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Search for Supersymmetry Using Final States with One Lepton, Jets, and Missing Transverse Momentum with the ATLAS Detector in $\sqrt{s} = 7$ TeV pp Collisions

G. Aad *et al.*[*]
(ATLAS Collaboration)

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This Letter presents the first search for supersymmetry in final states containing one isolated electron or muon, jets, and missing transverse momentum from $\sqrt{s} = 7$ TeV proton-proton collisions at the LHC. The data were recorded by the ATLAS experiment during 2010 and correspond to a total integrated luminosity of 35 pb^{-1}. No excess above the standard model background expectation is observed. Limits are set on the parameters of the minimal supergravity framework, extending previous limits. Within this framework, for $A_0 = 0$ GeV, $\tan\beta = 3$, and $\mu > 0$ and for equal squark and gluino masses, gluino masses below 700 GeV are excluded at 95% confidence level.

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Many extensions of the standard model predict the existence of new colored particles, such as the squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) of supersymmetric (SUSY) theories [1], which could be accessible at the LHC. The dominant SUSY production channels are squark-(anti)squark, squark-gluino, and gluino-gluino pair production. Squarks and gluinos are expected to decay to quarks, gluons, and the SUSY partners of the gauge bosons (charginos $\tilde{\chi}^{\pm}$ and neutralinos $\tilde{\chi}^{0}$), leading to events with energetic jets. In R-parity conserving SUSY models [2], the lightest supersymmetric particle is stable and escapes detection, giving rise to events with significant missing transverse momentum. In decay chains with charginos ($\tilde{q}_L \rightarrow q\tilde{\chi}^{\pm}$, $\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}^{\pm}$), chargino decay to the lightest supersymmetric particle can produce a high-momentum lepton. Currently, the most stringent limits on squark and gluino masses come from the LHC [3] and from the Tevatron [4–7].

This Letter reports on a search for events with exactly one isolated high-transverse momentum (p_T) electron or muon, at least three high-p_T jets, and significant missing transverse momentum. An exact definition of the signal region will be given elsewhere in this Letter. From an experimental point of view, the requirement of an isolated high-p_T lepton suppresses the QCD multijet background and facilitates triggering on interesting events. In addition to the signal region, three control regions are considered for the most important standard model backgrounds. A combined fit to the observed number of events in these four regions, together with an independent estimate of jets misidentified as leptons in QCD multijet events, is used to search for an excess of events in the signal region.

The analysis is sensitive to any new physics leading to such an excess and is not optimized for any particular model of SUSY. The results are interpreted within the MSUGRA-CMSSM (minimal supergravity or constrained minimal supersymmetric standard model) framework [8,9] in terms of limits on the universal scalar and gaugino mass parameters m_0 and $m_{1/2}$. These are presented for fixed values of the universal trilinear coupling parameter $A_0 = 0$ GeV, ratio of the vacuum expectation values of the two Higgs doublets $\tan\beta = 3$, and Higgs mixing parameter $\mu > 0$, in order to facilitate comparison with previous results.

The ATLAS detector [10] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle [11]. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field and by high-granularity liquid-argon sampling electromagnetic calorimeters. An iron-scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The end-cap and forward regions are instrumented with liquid-argon calorimetry for both electromagnetic and hadronic measurements. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting toroids, a system of precision tracking chambers, and detectors for triggering.

The data used in this analysis were recorded in 2010 at the LHC at a center-of-mass energy of 7 TeV. Application of beam, detector, and data-quality requirements results in a total integrated luminosity of 35 pb^{-1}, with an estimated uncertainty of 11% [12]. The data have been selected with single lepton (e or μ) triggers. The detailed trigger requirements vary throughout the data-taking period, but the thresholds are always low enough to ensure that leptons with $p_T > 20$ GeV lie in the efficiency plateau.

Fully simulated Monte Carlo event samples are used to develop and validate the analysis procedure, compute

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[*] Full author list given at the end of the article.

detector acceptance and reconstruction efficiency, and aid in the background determination. Samples of events for background processes are generated as described in detail in Ref. [13]. For the major backgrounds, top quark pair and W + jets production, MC@NLO [14] v3.41 and ALPGEN [15] v2.13 are used. Further samples include QCD multijet events, single top production, diboson production, and Drell-Yan dilepton events.

Monte Carlo signal events are generated with HERWIG++ [16] v2.4.2. The SUSY particle spectra and decay modes are calculated with ISAJET [17] v7.75. The SUSY samples are normalized by using next-to-leading order cross sections as determined by PROSPINO [18] v2.1. All signal and background samples are produced by using the ATLAS MC09 parameter tune [19] and a GEANT4 based [20] detector simulation [21].

Criteria for electron and muon identification closely follow those described in Ref. [22]. Electrons are reconstructed based on the presence of a cluster in the electromagnetic calorimeter matched to a track in the ID. Electrons in the signal region are required to pass the "tight" selection criteria, with $p_T > 20$ GeV and $|\eta| < 2.47$. Events are always vetoed if a "medium" electron is found in the electromagnetic calorimeter transition region $1.37 < |\eta| < 1.52$.

Muons are required to be identified either in both ID and MS systems (combined muons) or as a match between an extrapolated ID track and one or more segments in the MS. The ID track is required to have at least one pixel hit, more than five silicon microstrip detector hits, and a number of transition radiation tracker hits that varies with η. For combined muons, a good match between ID and MS tracks is required, and the p_T values measured by these two systems must be compatible within the resolution. The summed p_T of other ID tracks within a distance $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.2$ around the muon track is required to be less than 1.8 GeV. Only muons with $p_T > 20$ GeV and $|\eta| < 2.4$ are considered.

Jets are reconstructed by using the anti-k_t jet clustering algorithm [23] with a radius parameter $R = 0.4$. The inputs to this algorithm are clusters of calorimeter cells seeded by cells with energy significantly above the measured noise. Jets are constructed by performing a four-vector sum over these clusters, treating each cluster as an $(E, \vec{p})$ four-vector with zero mass. Jets are corrected for calorimeter noncompensation, upstream material, and other effects by using p_T- and η-dependent calibration factors obtained from Monte Carlo calculations and validated with extensive test-beam and collision-data studies [24]. Only jets with $p_T > 20$ GeV and $|\eta| < 2.5$ are considered. If a jet and a medium electron are both identified within a distance $\Delta R < 0.2$ of each other, the jet is discarded. Furthermore, identified medium electrons or muons are considered only if they satisfy $\Delta R > 0.4$ with respect to the closest remaining jet. Events are discarded if they contain any jet failing basic quality selection criteria, which reject detector noise and noncollision backgrounds [25].

The calculation of the missing transverse momentum E_T^{miss} is based on the modulus of the vectorial sum of the p_T of the reconstructed objects (jets with $p_T > 20$ GeV, but over the full calorimeter coverage $|\eta| < 4.9$, and the selected lepton), any additional nonisolated muons, and the calorimeter clusters not belonging to reconstructed objects.

Events are required to have at least one reconstructed primary vertex with at least five associated tracks. The selection criteria for signal and control regions are based on Monte Carlo studies prior to examining the data. The signal region is defined as follows. At least one identified electron or muon with $p_T > 20$ GeV is required. The cut value is motivated by the trigger thresholds as well as by the suppression of backgrounds. Events are rejected if they contain a second identified lepton with $p_T > 20$ GeV, because they are the subject of a future analysis. At least three jets with $p_T > 30$ GeV are required, the leading one of which must have $p_T > 60$ GeV. In order to reduce the background of events with fake E_T^{miss} from mismeasured jets, the missing transverse momentum vector $\vec{E}_T^{\text{miss}}$ is required not to point in the direction of any of the three leading jets: $\Delta\phi(\text{jet}_i, \vec{E}_T^{\text{miss}}) > 0.2$ $(i = 1, 2, 3)$. Further cuts are motivated by the suppression of backgrounds, in particular, from top quark and W + jets production, while retaining efficiency for the SUSY signal. The transverse mass between the lepton and the missing transverse momentum vector, $m_T = \sqrt{2p_T^\ell E_T^{\text{miss}}\{1 - \cos[\Delta\phi(\ell, E_T^{\text{miss}})]\}}$, is required to be larger than 100 GeV. E_T^{miss} must exceed 125 GeV and must satisfy $E_T^{\text{miss}} > 0.25 m_{\text{eff}}$, where the effective mass m_{eff} is the scalar sum of the p_T of the three leading jets, the p_T of the lepton, and E_T^{miss}. Finally, a cut is applied on the effective mass: $m_{\text{eff}} > 500$ GeV. The m_{eff} variable has been shown to give a good discrimination between signal and background and can be used to quantify the mass scale of SUSY events in case a signal is observed [26]. The efficiency for the SUSY signal in the MSUGRA-CMSSM model defined earlier varies between 0.01% for $m_{1/2} = 100$ GeV and 4% for $m_{1/2} = 350$ GeV, with a smaller dependence on m_0, for the electron channel and the muon channel separately. The inefficiency is dominated by the leptonic branching fractions in the SUSY signal for $m_{1/2} > 150$ GeV.

Backgrounds from several standard model processes could contaminate the signal region. Top quark pair production and W + jets production backgrounds are estimated from a combined fit to the number of observed events in three control regions, by using Monte Carlo simulations to derive the background in the signal region from the control regions. The background determination of QCD multijet production with a jet misidentified as an isolated lepton is data driven. Remaining backgrounds from other sources are estimated with simulations.

The three control regions have identical lepton and jet selection criteria as the signal region. The top control region is defined by a window in the two-dimensional plane of 30 GeV $< E_T^{\rm miss} <$ 80 GeV and 40 GeV $< m_T <$ 80 GeV and by requiring that at least one of the three leading jets is tagged as a b-quark jet. For the b tagging, the secondary vertex algorithm SV0 [27] is used, which, for $p_T = 60$ GeV jets, provides an efficiency of 50% for b-quark jets and a mistag rate of 0.5% for light-quark jets. The W control region is defined by the same window in the $E_T^{\rm miss} - m_T$ plane but with the requirement that none of the three hardest jets is b tagged. The QCD multijet control region is defined by demanding low missing transverse momentum $E_T^{\rm miss} <$ 40 GeV and low transverse mass $m_T <$ 40 GeV. This QCD control region is used only to estimate the QCD multijet background contribution to other background regions but not to the signal region. Instead, the electron and muon identification criteria are relaxed, obtaining a "loose" control sample that is dominated by QCD jets. A loose-tight matrix method, in close analogy to that described in Ref. [13], is then used to estimate the number of QCD multijet events with fake leptons in the signal region after final selection criteria: $0.0^{+0.5}_{-0.0}$ in the muon channel and $0.0^{+0.3}_{-0.0}$ in the electron channel.

Data are compared to expectations in Fig. 1. The standard model backgrounds in the figure are normalized to the theoretical cross sections, except for the multijet background, which is normalized to data in the QCD multijet control region. The data are in good agreement with the standard model expectations. After final selection, one event remains in the signal region in the electron channel and one event remains in the muon channel. Figure 1 also shows the expected distributions for the MSUGRA-CMSSM model point $m_0 = 360$ GeV and $m_{1/2} =$ 280 GeV. For this benchmark point, 2.9 signal events would be expected in the signal region, with an acceptance of 2.9% (3.0%) in the electron (muon) channel.

A combined fit to the number of observed events in the signal and control regions is performed. The assumption that the Monte Carlo simulation is able to predict the backgrounds in the signal region from the control regions is validated by checking additional control regions at low m_T and at low $E_T^{\rm miss}$. The defined control regions are not completely pure, and the combined fit takes the expected background cross-contaminations into account. The likelihood function of the fit can be written as $L(\mathbf{n}|s, \mathbf{b}, \boldsymbol{\theta}) = P_S \times P_W \times P_T \times P_Q \times C_{\rm Syst}$, where $\mathbf{n}$ represents the number of observed events in the data, s is the SUSY signal to be tested, $\mathbf{b}$ is the background, and $\boldsymbol{\theta}$ represents the systematic uncertainties, which are treated as nuisance parameters with a Gaussian probability density function. The four P functions on the right-hand side are Poisson probability distributions for event counts in the defined signal (S) and control regions (W, T, and Q for W, top pair, and QCD multijets, respectively), and $C_{\rm Syst}$ represents the constraints on systematic uncertainties, including correlations.

The dominant sources of systematic uncertainties in the background estimates arise from Monte Carlo modeling of the shape of the $E_T^{\rm miss}$ and m_T distributions in signal and control regions. These uncertainties are determined by

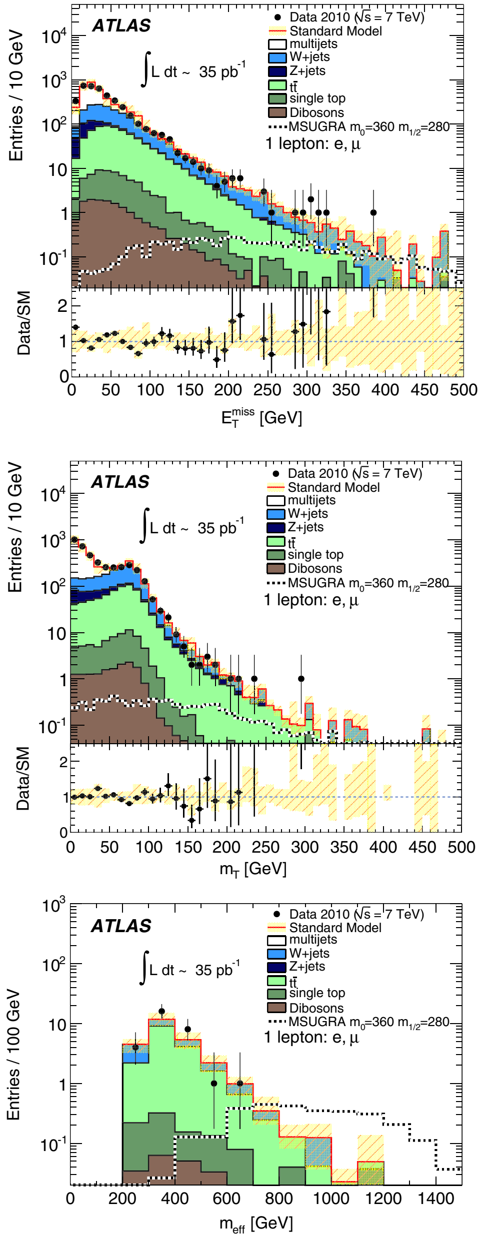

FIG. 1 (color online). Top: $E_T^{\rm miss}$ distribution after lepton and jet selection. Center: m_T distribution after lepton and jet selection. Bottom: Effective mass distribution after final selection criteria except for the cut on the effective mass itself. All plots are made for the electron and muon channel combined. Yellow bands indicate the uncertainty on the Monte Carlo prediction from finite Monte Carlo statistics and from the jet energy scale uncertainty.

