz¹⁰⁷, I. Yusuf^{28,an}, B. Zabinski³⁹, R. Zaidan⁶², A.M. Zaitsev^{129,aa}, A. Zaman¹⁴⁹, S. Zambito²³, L. Zanello^{133a,133b}, D. Zanzi¹⁰⁰, C. Zeitnitz¹⁷⁶, M. Zeman¹²⁷, A. Zemla^{38a}, K. Zengel²³, O. Zenin¹²⁹, T. Ženiš^{145a}, D. Zerwas¹¹⁶, G. Zevi della Porta⁵⁷, D. Zhang⁸⁸, F. Zhang¹⁷⁴, H. Zhang⁸⁹, J. Zhang⁶, L. Zhang¹⁵², X. Zhang^{33d}, Z. Zhang¹¹⁶, Z. Zhao^{33b}, A. Zhemchugov⁶⁴, J. Zhong¹¹⁹, B. Zhou⁸⁸, L. Zhou³⁵, N. Zhou¹⁶⁴, C.G. Zhu^{33d}, H. Zhu^{33a}, J. Zhu⁸⁸, Y. Zhu^{33b}, X. Zhuang^{33a}, K. Zhukov⁹⁵, A. Zibell¹⁷⁵, D. Zieminska⁶⁰, N.I. Zimine⁶⁴, C. Zimmermann⁸², R. Zimmermann²¹, S. Zimmermann²¹, S. Zimmermann⁴⁸, Z. Zinonos⁵⁴, M. Ziolkowski¹⁴², G. Zobernig¹⁷⁴, A. Zoccoli^{20a,20b}, M. zur Nedden¹⁶, G. Zurzolo^{103a,103b}, V. Zutshi¹⁰⁷, L. Zwalinski³⁰.

¹ Department of 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, Gazi University, Ankara; (c) Division of Physics, TOBB University of Economics and Technology, Ankara; (d) 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, 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) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

²⁰ (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, 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) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; ^(c) University Politehnica Bucharest, Bucharest; ^(d) 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, Laboratori Nazionali di Frascati; ^(b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ³⁸ ^(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; ^(b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- 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, Technische Universität 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 Grenoble-Alpes, CNRS/IN2P3, 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 Louisiana Tech University, Ruston LA, United States of America
- ⁷⁹ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁸⁰ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸¹ Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸² Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸³ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸⁴ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁵ Department of Physics, University of Massachusetts, Amherst MA, United States of America
- ⁸⁶ Department of Physics, McGill University, Montreal QC, Canada
- ⁸⁷ School of Physics, University of Melbourne, Victoria, Australia
- ⁸⁸ Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- ⁸⁹ Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- ⁹⁰ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹¹ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- ⁹² National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- ⁹³ Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
- ⁹⁴ Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ⁹⁵ P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁶ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁷ Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- ⁹⁸ D.V.Skobel'tsyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- ⁹⁹ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ¹⁰⁰ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰¹ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰² Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹⁰³ ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ¹⁰⁴ Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- ¹⁰⁵ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁶ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁷ Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- ¹⁰⁸ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹⁰⁹ Department of Physics, New York University, New York NY, United States of America
- ¹¹⁰ Ohio State University, Columbus OH, United States of America
- ¹¹¹ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹² Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- ¹¹³ Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- ¹¹⁴ Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁵ Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- ¹¹⁶ LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France