TABLE I. Numbers of observed events in the signal and background control regions, as well as their estimated values from the fit (see the text), for the electron (top part) and muon (bottom part) channels. The central values of the fitted sum of backgrounds in the control regions agree with the observations by construction. For comparison, nominal Monte Carlo expectations are given in parentheses for the signal region, the top control region, and the W control region.

Electron channel	Signal region	Top region	W region	QCD region
Observed events	1	80	202	1464
Fitted top events	1.34 ± 0.52 (1.29)	65 ± 12 (63)	32 ± 16 (31)	40 ± 11
Fitted W/Z events	0.47 ± 0.40 (0.46)	11.2 ± 4.6 (10.2)	161 ± 27 (146)	170 ± 34
Fitted QCD events	$0.0^{+0.3}_{-0.0}$	3.7 ± 7.6	9 ± 20	1254 ± 51
Fitted sum of background events	1.81 ± 0.75	80 ± 9	202 ± 14	1464 ± 38
Muon channel	**Signal region**	**Top region**	**W region**	**QCD region**
Observed events	1	93	165	346
Fitted top events	1.76 ± 0.67 (1.39)	85 ± 11 (67)	42 ± 19 (33)	50 ± 10
Fitted W/Z events	0.49 ± 0.36 (0.71)	7.7 ± 3.3 (11.6)	120 ± 26 (166)	71 ± 16
Fitted QCD events	$0.0^{+0.5}_{-0.0}$	0.3 ± 1.2	3 ± 12	225 ± 22
Fitted sum of background events	2.25 ± 0.94	93 ± 10	165 ± 13	346 ± 19

variation of the Monte Carlo generator, as well as by variations of internal generator parameters. The finite size of the data sample in the background control regions also contributes to the uncertainty. Experimental uncertainties are varied within their determined range and are dominated by the jet energy scale uncertainty [28], b-tagging uncertainties, and the uncertainty on the luminosity.

Systematic uncertainties on the SUSY signal are estimated by variation of the factorization and renormalization scales in PROSPINO and by including the parton density function uncertainties using the eigenvector sets provided by CTEQ6.6 [29]. Uncertainties are calculated separately for the individual production processes. Within the relevant kinematic range, typical uncertainties resulting from scale variations are 10%–16%, whereas parton density function uncertainties vary from 5% for $\tilde{q}\,\tilde{q}$ production to 15%–30% for $\tilde{g}\,\tilde{g}$ production.

The result of the combined fit to signal and control regions, leaving the number of signal events free in the signal region while not allowing for a signal contamination in the other regions, is shown in Table I. The observed number of events in the data is consistent with the standard model expectation.

Limits are set on contributions of new physics to the signal region. These limits are derived from the profile likelihood ratio $\Lambda(s) = -2[\ln L(\mathbf{n}|s, \hat{\hat{\mathbf{b}}}, \hat{\hat{\boldsymbol{\theta}}}) - \ln L(\mathbf{n}|\hat{s}, \hat{\mathbf{b}}, \hat{\boldsymbol{\theta}})]$, where $\hat{s}$, $\hat{\mathbf{b}}$, and $\hat{\boldsymbol{\theta}}$ maximize the likelihood function and $\hat{\hat{\mathbf{b}}}$ and $\hat{\hat{\boldsymbol{\theta}}}$ maximize the likelihood for a given choice of s. In the fit, s and $\hat{s}$ are constrained to be non-negative. The test statistic is $\Lambda(s)$. The exclusion p values are obtained from this by using pseudoexperiments, and the limits set are one-sided upper limits [30].

From the fit to a model with signal events only in the signal region, and leaving all nuisance parameters free, a 95% C.L. upper limit on the number of events from new physics in the signal region can be derived. This number is 2.2 in the electron channel and 2.5 in the muon channel. This corresponds to a 95% C.L. upper limit on the effective cross section for new processes in the signal region, including the effects of experimental acceptance and efficiency, of 0.065 pb for the electron channel and 0.073 pb for the muon channel.

Within the MSUGRA-CMSSM framework, limits are obtained from a second combined fit to the four regions, this time allowing for a signal in all four regions, i.e., including possible contamination of the control regions with signal events. The results are interpreted as limits in the $m_0 - m_{1/2}$ plane, as shown in Fig. 2. For the MSUGRA-CMSSM model considered and for equal squark and gluino masses, gluino masses below 700 GeV

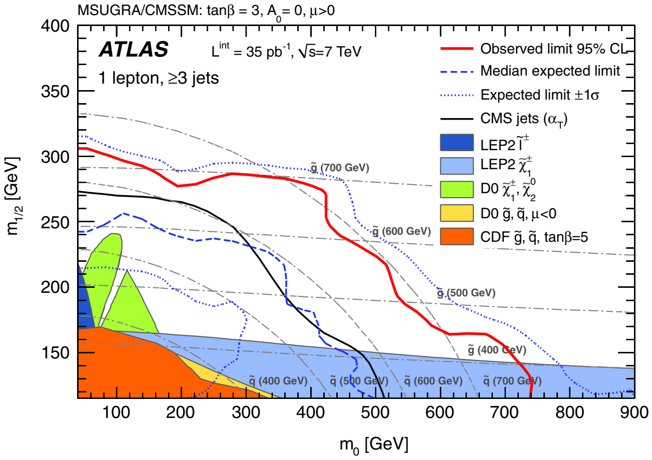

FIG. 2 (color online). Observed and expected 95% C.L. exclusion limits, as well as the ±1σ variation on the expected limit, in the combined electron and muon channels. Also shown are the published limits from CMS [3], CDF [4], and D0 [5,6], and the results from the LEP experiments [31].

are excluded at 95% C.L. The limits depend only moderately on $\tan\beta$.

In summary, the first ATLAS results on searches for supersymmetry with an isolated electron or muon, jets, and missing transverse momentum have been presented. In a data sample corresponding to 35 pb^{-1}, no significant deviations from the standard model expectation are observed. Limits on the cross section for new processes within the experimental acceptance and efficiency are set. For a chosen set of parameters within the MSUGRA-CMSSM framework, and for equal squark and gluino masses, gluino masses below 700 GeV are excluded at 95% C.L. These ATLAS results exceed previous limits set by other experiments [3–7].

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G. Aad,[48] B. Abbott,[111] J. Abdallah,[11] A. A. Abdelalim,[49] A. Abdesselam,[118] O. Abdinov,[10] B. Abi,[112] M. Abolins,[88] H. Abramowicz,[153] H. Abreu,[115] E. Acerbi,[89a,89b] B. S. Acharya,[164a,164b] D. L. Adams,[24] T. N. Addy,[56] J. Adelman,[175] M. Aderholz,[99] S. Adomeit,[98] P. Adragna,[75] T. Adye,[129] S. Aefsky,[22] J. A. Aguilar-Saavedra,[124b,b] M. Aharrouche,[81] S. P. Ahlen,[21] F. Ahles,[48] A. Ahmad,[148] M. Ahsan,[40] G. Aielli,[133a,133b] T. Akdogan,[18a] T. P. A. Åkesson,[79] G. Akimoto,[155] A. V. Akimov,[94] M. S. Alam,[1] M. A. Alam,[76] S. Albrand,[55] M. Aleksa,[29] I. N. Aleksandrov,[65] M. Aleppo,[89a,89b] F. Alessandria,[89a] C. Alexa,[25a] G. Alexander,[153] G. Alexandre,[49] T. Alexopoulos,[9] M. Alhroob,[20] M. Aliev,[15] G. Alimonti,[89a] J. Alison,[120] M. Aliyev,[10] P. P. Allport,[73] S. E. Allwood-Spiers,[53] J. Almond,[82] A. Aloisio,[102a,102b] R. Alon,[171] A. Alonso,[79] M. G. Alviggi,[102a,102b] K. Amako,[66] P. Amaral,[29] C. Amelung,[22] V. V. Ammosov,[128] A. Amorim,[124a,c] G. Amorós,[167] N. Amram,[153] C. Anastopoulos,[139] T. Andeen,[34] C. F. Anders,[20] K. J. Anderson,[30] A. Andreazza,[89a,89b] V. Andrei,[58a] M-L. Andrieux,[55] X. S. Anduaga,[70] A. Angerami,[34] F. Anghinolfi,[29] N. Anjos,[124a] A. Annovi,[47] A. Antonaki,[8] M. Antonelli,[47] S. Antonelli,[19a,19b] A. Antonov,[96] J. Antos,[144b] F. Anulli,[132a] S. Aoun,[83] L. Aperio Bella,[4] R. Apolle,[118] G. Arabidze,[88] I. Aracena,[143] Y. Arai,[66] A. T. H. Arce,[44] J. P. Archambault,[28] S. Arfaoui,[29,d] J-F. Arguin,[14] E. Arik,[18a,a] M. Arik,[18a] A. J. Armbruster,[87] O. Arnaez,[81] C. Arnault,[115] A. Artamonov,[95] G. Artoni,[132a,132b] D. Arutinov,[20] S. Asai,[155] R. Asfandiyarov,[172] S. Ask,[27] B. Åsman,[146a,146b] L. Asquith,[5] K. Assamagan,[24] A. Astbury,[169] A. Astvatsatourov,[52] G. Atoian,[175] B. Aubert,[4] B. Auerbach,[175] E. Auge,[115] K. Augsten,[127] M. Aurousseau,[4] N. Austin,[73] R. Avramidou,[9] D. Axen,[168] C. Ay,[54] G. Azuelos,[93,e] Y. Azuma,[155] M. A. Baak,[29] G. Baccaglioni,[89a] C. Bacci,[134a,134b] A. M. Bach,[14] H. Bachacou,[136] K. Bachas,[29] G. Bachy,[29] M. Backes,[49] M. Backhaus,[20] E. Badescu,[25a] P. Bagnaia,[132a,132b] S. Bahinipati,[2] Y. Bai,[32a] D. C. Bailey,[158] T. Bain,[158] J. T. Baines,[129] O. K. Baker,[175] M. D. Baker,[24] S. Baker,[77] F. Baltasar Dos Santos Pedrosa,[29] E. Banas,[38] P. Banerjee,[93] Sw. Banerjee,[169] D. Banfi,[29] A. Bangert,[137] V. Bansal,[169] H. S. Bansil,[17] L. Barak,[171] S. P. Baranov,[94] A. Barashkou,[65] A. Barbaro Galtieri,[14] T. Barber,[27] E. L. Barberio,[86] D. Barberis,[50a,50b] M. Barbero,[20] D. Y. Bardin,[65] T. Barillari,[99] M. Barisonzi,[174] T. Barklow,[143] N. Barlow,[27] B. M. Barnett,[129] R. M. Barnett,[14] A. Baroncelli,[134a] A. J. Barr,[118] F. Barreiro,[80] J. Barreiro Guimarães da Costa,[57] P. Barrillon,[115] R. Bartoldus,[143] A. E. Barton,[71] D. Bartsch,[20] V. Bartsch,[149] R. L. Bates,[53] L. Batkova,[144a] J. R. Batley,[27] A. Battaglia,[16] M. Battistin,[29] G. Battistoni,[89a] F. Bauer,[136] H. S. Bawa,[143,f] B. Beare,[158] T. Beau,[78] P. H. Beauchemin,[118] R. Beccherle,[50a] P. Bechtle,[41] H. P. Beck,[16] M. Beckingham,[48] K. H. Becks,[174] A. J. Beddall,[18c] A. Beddall,[18c] V. A. Bednyakov,[65] C. P. Bee,[83] M. Begel,[24] S. Behar Harpaz,[152] P. K. Behera,[63] M. Beimforde,[99] C. Belanger-Champagne,[166] P. J. Bell,[49] W. H. Bell,[49] G. Bella,[153] L. Bellagamba,[19a] F. Bellina,[29] G. Bellomo,[89a,89b] M. Bellomo,[119a] A. Belloni,[57] O. Beloborodova,[107] K. Belotskiy,[96] O. Beltramello,[29] S. Ben Ami,[152] O. Benary,[153] D. Benchekroun,[135a] C. Benchouk,[83] M. Bendel,[81] B. H. Benedict,[163] N. Benekos,[165] Y. Benhammou,[153] D. P. Benjamin,[44] M. Benoit,[115] J. R. Bensinger,[22] K. Benslama,[130] S. Bentvelsen,[105] D. Berge,[29] E. Bergeaas Kuutmann,[41] N. Berger,[4] F. Berghaus,[169] E. Berglund,[49] J. Beringer,[14] K. Bernardet,[83] P. Bernat,[77] R. Bernhard,[48] C. Bernius,[24] T. Berry,[76] A. Bertin,[19a,19b] F. Bertinelli,[29] F. Bertolucci,[122a,122b] M. I. Besana,[89a,89b] N. Besson,[136] S. Bethke,[99] W. Bhimji,[45] R. M. Bianchi,[29] M. Bianco,[72a,72b] O. Biebel,[98] S. P. Bieniek,[77] J. Biesiada,[14] M. Biglietti,[134a,134b] H. Bilokon,[47] M. Bindi,[19a,19b] S. Binet,[115] A. Bingul,[18c] C. Bini,[132a,132b] C. Biscarat,[177] U. Bitenc,[48] K. M. Black,[21] R. E. Blair,[5] J.-B. Blanchard,[115] G. Blanchot,[29] C. Blocker,[22] J. Blocki,[38] A. Blondel,[49] W. Blum,[81] U. Blumenschein,[54] G. J. Bobbink,[105] V. B. Bobrovnikov,[107] A. Bocci,[44] C. R. Boddy,[118] M. Boehler,[41] J. Boek,[174] N. Boelaert,[35] S. Böser,[77] J. A. Bogaerts,[29] A. Bogdanchikov,[107] A. Bogouch,[90,a] C. Bohm,[146a] V. Boisvert,[76] T. Bold,[163,g] V. Boldea,[25a] M. Bona,[75] V. G. Bondarenko,[96] M. Boonekamp,[136] G. Boorman,[76] C. N. Booth,[139] P. Booth,[139] S. Bordoni,[78] C. Borer,[16] A. Borisov,[128] G. Borissov,[71] I. Borjanovic,[12a] S. Borroni,[132a,132b] K. Bos,[105] D. Boscherini,[19a] M. Bosman,[11] H. Boterenbrood,[105] D. Botterill,[129] J. Bouchami,[93] J. Boudreau,[123] E. V. Bouhova-Thacker,[71] C. Boulahouache,[123] C. Bourdarios,[115] N. Bousson,[83] A. Boveia,[30] J. Boyd,[29] I. R. Boyko,[65] N. I. Bozhko,[128] I. Bozovic-Jelisavcic,[12b] J. Bracinik,[17] A. Braem,[29] E. Brambilla,[72a,72b] P. Branchini,[134a] G. W. Brandenburg,[57] A. Brandt,[7] G. Brandt,[15] O. Brandt,[54] U. Bratzler,[156] B. Brau,[84] J. E. Brau,[114]

H. M. Braun,[174] B. Brelier,[158] J. Bremer,[29] R. Brenner,[166] S. Bressler,[152] D. Breton,[115] N. D. Brett,[118]
P. G. Bright-Thomas,[17] D. Britton,[53] F. M. Brochu,[27] I. Brock,[20] R. Brock,[88] T. J. Brodbeck,[71] E. Brodet,[153]
F. Broggi,[89a] C. Bromberg,[88] G. Brooijmans,[34] W. K. Brooks,[31b] G. Brown,[82] E. Brubaker,[30]
P. A. Bruckman de Renstrom,[38] D. Bruncko,[144b] R. Bruneliere,[48] S. Brunet,[61] A. Bruni,[19a] G. Bruni,[19a]
M. Bruschi,[19a] T. Buanes,[13] F. Bucci,[49] J. Buchanan,[118] N. J. Buchanan,[2] P. Buchholz,[141] R. M. Buckingham,[118]
A. G. Buckley,[45] S. I. Buda,[25a] I. A. Budagov,[65] B. Budick,[108] V. Büscher,[81] L. Bugge,[117] D. Buira-Clark,[118]
E. J. Buis,[105] O. Bulekov,[96] M. Bunse,[42] T. Buran,[117] H. Burckhart,[29] S. Burdin,[73] T. Burgess,[13] S. Burke,[129]
E. Busato,[33] P. Bussey,[53] C. P. Buszello,[166] F. Butin,[29] B. Butler,[143] J. M. Butler,[21] C. M. Buttar,[53]
J. M. Butterworth,[77] W. Buttinger,[27] T. Byatt,[77] S. Cabrera Urbán,[167] M. Caccia,[89a,89b] D. Caforio,[19a,19b] O. Cakir,[3a]
P. Calafiura,[14] G. Calderini,[78] P. Calfayan,[98] R. Calkins,[106] L. P. Caloba,[23a] R. Caloi,[132a,132b] D. Calvet,[33] S. Calvet,[33]
R. Camacho Toro,[33] A. Camard,[78] P. Camarri,[133a,133b] M. Cambiaghi,[119a,119b] D. Cameron,[117] J. Cammin,[20]
S. Campana,[29] M. Campanelli,[77] V. Canale,[102a,102b] F. Canelli,[30] A. Canepa,[159a] J. Cantero,[80] L. Capasso,[102a,102b]
M. D. M. Capeans Garrido,[29] I. Caprini,[25a] M. Caprini,[25a] D. Capriotti,[99] M. Capua,[36a,36b] R. Caputo,[148]
C. Caramarcu,[25a] R. Cardarelli,[133a] T. Carli,[29] G. Carlino,[102a] L. Carminati,[89a,89b] B. Caron,[159a] S. Caron,[48]
C. Carpentieri,[48] G. D. Carrillo Montoya,[172] A. A. Carter,[75] J. R. Carter,[27] J. Carvalho,[124a,h] D. Casadei,[108]
M. P. Casado,[11] M. Cascella,[122a,122b] C. Caso,[50a,50b,a] A. M. Castaneda Hernandez,[172] E. Castaneda-Miranda,[172]
V. Castillo Gimenez,[167] N. F. Castro,[124b,b] G. Cataldi,[72a] F. Cataneo,[29] A. Catinaccio,[29] J. R. Catmore,[71] A. Cattai,[29]
G. Cattani,[133a,133b] S. Caughron,[88] D. Cauz,[164a,164c] A. Cavallari,[132a,132b] P. Cavalleri,[78] D. Cavalli,[89a]
M. Cavalli-Sforza,[11] V. Cavasinni,[122a,122b] A. Cazzato,[72a,72b] F. Ceradini,[134a,134b] A. S. Cerqueira,[23a] A. Cerri,[29]
L. Cerrito,[75] F. Cerutti,[47] S. A. Cetin,[18b] F. Cevenini,[102a,102b] A. Chafaq,[135a] D. Chakraborty,[106] K. Chan,[2]
B. Chapleau,[85] J. D. Chapman,[27] J. W. Chapman,[87] E. Chareyre,[78] D. G. Charlton,[17] V. Chavda,[82] S. Cheatham,[71]
S. Chekanov,[5] S. V. Chekulaev,[159a] G. A. Chelkov,[65] H. Chen,[24] L. Chen,[2] S. Chen,[32c] T. Chen,[32c] X. Chen,[172]
S. Cheng,[32a] A. Cheplakov,[65] V. F. Chepurnov,[65] R. Cherkaoui El Moursli,[135e] V. Chernyatin,[24] E. Cheu,[6]
S. L. Cheung,[158] L. Chevalier,[136] F. Chevallier,[136] G. Chiefari,[102a,102b] L. Chikovani,[51] J. T. Childers,[58a]
A. Chilingarov,[71] G. Chiodini,[72a] M. V. Chizhov,[65] G. Choudalakis,[30] S. Chouridou,[137] I. A. Christidi,[77]
A. Christov,[48] D. Chromek-Burckhart,[29] M. L. Chu,[151] J. Chudoba,[125] G. Ciapetti,[132a,132b] K. Ciba,[37] A. K. Ciftci,[3a]
R. Ciftci,[3a] D. Cinca,[33] V. Cindro,[74] M. D. Ciobotaru,[163] C. Ciocca,[19a,19b] A. Ciocio,[14] M. Cirilli,[87] M. Ciubancan,[25a]
A. Clark,[49] P. J. Clark,[45] W. Cleland,[123] J. C. Clemens,[83] B. Clement,[55] C. Clement,[146a,146b] R. W. Clifft,[129]
Y. Coadou,[83] M. Cobal,[164a,164c] A. Coccaro,[50a,50b] J. Cochran,[64] P. Coe,[118] J. G. Cogan,[143] J. Coggeshall,[165]
E. Cogneras,[177] C. D. Cojocaru,[28] J. Colas,[4] A. P. Colijn,[105] C. Collard,[115] N. J. Collins,[17] C. Collins-Tooth,[53]
J. Collot,[55] G. Colon,[84] R. Coluccia,[72a,72b] G. Comune,[88] P. Conde Muiño,[124a] E. Coniavitis,[118] M. C. Conidi,[11]
M. Consonni,[104] V. Consorti,[48] S. Constantinescu,[25a] C. Conta,[119a,119b] F. Conventi,[102a,i] J. Cook,[29] M. Cooke,[14]
B. D. Cooper,[77] A. M. Cooper-Sarkar,[118] N. J. Cooper-Smith,[76] K. Copic,[34] T. Cornelissen,[50a,50b] M. Corradi,[19a]
F. Corriveau,[85,j] A. Cortes-Gonzalez,[165] G. Cortiana,[99] G. Costa,[89a] M. J. Costa,[167] D. Costanzo,[139] T. Costin,[30]
D. Côté,[29] R. Coura Torres,[23a] L. Courneyea,[169] G. Cowan,[76] C. Cowden,[27] B. E. Cox,[82] K. Cranmer,[108]
M. Cristinziani,[20] G. Crosetti,[36a,36b] R. Crupi,[72a,72b] S. Crépé-Renaudin,[55] C. Cuenca Almenar,[175]
T. Cuhadar Donszelmann,[139] S. Cuneo,[50a,50b] M. Curatolo,[47] C. J. Curtis,[17] P. Cwetanski,[61] H. Czirr,[141]
Z. Czyczula,[117] S. D'Auria,[53] M. D'Onofrio,[73] A. D'Orazio,[132a,132b] A. Da Rocha Gesualdi Mello,[23a]
P. V. M. Da Silva,[23a] C. Da Via,[82] W. Dabrowski,[37] A. Dahlhoff,[48] T. Dai,[87] C. Dallapiccola,[84] S. J. Dallison,[129,a]
M. Dam,[35] M. Dameri,[50a,50b] D. S. Damiani,[137] H. O. Danielsson,[29] R. Dankers,[105] D. Dannheim,[99] V. Dao,[49]
G. Darbo,[50a] G. L. Darlea,[25b] C. Daum,[105] J. P. Dauvergne,[29] W. Davey,[86] T. Davidek,[126] N. Davidson,[86]
R. Davidson,[71] M. Davies,[93] A. R. Davison,[77] E. Dawe,[142] I. Dawson,[139] J. W. Dawson,[5,a] R. K. Daya,[39] K. De,[7]
R. de Asmundis,[102a] S. De Castro,[19a,19b] P. E. De Castro Faria Salgado,[24] S. De Cecco,[78] J. de Graat,[98]
N. De Groot,[104] P. de Jong,[105] C. De La Taille,[115] B. De Lotto,[164a,164c] L. De Mora,[71] L. De Nooij,[105]
M. De Oliveira Branco,[29] D. De Pedis,[132a] P. de Saintignon,[55] A. De Salvo,[132a] U. De Sanctis,[164a,164c] A. De Santo,[149]
J. B. De Vivie De Regie,[115] S. Dean,[77] D. V. Dedovich,[65] J. Degenhardt,[120] M. Dehchar,[118] M. Deile,[98]
C. Del Papa,[164a,164c] J. Del Peso,[80] T. Del Prete,[122a,122b] A. Dell'Acqua,[29] L. Dell'Asta,[89a,89b] M. Della Pietra,[102a,i]
D. della Volpe,[102a,102b] M. Delmastro,[29] P. Delpierre,[83] N. Delruelle,[29] P. A. Delsart,[55] C. Deluca,[148] S. Demers,[175]
M. Demichev,[65] B. Demirkoz,[11] J. Deng,[163] S. P. Denisov,[128] D. Derendarz,[38] J. E. Derkaoui,[135d] F. Derue,[78]
P. Dervan,[73] K. Desch,[20] E. Devetak,[148] P. O. Deviveiros,[158] A. Dewhurst,[129] B. DeWilde,[148] S. Dhaliwal,[158]
R. Dhullipudi,[24,k] A. Di Ciaccio,[133a,133b] L. Di Ciaccio,[4] A. Di Girolamo,[29] B. Di Girolamo,[29] S. Di Luise,[134a,134b]