-
- 117 Graduate School of Science, Osaka University, Osaka, Japan
- 118 Department of Physics, University of Oslo, Oslo, Norway
- 119 Department of Physics, Oxford University, Oxford, United Kingdom
- 120 ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- 121 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- 122 Petersburg Nuclear Physics Institute, Gatchina, Russia
- 123 ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- 124 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- 125 ^(a) Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa; ^(b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Department of Physics, University of Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Fisica, Universidade do Minho, Braga; ^(f) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); ^(g) Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- 126 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- 127 Czech Technical University in Prague, Praha, Czech Republic
- 128 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- 129 State Research Center Institute for High Energy Physics, Protvino, Russia
- 130 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- 131 Physics Department, University of Regina, Regina SK, Canada
- 132 Ritsumeikan University, Kusatsu, Shiga, Japan
- 133 ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- 134 ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 135 ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- 136 ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; ^(b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; ^(d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; ^(e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
- 137 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- 138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
- 139 Department of Physics, University of Washington, Seattle WA, United States of America
- 140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- 141 Department of Physics, Shinshu University, Nagano, Japan
- 142 Fachbereich Physik, Universität Siegen, Siegen, Germany
- 143 Department of Physics, Simon Fraser University, Burnaby BC, Canada
- 144 SLAC National Accelerator Laboratory, Stanford CA, United States of America
- 145 ^(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
- 146 ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) Department of Physics, University of Johannesburg, Johannesburg; ^(c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- 147 ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
- 148 Physics Department, Royal Institute of Technology, Stockholm, Sweden
- 149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
- 150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- 151 School of Physics, University of Sydney, Sydney, Australia
- 152 Institute of Physics, Academia Sinica, Taipei, Taiwan
- 153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- 154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- 155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- 156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- 157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- 158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

- ¹⁵⁹ Department of Physics, University of Toronto, Toronto ON, Canada
- ¹⁶⁰ ^(a) TRIUMF, Vancouver BC; ^(b) Department of Physics and Astronomy, York University, Toronto ON, Canada
- ¹⁶¹ Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
- ¹⁶² Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
- ¹⁶³ Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- ¹⁶⁴ Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
- ¹⁶⁵ ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- ¹⁶⁶ Department of Physics, University of Illinois, Urbana IL, United States of America
- ¹⁶⁷ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- ¹⁶⁸ 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
- ¹⁶⁹ Department of Physics, University of British Columbia, Vancouver BC, Canada
- ¹⁷⁰ Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- ¹⁷¹ Department of Physics, University of Warwick, Coventry, United Kingdom
- ¹⁷² Waseda University, Tokyo, Japan
- ¹⁷³ Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- ¹⁷⁴ Department of Physics, University of Wisconsin, Madison WI, United States of America
- ¹⁷⁵ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- ¹⁷⁶ Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- ¹⁷⁷ Department of Physics, Yale University, New Haven CT, United States of America
- ¹⁷⁸ Yerevan Physics Institute, Yerevan, Armenia
- ¹⁷⁹ Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- ^a Also at Department of Physics, King's College London, London, United Kingdom
- ^b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ^c Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ^d Also at TRIUMF, Vancouver BC, Canada
- ^e Also at Department of Physics, California State University, Fresno CA, United States of America
- ^f Also at Tomsk State University, Tomsk, Russia
- ^g Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ^h Also at Università di Napoli Parthenope, Napoli, Italy
- ⁱ Also at Institute of Particle Physics (IPP), Canada
- ^j Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
- ^k Also at Chinese University of Hong Kong, China
- ^l Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
- ^m Also at Louisiana Tech University, Ruston LA, United States of America
- ⁿ Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
- ^o Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
- ^p Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
- ^q Also at CERN, Geneva, Switzerland
- ^r Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
- ^s Also at Manhattan College, New York NY, United States of America
- ^t Also at Novosibirsk State University, Novosibirsk, Russia
- ^u Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^v Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- ^w Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^x Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ^y Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India
- ^z Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- ^{aa} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia

-
- ab* Also at Section de Physique, Université de Genève, Geneva, Switzerland
- ac* Also at International School for Advanced Studies (SISSA), Trieste, Italy
- ad* Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
- ae* Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
- af* Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- ag* Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- ah* Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
- ai* Also at Department of Physics, Oxford University, Oxford, United Kingdom
- aj* Also at Department of Physics, Nanjing University, Jiangsu, China
- ak* Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
- al* Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- am* Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
- an* Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
- * Deceased