A. Di Mattia,[88] B. Di Micco,[134a,134b] R. Di Nardo,[133a,133b] A. Di Simone,[133a,133b] R. Di Sipio,[19a,19b] M. A. Diaz,[31a] F. Diblen,[18c] E. B. Diehl,[87] H. Dietl,[99] J. Dietrich,[48] T. A. Dietzsch,[58a] S. Diglio,[115] K. Dindar Yagci,[39] J. Dingfelder,[20] C. Dionisi,[132a,132b] P. Dita,[25a] S. Dita,[25a] F. Dittus,[29] F. Djama,[83] R. Djilkibaev,[108] T. Djobava,[51] M. A. B. do Vale,[23a] A. Do Valle Wemans,[124a] T. K. O. Doan,[4] M. Dobbs,[85] R. Dobinson,[29,a] D. Dobos,[42] E. Dobson,[29] M. Dobson,[163] J. Dodd,[34] O. B. Dogan,[18a,a] C. Doglioni,[118] T. Doherty,[53] Y. Doi,[66,a] J. Dolejsi,[126] I. Dolenc,[74] Z. Dolezal,[126] B. A. Dolgoshein,[96,a] T. Dohmae,[155] M. Donadelli,[23b] M. Donega,[120] J. Donini,[55] J. Dopke,[174] A. Doria,[102a] A. Dos Anjos,[172] M. Dosil,[11] A. Dotti,[122a,122b] M. T. Dova,[70] J. D. Dowell,[17] A. D. Doxiadis,[105] A. T. Doyle,[53] Z. Drasal,[126] J. Drees,[174] N. Dressnandt,[120] H. Drevermann,[29] C. Driouichi,[35] M. Dris,[9] J. G. Drohan,[77] J. Dubbert,[99] T. Dubbs,[137] S. Dube,[14] E. Duchovni,[171] G. Duckeck,[98] A. Dudarev,[29] F. Dudziak,[64] M. Dührssen,[29] I. P. Duerdoth,[82] L. Duflot,[115] M-A. Dufour,[85] M. Dunford,[29] H. Duran Yildiz,[3b] R. Duxfield,[139] M. Dwuznik,[37] F. Dydak,[29] D. Dzahini,[55] M. Düren,[52] W. L. Ebenstein,[44] J. Ebke,[98] S. Eckert,[48] S. Eckweiler,[81] K. Edmonds,[81] C. A. Edwards,[76] I. Efthymiopoulos,[49] W. Ehrenfeld,[41] T. Ehrich,[99] T. Eifert,[29] G. Eigen,[13] K. Einsweiler,[14] E. Eisenhandler,[75] T. Ekelof,[166] M. El Kacimi,[4] M. Ellert,[166] S. Elles,[4] F. Ellinghaus,[81] K. Ellis,[75] N. Ellis,[29] J. Elmsheuser,[98] M. Elsing,[29] R. Ely,[14] D. Emeliyanov,[129] R. Engelmann,[148] A. Engl,[98] B. Epp,[62] A. Eppig,[87] J. Erdmann,[54] A. Ereditato,[16] D. Eriksson,[146a] J. Ernst,[1] M. Ernst,[24] J. Ernwein,[136] D. Errede,[165] S. Errede,[165] E. Ertel,[81] M. Escalier,[115] C. Escobar,[167] X. Espinal Curull,[11] B. Esposito,[47] F. Etienne,[83] A. I. Etienvre,[136] E. Etzion,[153] D. Evangelakou,[54] H. Evans,[61] L. Fabbri,[19a,19b] C. Fabre,[29] K. Facius,[35] R. M. Fakhrutdinov,[128] S. Falciano,[132a] A. C. Falou,[115] Y. Fang,[172] M. Fanti,[89a,89b] A. Farbin,[7] A. Farilla,[134a] J. Farley,[148] T. Farooque,[158] S. M. Farrington,[118] P. Farthouat,[29] D. Fasching,[172] P. Fassnacht,[29] D. Fassouliotis,[8] B. Fatholahzadeh,[158] A. Favareto,[89a,89b] L. Fayard,[115] S. Fazio,[36a,36b] R. Febbraro,[33] P. Federic,[144a] O. L. Fedin,[121] I. Fedorko,[29] W. Fedorko,[88] M. Fehling-Kaschek,[48] L. Feligioni,[83] D. Fellmann,[5] C. U. Felzmann,[86] C. Feng,[32d] E. J. Feng,[30] A. B. Fenyuk,[128] J. Ferencei,[144b] J. Ferland,[93] B. Fernandes,[124a,c] W. Fernando,[109] S. Ferrag,[53] J. Ferrando,[118] V. Ferrara,[41] A. Ferrari,[166] P. Ferrari,[105] R. Ferrari,[119a] A. Ferrer,[167] M. L. Ferrer,[47] D. Ferrere,[49] C. Ferretti,[87] A. Ferretto Parodi,[50a,50b] M. Fiascaris,[30] F. Fiedler,[81] A. Filipčič,[74] A. Filippas,[9] F. Filthaut,[104] M. Fincke-Keeler,[169] M. C. N. Fiolhais,[124a,h] L. Fiorini,[11] A. Firan,[39] G. Fischer,[41] P. Fischer,[20] M. J. Fisher,[109] S. M. Fisher,[129] J. Flammer,[29] M. Flechl,[48] I. Fleck,[141] J. Fleckner,[81] P. Fleischmann,[173] S. Fleischmann,[174] T. Flick,[174] L. R. Flores Castillo,[172] M. J. Flowerdew,[99] F. Föhlisch,[58a] M. Fokitis,[9] T. Fonseca Martin,[16] D. A. Forbush,[138] A. Formica,[136] A. Forti,[82] D. Fortin,[159a] J. M. Foster,[82] D. Fournier,[115] A. Foussat,[29] A. J. Fowler,[44] K. Fowler,[137] H. Fox,[71] P. Francavilla,[122a,122b] S. Franchino,[119a,119b] D. Francis,[29] T. Frank,[171] M. Franklin,[57] S. Franz,[29] M. Fraternali,[119a,119b] S. Fratina,[120] S. T. French,[27] R. Froeschl,[29] D. Froidevaux,[29] J. A. Frost,[27] C. Fukunaga,[156] E. Fullana Torregrosa,[29] J. Fuster,[167] C. Gabaldon,[29] O. Gabizon,[171] T. Gadfort,[24] S. Gadomski,[49] G. Gagliardi,[50a,50b] P. Gagnon,[61] C. Galea,[98] E. J. Gallas,[118] M. V. Gallas,[29] V. Gallo,[16] B. J. Gallop,[129] P. Gallus,[125] E. Galyaev,[40] K. K. Gan,[109] Y. S. Gao,[143,f] V. A. Gapienko,[128] A. Gaponenko,[14] F. Garberson,[175] M. Garcia-Sciveres,[14] C. García,[167] J. E. García Navarro,[49] R. W. Gardner,[30] N. Garelli,[29] H. Garitaonandia,[105] V. Garonne,[29] J. Garvey,[17] C. Gatti,[47] G. Gaudio,[119a] O. Gaumer,[49] B. Gaur,[141] L. Gauthier,[136] I. L. Gavrilenko,[94] C. Gay,[168] G. Gaycken,[20] J-C. Gayde,[29] E. N. Gazis,[9] P. Ge,[32d] C. N. P. Gee,[129] D. A. A. Geerts,[105] Ch. Geich-Gimbel,[20] K. Gellerstedt,[146a,146b] C. Gemme,[50a] A. Gemmell,[53] M. H. Genest,[98] S. Gentile,[132a,132b] S. George,[76] P. Gerlach,[174] A. Gershon,[153] C. Geweniger,[58a] H. Ghazlane,[135e] P. Ghez,[4] N. Ghodbane,[33] B. Giacobbe,[19a] S. Giagu,[132a,132b] V. Giakoumopoulou,[8] V. Giangiobbe,[122a,122b] F. Gianotti,[29] B. Gibbard,[24] A. Gibson,[158] S. M. Gibson,[29] G. F. Gieraltowski,[5] L. M. Gilbert,[118] M. Gilchriese,[14] V. Gilewsky,[91] D. Gillberg,[28] A. R. Gillman,[129] D. M. Gingrich,[2,e] J. Ginzburg,[153] N. Giokaris,[8] R. Giordano,[102a,102b] F. M. Giorgi,[15] P. Giovannini,[99] P. F. Giraud,[136] D. Giugni,[89a] P. Giusti,[19a] B. K. Gjelsten,[117] L. K. Gladilin,[97] C. Glasman,[80] J. Glatzer,[48] A. Glazov,[41] K. W. Glitza,[174] G. L. Glonti,[65] J. Godfrey,[142] J. Godlewski,[29] M. Goebel,[41] T. Göpfert,[43] C. Goeringer,[81] C. Gössling,[42] T. Göttfert,[99] S. Goldfarb,[87] D. Goldin,[39] T. Golling,[175] S. N. Golovnia,[128] A. Gomes,[124a,c] L. S. Gomez Fajardo,[41] R. Gonçalo,[76] L. Gonella,[20] A. Gonidec,[29] S. Gonzalez,[172] S. González de la Hoz,[167] M. L. Gonzalez Silva,[26] S. Gonzalez-Sevilla,[49] J. J. Goodson,[148] L. Goossens,[29] P. A. Gorbounov,[95] H. A. Gordon,[24] I. Gorelov,[103] G. Gorfine,[174] B. Gorini,[29] E. Gorini,[72a,72b] A. Gorišek,[74] E. Gornicki,[38] S. A. Gorokhov,[128] V. N. Goryachev,[128] B. Gosdzik,[41] M. Gosselink,[105] M. I. Gostkin,[65] M. Gouanère,[4] I. Gough Eschrich,[163] M. Gouighri,[135a] D. Goujdami,[135a] M. P. Goulette,[49] A. G. Goussiou,[138] C. Goy,[4] I. Grabowska-Bold,[163,g] V. Grabski,[176] P. Grafström,[29] C. Grah,[174] K-J. Grahn,[147] F. Grancagnolo,[72a] S. Grancagnolo,[15] V. Grassi,[148] V. Gratchev,[121] N. Grau,[34] H. M. Gray,[29] J. A. Gray,[148] E. Graziani,[134a]

O. G. Grebenyuk,[121] D. Greenfield,[129] T. Greenshaw,[73] Z. D. Greenwood,[24,k] I. M. Gregor,[41] P. Grenier,[143]
E. Griesmayer,[46] J. Griffiths,[138] N. Grigalashvili,[65] A. A. Grillo,[137] S. Grinstein,[11] P. L. Y. Gris,[33] Y. V. Grishkevich,[97]
J.-F. Grivaz,[115] J. Grognuz,[29] M. Groh,[99] E. Gross,[171] J. Grosse-Knetter,[54] J. Groth-Jensen,[79] M. Gruwe,[29]
K. Grybel,[141] V. J. Guarino,[5] D. Guest,[175] C. Guicheney,[33] A. Guida,[72a,72b] T. Guillemin,[4] S. Guindon,[54] H. Guler,[85,l]
J. Gunther,[125] B. Guo,[158] J. Guo,[34] A. Gupta,[30] Y. Gusakov,[65] V. N. Gushchin,[128] A. Gutierrez,[93] P. Gutierrez,[111]
N. Guttman,[153] O. Gutzwiller,[172] C. Guyot,[136] C. Gwenlan,[118] C. B. Gwilliam,[73] A. Haas,[143] S. Haas,[29] C. Haber,[14]
R. Hackenburg,[24] H. K. Hadavand,[39] D. R. Hadley,[17] P. Haefner,[99] F. Hahn,[29] S. Haider,[29] Z. Hajduk,[38]
H. Hakobyan,[176] J. Haller,[54] K. Hamacher,[174] P. Hamal,[113] A. Hamilton,[49] S. Hamilton,[161] H. Han,[32a] L. Han,[32b]
K. Hanagaki,[116] M. Hance,[120] C. Handel,[81] P. Hanke,[58a] C. J. Hansen,[166] J. R. Hansen,[35] J. B. Hansen,[35]
J. D. Hansen,[35] P. H. Hansen,[35] P. Hansson,[143] K. Hara,[160] G. A. Hare,[137] T. Harenberg,[174] D. Harper,[87]
R. D. Harrington,[21] O. M. Harris,[138] K. Harrison,[17] J. Hartert,[48] F. Hartjes,[105] T. Haruyama,[66] A. Harvey,[56]
S. Hasegawa,[101] Y. Hasegawa,[140] S. Hassani,[136] M. Hatch,[29] D. Hauff,[99] S. Haug,[16] M. Hauschild,[29] R. Hauser,[88]
M. Havranek,[20] B. M. Hawes,[118] C. M. Hawkes,[17] R. J. Hawkings,[29] D. Hawkins,[163] T. Hayakawa,[67] D Hayden,[76]
H. S. Hayward,[73] S. J. Haywood,[129] E. Hazen,[21] M. He,[32d] S. J. Head,[17] V. Hedberg,[79] L. Heelan,[7] S. Heim,[88]
B. Heinemann,[14] S. Heisterkamp,[35] L. Helary,[4] M. Heldmann,[48] M. Heller,[115] S. Hellman,[146a,146b] C. Helsens,[11]
R. C. W. Henderson,[71] M. Henke,[58a] A. Henrichs,[54] A. M. Henriques Correia,[29] S. Henrot-Versille,[115]
F. Henry-Couannier,[83] C. Hensel,[54] T. Henß,[174] Y. Hernández Jiménez,[167] R. Herrberg,[15] A. D. Hershenhorn,[152]
G. Herten,[48] R. Hertenberger,[98] L. Hervas,[29] N. P. Hessey,[105] A. Hidvegi,[146a] E. Higón-Rodriguez,[167] D. Hill,[5,a]
J. C. Hill,[27] N. Hill,[5] K. H. Hiller,[41] S. Hillert,[20] S. J. Hillier,[17] I. Hinchliffe,[14] E. Hines,[120] M. Hirose,[116] F. Hirsch,[42]
D. Hirschbuehl,[174] J. Hobbs,[148] N. Hod,[153] M. C. Hodgkinson,[139] P. Hodgson,[139] A. Hoecker,[29]
M. R. Hoeferkamp,[103] J. Hoffman,[39] D. Hoffmann,[83] M. Hohlfeld,[81] M. Holder,[141] A. Holmes,[118]
S. O. Holmgren,[146a] T. Holy,[127] J. L. Holzbauer,[88] Y. Homma,[67] L. Hooft van Huysduynen,[108] T. Horazdovsky,[127]
C. Horn,[143] S. Horner,[48] K. Horton,[118] J-Y. Hostachy,[55] T. Hott,[99] S. Hou,[151] M. A. Houlden,[73] A. Hoummada,[135a]
J. Howarth,[82] D. F. Howell,[118] I. Hristova,[41] J. Hrivnac,[115] I. Hruska,[125] T. Hryn'ova,[4] P. J. Hsu,[175] S.-C. Hsu,[14]
G. S. Huang,[111] Z. Hubacek,[127] F. Hubaut,[83] F. Huegging,[20] T. B. Huffman,[118] E. W. Hughes,[34] G. Hughes,[71]
R. E. Hughes-Jones,[82] M. Huhtinen,[29] P. Hurst,[57] M. Hurwitz,[14] U. Husemann,[41] N. Huseynov,[65,m] J. Huston,[88]
J. Huth,[57] G. Iacobucci,[102a] G. Iakovidis,[9] M. Ibbotson,[82] I. Ibragimov,[141] R. Ichimiya,[67] L. Iconomidou-Fayard,[115]
J. Idarraga,[115] M. Idzik,[37] P. Iengo,[4] O. Igonkina,[105] Y. Ikegami,[66] M. Ikeno,[66] Y. Ilchenko,[39] D. Iliadis,[154]
D. Imbault,[78] M. Imhaeuser,[174] M. Imori,[155] T. Ince,[20] J. Inigo-Golfin,[29] P. Ioannou,[8] M. Iodice,[134a] G. Ionescu,[4]
A. Irles Quiles,[167] K. Ishii,[66] A. Ishikawa,[67] M. Ishino,[66] R. Ishmukhametov,[39] T. Isobe,[155] C. Issever,[118] S. Istin,[18a]
Y. Itoh,[101] A. V. Ivashin,[128] W. Iwanski,[38] H. Iwasaki,[66] J. M. Izen,[40] V. Izzo,[102a] B. Jackson,[120] J. N. Jackson,[73]
P. Jackson,[143] M. R. Jaekel,[29] V. Jain,[61] K. Jakobs,[48] S. Jakobsen,[35] J. Jakubek,[127] D. K. Jana,[111] E. Jankowski,[158]
E. Jansen,[77] A. Jantsch,[99] M. Janus,[20] G. Jarlskog,[79] L. Jeanty,[57] K. Jelen,[37] I. Jen-La Plante,[30] P. Jenni,[29]
A. Jeremie,[4] P. Jež,[35] S. Jézéquel,[4] M. K. Jha,[19a] H. Ji,[172] W. Ji,[81] J. Jia,[148] Y. Jiang,[32b] M. Jimenez Belenguer,[41]
G. Jin,[32b] S. Jin,[32a] O. Jinnouchi,[157] M. D. Joergensen,[35] D. Joffe,[39] L. G. Johansen,[13] M. Johansen,[146a,146b]
K. E. Johansson,[146a] P. Johansson,[139] S. Johnert,[41] K. A. Johns,[6] K. Jon-And,[146a,146b] G. Jones,[82] R. W. L. Jones,[71]
T. W. Jones,[77] T. J. Jones,[73] O. Jonsson,[29] C. Joram,[29] P. M. Jorge,[124a,c] J. Joseph,[14] X. Ju,[130] V. Juranek,[125] P. Jussel,[62]
V. V. Kabachenko,[128] S. Kabana,[16] M. Kaci,[167] A. Kaczmarska,[38] P. Kadlecik,[35] M. Kado,[115] H. Kagan,[109]
M. Kagan,[57] S. Kaiser,[99] E. Kajomovitz,[152] S. Kalinin,[174] L. V. Kalinovskaya,[65] S. Kama,[39] N. Kanaya,[155]
M. Kaneda,[155] T. Kanno,[157] V. A. Kantserov,[96] J. Kanzaki,[66] B. Kaplan,[175] A. Kapliy,[30] J. Kaplon,[29] D. Kar,[43]
M. Karagoz,[118] M. Karnevskiy,[41] K. Karr,[5] V. Kartvelishvili,[71] A. N. Karyukhin,[128] L. Kashif,[172] A. Kasmi,[39]
R. D. Kass,[109] A. Kastanas,[13] M. Kataoka,[4] Y. Kataoka,[155] E. Katsoufis,[9] J. Katzy,[41] V. Kaushik,[6] K. Kawagoe,[67]
T. Kawamoto,[155] G. Kawamura,[81] M. S. Kayl,[105] V. A. Kazanin,[107] M. Y. Kazarinov,[65] S. I. Kazi,[86] J. R. Keates,[82]
R. Keeler,[169] R. Kehoe,[39] M. Keil,[54] G. D. Kekelidze,[65] M. Kelly,[82] J. Kennedy,[98] M. Kenyon,[53] O. Kepka,[125]
N. Kerschen,[29] B. P. Kerševan,[74] S. Kersten,[174] K. Kessoku,[155] C. Ketterer,[48] M. Khakzad,[28] F. Khalil-zada,[10]
H. Khandanyan,[165] A. Khanov,[112] D. Kharchenko,[65] A. Khodinov,[148] A. G. Kholodenko,[128] A. Khomich,[58a]
T. J. Khoo,[27] G. Khoriauli,[20] N. Khovanskiy,[65] V. Khovanskiy,[95] E. Khramov,[65] J. Khubua,[51] G. Kilvington,[76]
H. Kim,[7] M. S. Kim,[2] P. C. Kim,[143] S. H. Kim,[160] N. Kimura,[170] O. Kind,[15] B. T. King,[73] M. King,[67] R. S. B. King,[118]
J. Kirk,[129] G. P. Kirsch,[118] L. E. Kirsch,[22] A. E. Kiryunin,[99] D. Kisielewska,[37] T. Kittelmann,[123] A. M. Kiver,[128]
H. Kiyamura,[67] E. Kladiva,[144b] J. Klaiber-Lodewigs,[42] M. Klein,[73] U. Klein,[73] K. Kleinknecht,[81] M. Klemetti,[85]
A. Klier,[171] A. Klimentov,[24] R. Klingenberg,[42] E. B. Klinkby,[35] T. Klioutchnikova,[29] P. F. Klok,[104] S. Klous,[105]

E.-E. Kluge,[58a] T. Kluge,[73] P. Kluit,[105] S. Kluth,[99] E. Kneringer,[62] J. Knobloch,[29] E.B.F.G. Knoops,[83] A. Knue,[54]
B. R. Ko,[44] T. Kobayashi,[155] M. Kobel,[43] B. Koblitz,[29] M. Kocian,[143] A. Kocnar,[113] P. Kodys,[126] K. Köneke,[29]
A. C. König,[104] S. Koenig,[81] S. König,[48] L. Köpke,[81] F. Koetsveld,[104] P. Koevesarki,[20] T. Koffas,[29] E. Koffeman,[105]
F. Kohn,[54] Z. Kohout,[127] T. Kohriki,[66] T. Koi,[143] T. Kokott,[20] G. M. Kolachev,[107] H. Kolanoski,[15] V. Kolesnikov,[65]
I. Koletsou,[89a] J. Koll,[88] D. Kollar,[29] M. Kollefrath,[48] S. D. Kolya,[82] A. A. Komar,[94] J. R. Komaragiri,[142] T. Kondo,[66]
T. Kono,[41,n] A. I. Kononov,[48] R. Konoplich,[108,o] N. Konstantinidis,[77] A. Kootz,[174] S. Koperny,[37] S. V. Kopikov,[128]
K. Korcyl,[38] K. Kordas,[154] V. Koreshev,[128] A. Korn,[14] A. Korol,[107] I. Korolkov,[11] E. V. Korolkova,[139]
V. A. Korotkov,[128] O. Kortner,[99] S. Kortner,[99] V. V. Kostyukhin,[20] M. J. Kotamäki,[29] S. Kotov,[99] V. M. Kotov,[65]
C. Kourkoumelis,[8] V. Kouskoura,[154] A. Koutsman,[105] R. Kowalewski,[169] T. Z. Kowalski,[37] W. Kozanecki,[136]
A. S. Kozhin,[128] V. Kral,[127] V. A. Kramarenko,[97] G. Kramberger,[74] O. Krasel,[42] M. W. Krasny,[78]
A. Krasznahorkay,[108] J. Kraus,[88] A. Kreisel,[153] F. Krejci,[127] J. Kretzschmar,[73] N. Krieger,[54] P. Krieger,[158]
K. Kroeninger,[54] H. Kroha,[99] J. Kroll,[120] J. Kroseberg,[20] J. Krstic,[12a] U. Kruchonak,[65] H. Krüger,[20]
Z. V. Krumshteyn,[65] A. Kruth,[20] T. Kubota,[155] S. Kuehn,[48] A. Kugel,[58c] T. Kuhl,[174] D. Kuhn,[62] V. Kukhtin,[65]
Y. Kulchitsky,[90] S. Kuleshov,[31b] C. Kummer,[98] M. Kuna,[83] N. Kundu,[118] J. Kunkle,[120] A. Kupco,[125] H. Kurashige,[67]
M. Kurata,[160] Y. A. Kurochkin,[90] V. Kus,[125] W. Kuykendall,[138] M. Kuze,[157] P. Kuzhir,[91] O. Kvasnicka,[125] R. Kwee,[15]
A. La Rosa,[29] L. La Rotonda,[36a,36b] L. Labarga,[80] J. Labbe,[4] C. Lacasta,[167] F. Lacava,[132a,132b] H. Lacker,[15]
D. Lacour,[78] V. R. Lacuesta,[167] E. Ladygin,[65] R. Lafaye,[4] B. Laforge,[78] T. Lagouri,[80] S. Lai,[48] E. Laisne,[55]
M. Lamanna,[29] C. L. Lampen,[6] W. Lampl,[6] E. Lancon,[136] U. Landgraf,[48] M. P. J. Landon,[75] H. Landsman,[152]
J. L. Lane,[82] C. Lange,[41] A. J. Lankford,[163] F. Lanni,[24] K. Lantzsch,[29] V. V. Lapin,[128,a] S. Laplace,[78] C. Lapoire,[20]
J. F. Laporte,[136] T. Lari,[89a] A. V. Larionov,[128] A. Larner,[118] C. Lasseur,[29] M. Lassnig,[29] W. Lau,[118] P. Laurelli,[47]
A. Lavorato,[118] W. Lavrijsen,[14] P. Laycock,[73] A. B. Lazarev,[65] A. Lazzaro,[89a,89b] O. Le Dortz,[78] E. Le Guirriec,[83]
C. Le Maner,[158] E. Le Menedeu,[136] M. Leahu,[29] A. Lebedev,[64] C. Lebel,[93] T. LeCompte,[5] F. Ledroit-Guillon,[55]
H. Lee,[105] J. S. H. Lee,[150] S. C. Lee,[151] L. Lee,[175] M. Lefebvre,[169] M. Legendre,[136] A. Leger,[49] B. C. LeGeyt,[120]
F. Legger,[98] C. Leggett,[14] M. Lehmacher,[20] G. Lehmann Miotto,[29] X. Lei,[6] M. A. L. Leite,[23b] R. Leitner,[126]
D. Lellouch,[171] J. Lellouch,[78] M. Leltchouk,[34] V. Lendermann,[58a] K. J. C. Leney,[145b] T. Lenz,[174] G. Lenzen,[174]
B. Lenzi,[136] K. Leonhardt,[43] S. Leontsinis,[9] C. Leroy,[93] J-R. Lessard,[169] J. Lesser,[146a] C. G. Lester,[27]
A. Leung Fook Cheong,[172] J. Levêque,[83] D. Levin,[87] L. J. Levinson,[171] M. S. Levitski,[128] M. Lewandowska,[21]
G. H. Lewis,[108] M. Leyton,[15] B. Li,[83] H. Li,[172] S. Li,[32b] X. Li,[87] Z. Liang,[39] Z. Liang,[118,p] B. Liberti,[133a] P. Lichard,[29]
M. Lichtnecker,[98] K. Lie,[165] W. Liebig,[13] R. Lifshitz,[152] J. N. Lilley,[17] A. Limosani,[86] M. Limper,[63] S. C. Lin,[151,q]
F. Linde,[105] J. T. Linnemann,[88] E. Lipeles,[120] L. Lipinsky,[125] A. Lipniacka,[13] T. M. Liss,[165] D. Lissauer,[24] A. Lister,[49]
A. M. Litke,[137] C. Liu,[28] D. Liu,[151,r] H. Liu,[87] J. B. Liu,[87] M. Liu,[32b] S. Liu,[2] Y. Liu,[32b] M. Livan,[119a,119b]
S. S. A. Livermore,[118] A. Lleres,[55] S. L. Lloyd,[75] E. Lobodzinska,[41] P. Loch,[6] W. S. Lockman,[137] S. Lockwitz,[175]
T. Loddenkoetter,[20] F. K. Loebinger,[82] A. Loginov,[175] C. W. Loh,[168] T. Lohse,[15] K. Lohwasser,[48] M. Lokajicek,[125]
J. Loken,[118] V. P. Lombardo,[89a] R. E. Long,[71] L. Lopes,[124a,c] D. Lopez Mateos,[34,s] M. Losada,[162] P. Loscutoff,[14]
F. Lo Sterzo,[132a,132b] M. J. Losty,[159a] X. Lou,[40] A. Lounis,[115] K. F. Loureiro,[162] J. Love,[21] P. A. Love,[71]
A. J. Lowe,[143,f] F. Lu,[32a] J. Lu,[2] L. Lu,[39] H. J. Lubatti,[138] C. Luci,[132a,132b] A. Lucotte,[55] A. Ludwig,[43] D. Ludwig,[41]
I. Ludwig,[48] J. Ludwig,[48] F. Luehring,[61] G. Luijckx,[105] D. Lumb,[48] L. Luminari,[132a] E. Lund,[117] B. Lund-Jensen,[147]
B. Lundberg,[79] J. Lundberg,[146a,146b] J. Lundquist,[35] M. Lungwitz,[81] A. Lupi,[122a,122b] G. Lutz,[99] D. Lynn,[24] J. Lys,[14]
E. Lytken,[79] H. Ma,[24] L. L. Ma,[172] J. A. Macana Goia,[93] G. Maccarrone,[47] A. Macchiolo,[99] B. Maček,[74]
J. Machado Miguens,[124a] D. Macina,[49] R. Mackeprang,[35] R. J. Madaras,[14] W. F. Mader,[43] R. Maenner,[58c]
T. Maeno,[24] P. Mättig,[174] S. Mättig,[41] P. J. Magalhaes Martins,[124a,h] L. Magnoni,[29] E. Magradze,[51] C. A. Magrath,[104]
Y. Mahalalel,[153] K. Mahboubi,[48] G. Mahout,[17] C. Maiani,[132a,132b] C. Maidantchik,[23a] A. Maio,[124a,c] S. Majewski,[24]
Y. Makida,[66] N. Makovec,[115] P. Mal,[6] Pa. Malecki,[38] P. Malecki,[38] V. P. Maleev,[121] F. Malek,[55] U. Mallik,[63]
D. Malon,[5] S. Maltezos,[9] V. Malyshev,[107] S. Malyukov,[65] R. Mameghani,[98] J. Mamuzic,[12b] A. Manabe,[66]
L. Mandelli,[89a] I. Mandić,[74] R. Mandrysch,[15] J. Maneira,[124a] P. S. Mangeard,[88] I. D. Manjavidze,[65] A. Mann,[54]
P. M. Manning,[137] A. Manousakis-Katsikakis,[8] B. Mansoulie,[136] A. Manz,[99] A. Mapelli,[29] L. Mapelli,[29] L. March,[80]
J. F. Marchand,[29] F. Marchese,[133a,133b] M. Marchesotti,[29] G. Marchiori,[78] M. Marcisovsky,[125] A. Marin,[21,a]
C. P. Marino,[61] F. Marroquim,[23a] R. Marshall,[82] Z. Marshall,[34,s] F. K. Martens,[158] S. Marti-Garcia,[167] A. J. Martin,[175]
B. Martin,[29] B. Martin,[88] F. F. Martin,[120] J. P. Martin,[93] Ph. Martin,[55] T. A. Martin,[17] B. Martin dit Latour,[49]
M. Martinez,[11] V. Martinez Outschoorn,[57] A. C. Martyniuk,[82] M. Marx,[82] F. Marzano,[132a] A. Marzin,[111] L. Masetti,[81]
T. Mashimo,[155] R. Mashinistov,[94] J. Masik,[82] A. L. Maslennikov,[107] M. Maß,[42] I. Massa,[19a,19b] G. Massaro,[105]

N. Massol,[4] A. Mastroberardino,[36a,36b] T. Masubuchi,[155] M. Mathes,[20] P. Matricon,[115] H. Matsumoto,[155]
H. Matsunaga,[155] T. Matsushita,[67] C. Mattravers,[118,t] J. M. Maugain,[29] S. J. Maxfield,[73] D. A. Maximov,[107]
E. N. May,[5] A. Mayne,[139] R. Mazini,[151] M. Mazur,[20] M. Mazzanti,[89a] E. Mazzoni,[122a,122b] S. P. Mc Kee,[87]
A. McCarn,[165] R. L. McCarthy,[148] T. G. McCarthy,[28] N. A. McCubbin,[129] K. W. McFarlane,[56] J. A. Mcfayden,[139]
H. McGlone,[53] G. Mchedlidze,[51] R. A. McLaren,[29] T. Mclaughlan,[17] S. J. McMahon,[129] R. A. McPherson,[169,j]
A. Meade,[84] J. Mechnich,[105] M. Mechtel,[174] M. Medinnis,[41] R. Meera-Lebbai,[111] T. Meguro,[116] R. Mehdiyev,[93]
S. Mehlhase,[35] A. Mehta,[73] K. Meier,[58a] J. Meinhardt,[48] B. Meirose,[79] C. Melachrinos,[30] B. R. Mellado Garcia,[172]
L. Mendoza Navas,[162] Z. Meng,[151,r] A. Mengarelli,[19a,19b] S. Menke,[99] C. Menot,[29] E. Meoni,[11] K. M. Mercurio,[57]
P. Mermod,[118] L. Merola,[102a,102b] C. Meroni,[89a] F. S. Merritt,[30] A. Messina,[29] J. Metcalfe,[103] A. S. Mete,[64]
S. Meuser,[20] C. Meyer,[81] J-P. Meyer,[136] J. Meyer,[173] J. Meyer,[54] T. C. Meyer,[29] W. T. Meyer,[64] J. Miao,[32d]
S. Michal,[29] L. Micu,[25a] R. P. Middleton,[129] P. Miele,[29] S. Migas,[73] L. Mijović,[41] G. Mikenberg,[171]
M. Mikestikova,[125] B. Mikulec,[49] M. Mikuž,[74] D. W. Miller,[143] R. J. Miller,[88] W. J. Mills,[168] C. Mills,[57] A. Milov,[171]
D. A. Milstead,[146a,146b] D. Milstein,[171] A. A. Minaenko,[128] M. Miñano,[167] I. A. Minashvili,[65] A. I. Mincer,[108]
B. Mindur,[37] M. Mineev,[65] Y. Ming,[130] L. M. Mir,[11] G. Mirabelli,[132a] L. Miralles Verge,[11] A. Misiejuk,[76]
J. Mitrevski,[137] G. Y. Mitrofanov,[128] V. A. Mitsou,[167] S. Mitsui,[66] P. S. Miyagawa,[82] K. Miyazaki,[67]
J. U. Mjörnmark,[79] T. Moa,[146a,146b] P. Mockett,[138] S. Moed,[57] V. Moeller,[27] K. Mönig,[41] N. Möser,[20]
S. Mohapatra,[148] B. Mohn,[13] W. Mohr,[48] S. Mohrdieck-Möck,[99] A. M. Moisseev,[128,a] R. Moles-Valls,[167]
J. Molina-Perez,[29] L. Moneta,[49] J. Monk,[77] E. Monnier,[83] S. Montesano,[89a,89b] F. Monticelli,[70] S. Monzani,[19a,19b]
R. W. Moore,[2] G. F. Moorhead,[86] C. Mora Herrera,[49] A. Moraes,[53] A. Morais,[124a,c] N. Morange,[136] J. Morel,[54]
G. Morello,[36a,36b] D. Moreno,[81] M. Moreno Llácer,[167] P. Morettini,[50a] M. Morii,[57] J. Morin,[75] Y. Morita,[66]
A. K. Morley,[29] G. Mornacchi,[29] M-C. Morone,[49] S. V. Morozov,[96] J. D. Morris,[75] H. G. Moser,[99] M. Mosidze,[51]
J. Moss,[109] R. Mount,[143] E. Mountricha,[9] S. V. Mouraviev,[94] E. J. W. Moyse,[84] M. Mudrinic,[12b] F. Mueller,[58a]
J. Mueller,[123] K. Mueller,[20] T. A. Müller,[98] D. Muenstermann,[42] A. Muijs,[105] A. Muir,[168] Y. Munwes,[153]
K. Murakami,[66] W. J. Murray,[129] I. Mussche,[105] E. Musto,[102a,102b] A. G. Myagkov,[128] M. Myska,[125] J. Nadal,[11]
K. Nagai,[160] K. Nagano,[66] Y. Nagasaka,[60] A. M. Nairz,[29] Y. Nakahama,[115] K. Nakamura,[155] I. Nakano,[110]
G. Nanava,[20] A. Napier,[161] M. Nash,[77,t] N. R. Nation,[21] T. Nattermann,[20] T. Naumann,[41] G. Navarro,[162] H. A. Neal,[87]
E. Nebot,[80] P.Yu. Nechaeva,[94] A. Negri,[119a,119b] G. Negri,[29] S. Nektarijevic,[49] A. Nelson,[64] S. Nelson,[143]
T. K. Nelson,[143] S. Nemecek,[125] P. Nemethy,[108] A. A. Nepomuceno,[23a] M. Nessi,[29,u] S. Y. Nesterov,[121]
M. S. Neubauer,[165] A. Neusiedl,[81] R. M. Neves,[108] P. Nevski,[24] P. R. Newman,[17] R. B. Nickerson,[118]
R. Nicolaidou,[136] L. Nicolas,[139] B. Nicquevert,[29] F. Niedercorn,[115] J. Nielsen,[137] T. Niinikoski,[29] A. Nikiforov,[15]
V. Nikolaenko,[128] K. Nikolaev,[65] I. Nikolic-Audit,[78] K. Nikolopoulos,[24] H. Nilsen,[48] P. Nilsson,[7] Y. Ninomiya,[155]
A. Nisati,[132a] T. Nishiyama,[67] R. Nisius,[99] L. Nodulman,[5] M. Nomachi,[116] I. Nomidis,[154] H. Nomoto,[155]
M. Nordberg,[29] B. Nordkvist,[146a,146b] P. R. Norton,[129] J. Novakova,[126] M. Nozaki,[66] M. Nožička,[41] L. Nozka,[113]
I. M. Nugent,[159a] A.-E. Nuncio-Quiroz,[20] G. Nunes Hanninger,[20] T. Nunnemann,[98] E. Nurse,[77] T. Nyman,[29]
B. J. O'Brien,[45] S. W. O'Neale,[17,a] D. C. O'Neil,[142] V. O'Shea,[53] F. G. Oakham,[28,e] H. Oberlack,[99] J. Ocariz,[78]
A. Ochi,[67] S. Oda,[155] S. Odaka,[66] J. Odier,[83] H. Ogren,[61] A. Oh,[82] S. H. Oh,[44] C. C. Ohm,[146a,146b] T. Ohshima,[101]
H. Ohshita,[140] T. K. Ohska,[66] T. Ohsugi,[59] S. Okada,[67] H. Okawa,[163] Y. Okumura,[101] T. Okuyama,[155] M. Olcese,[50a]
A. G. Olchevski,[65] M. Oliveira,[124a,h] D. Oliveira Damazio,[24] E. Oliver Garcia,[167] D. Olivito,[120] A. Olszewski,[38]
J. Olszowska,[38] C. Omachi,[67] A. Onofre,[124a,v] P. U. E. Onyisi,[30] C. J. Oram,[159a] G. Ordonez,[104] M. J. Oreglia,[30]
F. Orellana,[49] Y. Oren,[153] D. Orestano,[134a,134b] I. Orlov,[107] C. Oropeza Barrera,[53] R. S. Orr,[158] E. O. Ortega,[130]
B. Osculati,[50a,50b] R. Ospanov,[120] C. Osuna,[11] G. Otero y Garzon,[26] J.P Ottersbach,[105] M. Ouchrif,[135d]
F. Ould-Saada,[117] A. Ouraou,[136] Q. Ouyang,[32a] M. Owen,[82] S. Owen,[139] A. Oyarzun,[31b] O. K. Øye,[13] V. E. Ozcan,[18a]
N. Ozturk,[7] A. Pacheco Pages,[11] C. Padilla Aranda,[11] E. Paganis,[139] F. Paige,[24] K. Pajchel,[117] S. Palestini,[29]
D. Pallin,[33] A. Palma,[124a,c] J. D. Palmer,[17] Y. B. Pan,[172] E. Panagiotopoulou,[9] B. Panes,[31a] N. Panikashvili,[87]
S. Panitkin,[24] D. Pantea,[25a] M. Panuskova,[125] V. Paolone,[123] A. Paoloni,[133a,133b] A. Papadelis,[146a]
Th.D. Papadopoulou,[9] A. Paramonov,[5] W. Park,[24,w] M. A. Parker,[27] F. Parodi,[50a,50b] J. A. Parsons,[34] U. Parzefall,[48]
E. Pasqualucci,[132a] A. Passeri,[134a] F. Pastore,[134a,134b] Fr. Pastore,[29] G. Pásztor,[49,x] S. Pataraia,[172] N. Patel,[150]
J. R. Pater,[82] S. Patricelli,[102a,102b] T. Pauly,[29] M. Pecsy,[144a] M. I. Pedraza Morales,[172] S. V. Peleganchuk,[107]
H. Peng,[172] R. Pengo,[29] A. Penson,[34] J. Penwell,[61] M. Perantoni,[23a] K. Perez,[34,s] T. Perez Cavalcanti,[41]
E. Perez Codina,[11] M. T. Pérez García-Estañ,[167] V. Perez Reale,[34] I. Peric,[20] L. Perini,[89a,89b] H. Pernegger,[29]
R. Perrino,[72a] P. Perrodo,[4] S. Persembe,[3a] V. D. Peshekhonov,[65] O. Peters,[105] B. A. Petersen,[29] J. Petersen,[29]

T. C. Petersen,[35] E. Petit,[83] A. Petridis,[154] C. Petridou,[154] E. Petrolo,[132a] F. Petrucci,[134a,134b] D. Petschull,[41]
M. Petteni,[142] R. Pezoa,[31b] A. Phan,[86] A. W. Phillips,[27] P. W. Phillips,[129] G. Piacquadio,[29] E. Piccaro,[75]
M. Piccinini,[19a,19b] A. Pickford,[53] S. M. Piec,[41] R. Piegaia,[26] J. E. Pilcher,[30] A. D. Pilkington,[82] J. Pina,[124a,c]
M. Pinamonti,[164a,164c] A. Pinder,[118] J. L. Pinfold,[2] J. Ping,[32c] B. Pinto,[124a,c] O. Pirotte,[29] C. Pizio,[89a,89b]
R. Placakyte,[41] M. Plamondon,[169] W. G. Plano,[82] M.-A. Pleier,[24] A. V. Pleskach,[128] A. Poblaguev,[24] S. Poddar,[58a]
F. Podlyski,[33] L. Poggioli,[115] T. Poghosyan,[20] M. Pohl,[49] F. Polci,[55] G. Polesello,[119a] A. Policicchio,[138] A. Polini,[19a]
J. Poll,[75] V. Polychronakos,[24] D. M. Pomarede,[136] D. Pomeroy,[22] K. Pommès,[29] L. Pontecorvo,[132a] B. G. Pope,[88]
G. A. Popeneciu,[25a] D. S. Popovic,[12a] A. Poppleton,[29] X. Portell Bueso,[48] R. Porter,[163] C. Posch,[21] G. E. Pospelov,[99]
S. Pospisil,[127] I. N. Potrap,[99] C. J. Potter,[149] C. T. Potter,[114] G. Poulard,[29] J. Poveda,[172] R. Prabhu,[77] P. Pralavorio,[83]
S. Prasad,[57] R. Pravahan,[7] S. Prell,[64] K. Pretzl,[16] L. Pribyl,[29] D. Price,[61] L. E. Price,[5] M. J. Price,[29] P. M. Prichard,[73]
D. Prieur,[123] M. Primavera,[72a] K. Prokofiev,[108] F. Prokoshin,[31b] S. Protopopescu,[24] J. Proudfoot,[5] X. Prudent,[43]
H. Przysiezniak,[4] S. Psoroulas,[20] E. Ptacek,[114] J. Purdham,[87] M. Purohit,[24,w] P. Puzo,[115] Y. Pylypchenko,[117]
J. Qian,[87] Z. Qian,[83] Z. Qin,[41] A. Quadt,[54] D. R. Quarrie,[14] W. B. Quayle,[172] F. Quinonez,[31a] M. Raas,[104]
V. Radescu,[58b] B. Radics,[20] T. Rador,[18a] F. Ragusa,[89a,89b] G. Rahal,[177] A. M. Rahimi,[109] D. Rahm,[24]
S. Rajagopalan,[24] S. Rajek,[42] M. Rammensee,[48] M. Rammes,[141] M. Ramstedt,[146a,146b] K. Randrianarivony,[28]
P. N. Ratoff,[71] F. Rauscher,[98] E. Rauter,[99] M. Raymond,[29] A. L. Read,[117] D. M. Rebuzzi,[119a,119b] A. Redelbach,[173]
G. Redlinger,[24] R. Reece,[120] K. Reeves,[40] A. Reichold,[105] E. Reinherz-Aronis,[153] A. Reinsch,[114] I. Reisinger,[42]
D. Reljic,[12a] C. Rembser,[29] Z. L. Ren,[151] A. Renaud,[115] P. Renkel,[39] B. Rensch,[35] M. Rescigno,[132a] S. Resconi,[89a]
B. Resende,[136] P. Reznicek,[98] R. Rezvani,[158] A. Richards,[77] R. Richter,[99] E. Richter-Was,[38,y] M. Ridel,[78] S. Rieke,[81]
M. Rijpstra,[105] M. Rijssenbeek,[148] A. Rimoldi,[119a,119b] L. Rinaldi,[19a] R. R. Rios,[39] I. Riu,[11] G. Rivoltella,[89a,89b]
F. Rizatdinova,[112] E. Rizvi,[75] S. H. Robertson,[85,j] A. Robichaud-Veronneau,[49] D. Robinson,[27] J. E. M. Robinson,[77]
M. Robinson,[114] A. Robson,[53] J. G. Rocha de Lima,[106] C. Roda,[122a,122b] D. Roda Dos Santos,[29] S. Rodier,[80]
D. Rodriguez,[162] Y. Rodriguez Garcia,[15] A. Roe,[54] S. Roe,[29] O. Røhne,[117] V. Rojo,[1] S. Rolli,[161] A. Romaniouk,[96]
V. M. Romanov,[65] G. Romeo,[26] D. Romero Maltrana,[31a] L. Roos,[78] E. Ros,[167] S. Rosati,[138] M. Rose,[76]
G. A. Rosenbaum,[158] E. I. Rosenberg,[64] P. L. Rosendahl,[13] L. Rosselet,[49] V. Rossetti,[11] E. Rossi,[102a,102b]
L. P. Rossi,[50a] L. Rossi,[89a,89b] M. Rotaru,[25a] I. Roth,[171] J. Rothberg,[138] I. Rottländer,[20] D. Rousseau,[115]
C. R. Royon,[136] A. Rozanov,[83] Y. Rozen,[152] X. Ruan,[115] I. Rubinskiy,[41] B. Ruckert,[98] N. Ruckstuhl,[105] V. I. Rud,[97]
G. Rudolph,[62] F. Rühr,[6] F. Ruggieri,[134a,134b] A. Ruiz-Martinez,[64] E. Rulikowska-Zarebska,[37] V. Rumiantsev,[91,a]
L. Rumyantsev,[65] K. Runge,[48] O. Runolfsson,[20] Z. Rurikova,[48] N. A. Rusakovich,[65] D. R. Rust,[61] J. P. Rutherfoord,[6]
C. Ruwiedel,[14] P. Ruzicka,[125] Y. F. Ryabov,[121] V. Ryadovikov,[128] P. Ryan,[88] M. Rybar,[126] G. Rybkin,[115]
N. C. Ryder,[118] S. Rzaeva,[10] A. F. Saavedra,[150] I. Sadeh,[153] H.F-W. Sadrozinski,[137] R. Sadykov,[65]
F. Safai Tehrani,[132a,132b] H. Sakamoto,[155] G. Salamanna,[105] A. Salamon,[133a] M. Saleem,[111] D. Salihagic,[99]
A. Salnikov,[143] J. Salt,[167] B. M. Salvachua Ferrando,[5] D. Salvatore,[36a,36b] F. Salvatore,[149] A. Salzburger,[29]
D. Sampsonidis,[154] B. H. Samset,[117] H. Sandaker,[13] H. G. Sander,[81] M. P. Sanders,[98] M. Sandhoff,[174] P. Sandhu,[158]
T. Sandoval,[27] R. Sandstroem,[105] S. Sandvoss,[174] D. P. C. Sankey,[129] A. Sansoni,[47] C. Santamarina Rios,[85]
C. Santoni,[33] R. Santonico,[133a,133b] H. Santos,[124a] J. G. Saraiva,[124a,c] T. Sarangi,[172] E. Sarkisyan-Grinbaum,[7]
F. Sarri,[122a,122b] G. Sartisohn,[174] O. Sasaki,[66] T. Sasaki,[66] N. Sasao,[68] I. Satsounkevitch,[90] G. Sauvage,[4]
J. B. Sauvan,[115] P. Savard,[158,e] V. Savinov,[123] D. O. Savu,[29] P. Savva,[9] L. Sawyer,[24,k] D. H. Saxon,[53] L. P. Says,[33]
C. Sbarra,[19a,19b] A. Sbrizzi,[19a,19b] O. Scallon,[93] D. A. Scannicchio,[163] J. Schaarschmidt,[115] P. Schacht,[99]
U. Schäfer,[81] S. Schaetzel,[58b] A. C. Schaffer,[115] D. Schaile,[98] R. D. Schamberger,[148] A. G. Schamov,[107] V. Scharf,[58a]
V. A. Schegelsky,[121] D. Scheirich,[87] M. I. Scherzer,[14] C. Schiavi,[50a,50b] J. Schieck,[98] M. Schioppa,[36a,36b]
S. Schlenker,[29] J. L. Schlereth,[5] E. Schmidt,[48] M. P. Schmidt,[175,a] K. Schmieden,[20] C. Schmitt,[81] M. Schmitz,[20]
A. Schöning,[58b] M. Schott,[29] D. Schouten,[142] J. Schovancova,[125] M. Schram,[85] C. Schroeder,[81] N. Schroer,[58c]
S. Schuh,[29] G. Schuler,[29] J. Schultes,[174] H.-C. Schultz-Coulon,[58a] H. Schulz,[15] J. W. Schumacher,[20]
M. Schumacher,[48] B. A. Schumm,[137] Ph. Schune,[136] C. Schwanenberger,[82] A. Schwartzman,[143] Ph. Schwemling,[78]
R. Schwienhorst,[88] R. Schwierz,[43] J. Schwindling,[136] W. G. Scott,[129] J. Searcy,[114] E. Sedykh,[121] E. Segura,[11]
S. C. Seidel,[103] A. Seiden,[137] F. Seifert,[43] J. M. Seixas,[23a] G. Sekhniaidze,[102a] D. M. Seliverstov,[121] B. Sellden,[146a]
G. Sellers,[73] M. Seman,[144b] N. Semprini-Cesari,[19a,19b] C. Serfon,[98] L. Serin,[115] R. Seuster,[99] H. Severini,[111]
M. E. Sevior,[86] A. Sfyrla,[29] E. Shabalina,[54] M. Shamim,[114] L. Y. Shan,[32a] J. T. Shank,[21] Q. T. Shao,[86] M. Shapiro,[14]
P. B. Shatalov,[95] L. Shaver,[6] C. Shaw,[53] K. Shaw,[164a,164c] D. Sherman,[175] P. Sherwood,[77] A. Shibata,[108] S. Shimizu,[29]
M. Shimojima,[100] T. Shin,[56] A. Shmeleva,[94] M. J. Shochet,[30] D. Short,[118] M. A. Shupe,[6] P. Sicho,[125]

A. Sidoti,[132a,132b] A. Siebel,[174] F. Siegert,[48] J. Siegrist,[14] Dj. Sijacki,[12a] O. Silbert,[171] J. Silva,[124a,c] Y. Silver,[153]
D. Silverstein,[143] S. B. Silverstein,[146a] V. Simak,[127] O. Simard,[136] Lj. Simic,[12a] S. Simion,[115] B. Simmons,[77]
M. Simonyan,[35] P. Sinervo,[158] N. B. Sinev,[114] V. Sipica,[141] G. Siragusa,[81] A. N. Sisakyan,[65] S.Yu. Sivoklokov,[97]
J. Sjölin,[146a,146b] T. B. Sjursen,[13] L. A. Skinnari,[14] K. Skovpen,[107] P. Skubic,[111] N. Skvorodnev,[22] M. Slater,[17]
T. Slavicek,[127] K. Sliwa,[161] T. J. Sloan,[71] J. Sloper,[29] V. Smakhtin,[171] S.Yu. Smirnov,[96] L. N. Smirnova,[97]
O. Smirnova,[79] B. C. Smith,[57] D. Smith,[143] K. M. Smith,[53] M. Smizanska,[71] K. Smolek,[127] A. A. Snesarev,[94]
S. W. Snow,[82] J. Snow,[111] J. Snuverink,[105] S. Snyder,[24] M. Soares,[124a] R. Sobie,[169,j] J. Sodomka,[127] A. Soffer,[153]
C. A. Solans,[167] M. Solar,[127] J. Solc,[127] E. Soldatov,[96] U. Soldevila,[167] E. Solfaroli Camillocci,[132a,132b]
A. A. Solodkov,[128] O. V. Solovyanov,[128] J. Sondericker,[24] N. Soni,[2] V. Sopko,[127] B. Sopko,[127] M. Sorbi,[89a,89b]
M. Sosebee,[7] A. Soukharev,[107] S. Spagnolo,[72a,72b] F. Spanò,[34] R. Spighi,[19a] G. Spigo,[29] F. Spila,[132a,132b]
E. Spiriti,[134a] R. Spiwoks,[29] M. Spousta,[126] T. Spreitzer,[158] B. Spurlock,[7] R. D. St. Denis,[53] T. Stahl,[141]
J. Stahlman,[120] R. Stamen,[58a] E. Stanecka,[29] R. W. Stanek,[5] C. Stanescu,[134a] S. Stapnes,[117] E. A. Starchenko,[128]
J. Stark,[55] P. Staroba,[125] P. Starovoitov,[91] A. Staude,[98] P. Stavina,[144a] G. Stavropoulos,[14] G. Steele,[53] P. Steinbach,[43]
P. Steinberg,[24] I. Stekl,[127] B. Stelzer,[142] H. J. Stelzer,[41] O. Stelzer-Chilton,[159a] H. Stenzel,[52] K. Stevenson,[75]
G. A. Stewart,[53] J. A. Stillings,[20] T. Stockmanns,[20] M. C. Stockton,[29] K. Stoerig,[48] G. Stoicea,[25a] S. Stonjek,[99]
P. Strachota,[126] A. R. Stradling,[7] A. Straessner,[43] J. Strandberg,[87] S. Strandberg,[146a,146b] A. Strandlie,[117]
M. Strang,[109] E. Strauss,[143] M. Strauss,[111] P. Strizenec,[144b] R. Ströhmer,[173] D. M. Strom,[114] J. A. Strong,[76,a]
R. Stroynowski,[39] J. Strube,[129] B. Stugu,[13] I. Stumer,[24,a] J. Stupak,[148] P. Sturm,[174] D. A. Soh,[151,p] D. Su,[143]
HS. Subramania,[2] Y. Sugaya,[116] T. Sugimoto,[101] C. Suhr,[106] K. Suita,[67] M. Suk,[126] V. V. Sulin,[94] S. Sultansoy,[3d]
T. Sumida,[29] X. Sun,[55] J. E. Sundermann,[48] K. Suruliz,[164a,164b] S. Sushkov,[11] G. Susinno,[36a,36b] M. R. Sutton,[139]
Y. Suzuki,[66] Yu.M. Sviridov,[128] S. Swedish,[168] I. Sykora,[144a] T. Sykora,[126] B. Szeless,[29] J. Sánchez,[167] D. Ta,[105]
K. Tackmann,[29] A. Taffard,[163] R. Tafirout,[159a] A. Taga,[117] N. Taiblum,[153] Y. Takahashi,[101] H. Takai,[24]
R. Takashima,[69] H. Takeda,[67] T. Takeshita,[140] M. Talby,[83] A. Talyshev,[107] M. C. Tamsett,[24] J. Tanaka,[155]
R. Tanaka,[115] S. Tanaka,[131] S. Tanaka,[66] Y. Tanaka,[100] K. Tani,[67] N. Tannoury,[83] G. P. Tappern,[29] S. Tapprogge,[81]
D. Tardif,[158] S. Tarem,[152] F. Tarrade,[24] G. F. Tartarelli,[89a] P. Tas,[126] M. Tasevsky,[125] E. Tassi,[36a,36b] M. Tatarkhanov,[14]
C. Taylor,[77] F. E. Taylor,[92] G. N. Taylor,[86] W. Taylor,[159b] M. Teixeira Dias Castanheira,[75] P. Teixeira-Dias,[76]
K. K. Temming,[48] H. Ten Kate,[29] P. K. Teng,[151] Y. D. Tennenbaum-Katan,[152] S. Terada,[66] K. Terashi,[155] J. Terron,[80]
M. Terwort,[41,n] M. Testa,[47] R. J. Teuscher,[158,j] C. M. Tevlin,[82] J. Thadome,[174] J. Therhaag,[20] T. Theveneaux-Pelzer,[78]
M. Thioye,[175] S. Thoma,[48] J. P. Thomas,[17] E. N. Thompson,[84] P. D. Thompson,[17] P. D. Thompson,[158]
A. S. Thompson,[53] E. Thomson,[120] M. Thomson,[27] R. P. Thun,[87] T. Tic,[125] V. O. Tikhomirov,[94] Y. A. Tikhonov,[107]
C.J.W.P. Timmermans,[104] P. Tipton,[175] F. J. Tique Aires Viegas,[29] S. Tisserant,[83] J. Tobias,[48] B. Toczek,[37]
T. Todorov,[4] S. Todorova-Nova,[161] B. Toggerson,[163] J. Tojo,[66] S. Tokár,[144a] K. Tokunaga,[67] K. Tokushuku,[66]
K. Tollefson,[88] M. Tomoto,[101] L. Tompkins,[14] K. Toms,[103] A. Tonazzo,[134a,134b] G. Tong,[32a] A. Tonoyan,[13]
C. Topfel,[16] N. D. Topilin,[65] I. Torchiani,[29] E. Torrence,[114] E. Torró Pastor,[167] J. Toth,[83,x] F. Touchard,[83]
D. R. Tovey,[139] D. Traynor,[75] T. Trefzger,[173] J. Treis,[20] L. Tremblet,[29] A. Tricoli,[29] I. M. Trigger,[159a]
S. Trincaz-Duvoid,[78] T. N. Trinh,[78] M. F. Tripiana,[70] N. Triplett,[64] W. Trischuk,[158] A. Trivedi,[24,w] B. Trocmé,[55]
C. Troncon,[89a] M. Trottier-McDonald,[142] A. Trzupek,[38] C. Tsarouchas,[29] J.C-L. Tseng,[118] M. Tsiakiris,[105]
P. V. Tsiareshka,[90] D. Tsionou,[4] G. Tsipolitis,[9] V. Tsiskaridze,[48] E. G. Tskhadadze,[51] I. I. Tsukerman,[95] V. Tsulaia,[123]
J.-W. Tsung,[20] S. Tsuno,[66] D. Tsybychev,[148] A. Tua,[139] J. M. Tuggle,[30] M. Turala,[38] D. Turecek,[127] I. Turk Cakir,[3e]
E. Turlay,[105] P. M. Tuts,[34] A. Tykhonov,[74] M. Tylmad,[146a,146b] M. Tyndel,[129] D. Typaldos,[17] H. Tyrvainen,[29]
G. Tzanakos,[8] K. Uchida,[20] I. Ueda,[155] R. Ueno,[28] M. Ugland,[13] M. Uhlenbrock,[20] M. Uhrmacher,[54] F. Ukegawa,[160]
G. Unal,[29] D. G. Underwood,[5] A. Undrus,[24] G. Unel,[163] Y. Unno,[66] D. Urbaniec,[34] E. Urkovsky,[153] P. Urquijo,[49]
P. Urrejola,[31a] G. Usai,[7] M. Uslenghi,[119a,119b] L. Vacavant,[83] V. Vacek,[127] B. Vachon,[85] S. Vahsen,[14] C. Valderanis,[99]
J. Valenta,[125] P. Valente,[132a] S. Valentinetti,[19a,19b] S. Valkar,[126] E. Valladolid Gallego,[167] S. Vallecorsa,[152]
J. A. Valls Ferrer,[167] H. van der Graaf,[105] E. van der Kraaij,[105] R. Van Der Leeuw,[105] E. van der Poel,[105]
D. van der Ster,[29] B. Van Eijk,[105] N. van Eldik,[84] P. van Gemmeren,[5] Z. van Kesteren,[105] I. van Vulpen,[105]
W. Vandelli,[29] G. Vandoni,[29] A. Vaniachine,[5] P. Vankov,[41] F. Vannucci,[78] F. Varela Rodriguez,[29] R. Vari,[132a]
E. W. Varnes,[6] D. Varouchas,[14] A. Vartapetian,[7] K. E. Varvell,[150] V. I. Vassilakopoulos,[56] F. Vazeille,[33]
G. Vegni,[89a,89b] J. J. Veillet,[115] C. Vellidis,[8] F. Veloso,[124a] R. Veness,[29] S. Veneziano,[132a] A. Ventura,[72a,72b]
D. Ventura,[138] M. Venturi,[48] N. Venturi,[16] V. Vercesi,[119a] M. Verducci,[138] W. Verkerke,[105] J. C. Vermeulen,[105]
A. Vest,[43] M. C. Vetterli,[142,e] I. Vichou,[165] T. Vickey,[145b,z] G. H. A. Viehhauser,[118] S. Viel,[168] M. Villa,[19a,19b]

M. Villaplana Perez,[167] E. Vilucchi,[47] M. G. Vincter,[28] E. Vinek,[29] V. B. Vinogradov,[65] M. Virchaux,[136,a] S. Viret,[33]
J. Virzi,[14] A. Vitale,[19a,19b] O. Vitells,[171] M. Viti,[41] I. Vivarelli,[48] F. Vives Vaque,[11] S. Vlachos,[9] M. Vlasak,[127]
N. Vlasov,[20] A. Vogel,[20] P. Vokac,[127] M. Volpi,[11] G. Volpini,[89a] H. von der Schmitt,[99] J. von Loeben,[99]
H. von Radziewski,[48] E. von Toerne,[20] V. Vorobel,[126] A. P. Vorobiev,[128] V. Vorwerk,[11] M. Vos,[167] R. Voss,[29]
T. T. Voss,[174] J. H. Vossebeld,[73] A. S. Vovenko,[128] N. Vranjes,[12a] M. Vranjes Milosavljevic,[12a] V. Vrba,[125]
M. Vreeswijk,[105] T. Vu Anh,[81] R. Vuillermet,[29] I. Vukotic,[115] W. Wagner,[174] P. Wagner,[120] H. Wahlen,[174]
J. Wakabayashi,[101] J. Walbersloh,[42] S. Walch,[87] J. Walder,[71] R. Walker,[98] W. Walkowiak,[141] R. Wall,[175] P. Waller,[73]
C. Wang,[44] H. Wang,[172] J. Wang,[151] J. Wang,[32d] J. C. Wang,[138] R. Wang,[103] S. M. Wang,[151] A. Warburton,[85]
C. P. Ward,[27] M. Warsinsky,[48] P. M. Watkins,[17] A. T. Watson,[17] M. F. Watson,[17] G. Watts,[138] S. Watts,[82]
A. T. Waugh,[150] B. M. Waugh,[77] J. Weber,[42] M. Weber,[129] M. S. Weber,[16] P. Weber,[54] A. R. Weidberg,[118]
P. Weigell,[99] J. Weingarten,[54] C. Weiser,[48] H. Wellenstein,[22] P. S. Wells,[29] M. Wen,[47] T. Wenaus,[24] S. Wendler,[123]
Z. Weng,[151,p] T. Wengler,[29] S. Wenig,[29] N. Wermes,[20] M. Werner,[48] P. Werner,[29] M. Werth,[163] M. Wessels,[58a]
K. Whalen,[28] S. J. Wheeler-Ellis,[163] S. P. Whitaker,[21] A. White,[7] M. J. White,[86] S. White,[24] S. R. Whitehead,[118]
D. Whiteson,[163] D. Whittington,[61] F. Wicek,[115] D. Wicke,[174] F. J. Wickens,[129] W. Wiedenmann,[172] M. Wielers,[129]
P. Wienemann,[20] C. Wiglesworth,[73] L. A. M. Wiik,[48] P. A. Wijeratne,[77] A. Wildauer,[167] M. A. Wildt,[41,n]
I. Wilhelm,[126] H. G. Wilkens,[29] J. Z. Will,[98] E. Williams,[34] H. H. Williams,[120] W. Willis,[34] S. Willocq,[84]
J. A. Wilson,[17] M. G. Wilson,[143] A. Wilson,[87] I. Wingerter-Seez,[4] S. Winkelmann,[48] F. Winklmeier,[29] M. Wittgen,[143]
M. W. Wolter,[38] H. Wolters,[124a,h] G. Wooden,[118] B. K. Wosiek,[38] J. Wotschack,[29] M. J. Woudstra,[84] K. Wraight,[53]
C. Wright,[53] B. Wrona,[73] S. L. Wu,[172] X. Wu,[49] Y. Wu,[32b] E. Wulf,[34] R. Wunstorf,[42] B. M. Wynne,[45] L. Xaplanteris,[9]
S. Xella,[35] S. Xie,[48] Y. Xie,[32a] C. Xu,[32b] D. Xu,[139] G. Xu,[32a] B. Yabsley,[150] M. Yamada,[66] A. Yamamoto,[66]
K. Yamamoto,[64] S. Yamamoto,[155] T. Yamamura,[155] J. Yamaoka,[44] T. Yamazaki,[155] Y. Yamazaki,[67] Z. Yan,[21]
H. Yang,[87] U. K. Yang,[82] Y. Yang,[61] Y. Yang,[32a] Z. Yang,[146a,146b] S. Yanush,[91] W-M. Yao,[14] Y. Yao,[14] Y. Yasu,[66]
G. V. Ybeles Smit,[130] J. Ye,[39] S. Ye,[24] M. Yilmaz,[3c] R. Yoosoofmiya,[123] K. Yorita,[170] R. Yoshida,[5] C. Young,[143]
S. Youssef,[21] D. Yu,[24] J. Yu,[7] J. Yu,[32c,aa] L. Yuan,[32a,bb] A. Yurkewicz,[148] V. G. Zaets,[128] R. Zaidan,[63] A. M. Zaitsev,[128]
Z. Zajacova,[29] Yo.K. Zalite,[121] L. Zanello,[132a,132b] P. Zarzhitsky,[39] A. Zaytsev,[107] C. Zeitnitz,[174] M. Zeller,[175]
P. F. Zema,[29] A. Zemla,[38] C. Zendler,[20] A. V. Zenin,[128] O. Zenin,[128] T. Ženiš,[144a] Z. Zenonos,[122a,122b] S. Zenz,[14]
D. Zerwas,[115] G. Zevi della Porta,[57] Z. Zhan,[32d] D. Zhang,[32b] H. Zhang,[88] J. Zhang,[5] X. Zhang,[32d] Z. Zhang,[115]
L. Zhao,[108] T. Zhao,[138] Z. Zhao,[32b] A. Zhemchugov,[65] S. Zheng,[32a] J. Zhong,[151,cc] B. Zhou,[87] N. Zhou,[163]
Y. Zhou,[151] C. G. Zhu,[32d] H. Zhu,[41] Y. Zhu,[172] X. Zhuang,[98] V. Zhuravlov,[99] D. Zieminska,[61] B. Zilka,[144a]
R. Zimmermann,[20] S. Zimmermann,[20] S. Zimmermann,[48] M. Ziolkowski,[141] R. Zitoun,[4] L. Živković,[34]
V. V. Zmouchko,[128,a] G. Zobernig,[172] A. Zoccoli,[19a,19b] Y. Zolnierowski,[4] A. Zsenei,[29] M. zur Nedden,[15]
V. Zutshi,[106] and L. Zwalinski[29]

(ATLAS Collaboration)

[1]*University at Albany, Albany, New York, USA*
[2]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[3a]*Department of Physics, Ankara University, Ankara, Turkey*
[3b]*Department of Physics, Dumlupinar University, Kutahya, Turkey*
[3c]*Department of Physics, Gazi University, Ankara, Turkey*
[3d]*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
[3e]*Turkish Atomic Energy Authority, Ankara, Turkey*
[4]*LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France*
[5]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*
[6]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[7]*Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA*
[8]*Physics Department, University of Athens, Athens, Greece*
[9]*Physics Department, National Technical University of Athens, Zografou, Greece*
[10]*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
[11]*Institut de Física d'Altes Energies and Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain*
[12a]*Institute of Physics, University of Belgrade, Belgrade, Serbia*
[12b]*Vinca Institute of Nuclear Sciences, Belgrade, Serbia*
[13]*Department for Physics and Technology, University of Bergen, Bergen, Norway*
[14]*Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA*

[15]*Department of Physics, Humboldt University, Berlin, Germany*
[16]*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[17]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[18a]*Department of Physics, Bogazici University, Istanbul, Turkey*
[18b]*Division of Physics, Dogus University, Istanbul, Turkey*
[18c]*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
[18d]*Department of Physics, Istanbul Technical University, Istanbul, Turkey*
[19a]*INFN Sezione di Bologna, Italy*
[19b]*Dipartimento di Fisica, Università di Bologna, Bologna, Italy*
[20]*Physikalisches Institut, University of Bonn, Bonn, Germany*
[21]*Department of Physics, Boston University, Boston, Massachusetts, USA*
[22]*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
[23a]*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
[23b]*Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil*
[24]*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
[25a]*National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[25b]*University Politehnica Bucharest, Bucharest, Romania*
[25c]*West University in Timisoara, Timisoara, Romania*
[26]*Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
[27]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[28]*Department of Physics, Carleton University, Ottawa, Ontario, Canada*
[29]*CERN, Geneva, Switzerland*
[30]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
[31a]*Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago, Chile*
[31b]*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[32a]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
[32b]*Department of Modern Physics, University of Science and Technology of China, Anhui, China*
[32c]*Department of Physics, Nanjing University, Jiangsu, China*
[32d]*High Energy Physics Group, Shandong University, Shandong, China*
[33]*Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France*
[34]*Nevis Laboratory, Columbia University, Irvington, New York, USA*
[35]*Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark*
[36a]*INFN Gruppo Collegato di Cosenza, Italy*
[36b]*Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy*
[37]*Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland*
[38]*The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland*
[39]*Physics Department, Southern Methodist University, Dallas, Texas, USA*
[40]*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
[41]*DESY, Hamburg and Zeuthen, Germany*
[42]*Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
[43]*Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany*
[44]*Department of Physics, Duke University, Durham, North Carolina, USA*
[45]*SUPA–School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[46]*Fachhochschule Wiener Neustadt, Wiener Neustadt, Austria*
[47]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[48]*Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany*
[49]*Section de Physique, Université de Genève, Geneva, Switzerland*
[50a]*INFN Sezione di Genova, Italy*
[50b]*Dipartimento di Fisica, Università di Genova, Genova, Italy*
[51]*Institute of Physics and HEP Institute, Georgian Academy of Sciences and Tbilisi State University, Tbilisi, Georgia*
[52]*II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
[53]*SUPA–School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[54]*II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany*
[55]*Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France*
[56]*Department of Physics, Hampton University, Hampton, Virginia, USA*
[57]*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*
[58a]*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[58b]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[58c]*ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany*

[59]*Faculty of Science, Hiroshima University, Hiroshima, Japan*
[60]*Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
[61]*Department of Physics, Indiana University, Bloomington, Indiana, USA*
[62]*Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
[63]*University of Iowa, Iowa City, Iowa, USA*
[64]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
[65]*Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia*
[66]*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
[67]*Graduate School of Science, Kobe University, Kobe, Japan*
[68]*Faculty of Science, Kyoto University, Kyoto, Japan*
[69]*Kyoto University of Education, Kyoto, 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*
[72a]*INFN Sezione di Lecce, Italy*
[72b]*Dipartimento di 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]*Department of Physics, Queen Mary University of London, London, United Kingdom*
[76]*Department of Physics, Royal Holloway University of London, Surrey, United Kingdom*
[77]*Department of Physics and Astronomy, University College London, London, United Kingdom*
[78]*Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*
[79]*Fysiska institutionen, Lunds universitet, Lund, Sweden*
[80]*Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain*
[81]*Institut für Physik, Universität Mainz, Mainz, Germany*
[82]*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[83]*CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France*
[84]*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
[85]*Department of Physics, McGill University, Montreal, Quebec, Canada*
[86]*School of Physics, University of Melbourne, Victoria, Australia*
[87]*Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA*
[88]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
[89a]*INFN Sezione di Milano, Italy*
[89b]*Dipartimento di Fisica, Università di Milano, Milano, Italy*
[90]*B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus*
[91]*National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus*
[92]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[93]*Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada*
[94]*P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia*
[95]*Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
[96]*Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia*
[97]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
[98]*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
[99]*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
[100]*Nagasaki Institute of Applied Science, Nagasaki, Japan*
[101]*Graduate School of Science, Nagoya University, Nagoya, Japan*
[102a]*INFN Sezione di Napoli, Italy*
[102b]*Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy*
[103]*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
[104]*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, The Netherlands*
[105]*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, The Netherlands*
[106]*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
[107]*Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia*
[108]*Department of Physics, New York University, New York, New York, USA*
[109]*The Ohio State University, Columbus, Ohio, USA*
[110]*Faculty of Science, Okayama University, Okayama, Japan*
[111]*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
[112]*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
[113]*Palacký University, RCPTM, Olomouc, Czech Republic*
[114]*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
[115]*LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France*
[116]*Graduate School of Science, Osaka University, Osaka, Japan*

[117]*Department of Physics, University of Oslo, Oslo, Norway*
[118]*Department of Physics, Oxford University, Oxford, United Kingdom*
[119a]*INFN Sezione di Pavia, Italy*
[119b]*Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy*
[120]*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
[121]*Petersburg Nuclear Physics Institute, Gatchina, Russia*
[122a]*INFN Sezione di Pisa, Italy*
[122b]*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
[123]*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
[124a]*Laboratorio de Instrumentacao e Fisica Experimental de Particulas–LIP, Lisboa, Portugal*
[124b]*Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Portugal*
[125]*Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
[126]*Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic*
[127]*Czech Technical University in Prague, Praha, Czech Republic*
[128]*State Research Center Institute for High Energy Physics, Protvino, Russia*
[129]*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
[130]*Physics Department, University of Regina, Regina, Saskatchewan, Canada*
[131]*Ritsumeikan University, Kusatsu, Shiga, Japan*
[132a]*INFN Sezione di Roma I, Italy*
[132b]*Dipartimento di Fisica, Università La Sapienza, Roma, Italy*
[133a]*INFN Sezione di Roma Tor Vergata, Italy*
[133b]*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
[134a]*INFN Sezione di Roma Tre, Italy*
[134b]*Dipartimento di Fisica, Università Roma Tre, Roma, Italy*
[135a]*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies–Université Hassan II, Casablanca, Morocco*
[135b]*Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat, Morocco*
[135c]*Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000, Morocco*
[135d]*Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco*
[135e]*Faculté des Sciences, Université Mohammed V, Rabat, Morocco*
[136]*DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France*
[137]*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
[138]*Department of Physics, University of Washington, Seattle, Washington, USA*
[139]*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
[140]*Department of Physics, Shinshu University, Nagano, Japan*
[141]*Fachbereich Physik, Universität Siegen, Siegen, Germany*
[142]*Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada*
[143]*SLAC National Accelerator Laboratory, Stanford, California, USA*
[144a]*Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic*
[144b]*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
[145a]*Department of Physics, University of Johannesburg, Johannesburg, South Africa*
[145b]*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
[146a]*Department of Physics, Stockholm University, Sweden*
[146b]*The Oskar Klein Centre, Stockholm, Sweden*
[147]*Physics Department, Royal Institute of Technology, Stockholm, Sweden*
[148]*Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA*
[149]*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
[150]*School of Physics, University of Sydney, Sydney, Australia*
[151]*Institute of Physics, Academia Sinica, Taipei, Taiwan*
[152]*Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel*
[153]*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
[154]*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[155]*International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan*
[156]*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
[157]*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
[158]*Department of Physics, University of Toronto, Toronto, Ontario, Canada*
[159a]*TRIUMF, Vancouver, British Columbia, Canada*
[159b]*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
[160]*Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan*
[161]*Science and Technology Center, Tufts University, Medford, Massachusetts, USA*

[162]*Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*
[163]*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
[164a]*INFN Gruppo Collegato di Udine, Italy*
[164b]*ICTP, Trieste, Italy*
[164c]*Dipartimento di Fisica, Università di Udine, Udine, Italy*
[165]*Department of Physics, University of Illinois, Urbana, Illinois, USA*
[166]*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
[167]*Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingenierá Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain*
[168]*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
[169]*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*
[170]*Waseda University, Tokyo, Japan*
[171]*Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*
[172]*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
[173]*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*
[174]*Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
[175]*Department of Physics, Yale University, New Haven, Connecticut, USA*
[176]*Yerevan Physics Institute, Yerevan, Armenia*
[177]*Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France*
[178]*Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal*
[179]*Department of Physics, University of Coimbra, Coimbra, Portugal*
[180]*Institute of Particle Physics (IPP), Canada*
[181]*Università di Napoli Parthenope, Napoli, Italy*
[182]*California Institute of Technology, Pasadena, California, USA*
[183]*Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany*
[184]*Manhattan College, New York, New York, USA*
[185]*Departamento de Fisica, Universidade de Minho, Braga, Portugal*
[186]*School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China*
[187]*KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary*
[188]*Institute of Physics, Jagiellonian University, Krakow, Poland*
[189]*Department of Physics, California State University, Fresno, California, USA*
[190]*Louisiana Tech University, Ruston, Louisiana, USA*
[191]*Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan*
[192]*Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina, USA*

[a] Deceased.

[b] Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas–LIP, Lisboa, Portugal.

[c] Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.

[d] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

[e] Also at TRIUMF, Vancouver BC, Canada.

[f] Also at Department of Physics, California State University, Fresno, CA, USA.

[g] Also at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland.

[h] Also at Department of Physics, University of Coimbra, Coimbra, Portugal.

[i] Also at Università di Napoli Parthenope, Napoli, Italy.

[j] Also at Institute of Particle Physics (IPP), Canada.

[k] Also at Louisiana Tech University, Ruston, LA, USA.

[l] Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.

[m] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

[n] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

[o] Also at Manhattan College, New York, NY, USA.

[p] Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.

[q] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

[r] Also at High Energy Physics Group, Shandong University, Shandong, China.

[s] Also at California Institute of Technology, Pasadena, CA, USA.

[t] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

[u] Also at Section de Physique, Université de Genève, Geneva, Switzerland.

[v] Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.

[w] Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
[x] Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
[y] Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
[z] Also at Department of Physics, Oxford University, Oxford, United Kingdom.
[aa] Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France.
[bb] Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
[cc] Also at Department of Physics, Nanjing University, Jiangsu, China.