Search for magnetic monopoles in sqrt(s) = 7 TeV pp collisions with the ATLAS detector

G. Aad, S. Albrand, Q. Buat, B. Clement, J. Collot, S. Crépé-Renaudin, B. Dechenaux, T. Delemontex, P.A. Delsart, M.H. Genest, et al.

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Abstract

This Letter presents a search for magnetic monopoles with the ATLAS detector at the CERN Large Hadron Collider using an integrated luminosity of 2.0 fb^{-1} of pp collisions recorded at a center-of-mass energy of $\sqrt{s} = 7$ TeV. No event is found in the signal region, leading to an upper limit on the production cross section at 95% confidence level of $1.6/\epsilon$ fb for Dirac magnetic monopoles with the minimum unit magnetic charge and with mass between 200 GeV and 1500 GeV, where ϵ is the monopole reconstruction efficiency. The efficiency ϵ is high and uniform in the fiducial region given by pseudorapidity $|\eta| < 1.37$ and transverse kinetic energy $600–700 < E^{\rm kin} \sin\theta < 1400$ GeV. The minimum value of 700 GeV is for monopoles of mass 200 GeV, whereas the minimum value of 600 GeV is applicable for higher mass monopoles. Therefore, the upper limit on the production cross section at 95% confidence level is 2 fb in this fiducial region. Assuming the kinematic distributions from Drell-Yan pair production of spin-1/2 Dirac magnetic monopoles, the efficiency is in the range 1%–10%, leading to an upper limit on the cross section at 95% confidence level that varies from 145 fb to 16 fb for monopoles with mass between 200 GeV and 1200 GeV. This limit is weaker than the fiducial limit because most of these monopoles lie outside the fiducial region.

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Magnetic monopoles have long been the subject of dedicated search efforts for three main reasons: their introduction into the theory of electromagnetism would restore the symmetry between electricity and magnetism in Maxwell's equations; their existence would explain the quantization of electric charge [1]; and they appear in many grand unified theories [2]. However, to date no experimental evidence of a magnetically charged object exists.

Recent searches for magnetic monopoles from astrophysical sources [3–9] are complemented by searches at colliders [10–14]. This Letter describes a search for magnetic monopoles in proton–proton collisions recorded at a center-of-mass energy of $\sqrt{s} = 7$ TeV using the ATLAS detector at the CERN Large Hadron Collider (LHC).

The Dirac quantization condition [1], given in Gaussian units, leads to a prediction for the minimum unit magnetic charge g:

$$\frac{ge}{\hbar c} = \frac{1}{2} \Rightarrow \frac{g}{e} = \frac{1}{2\alpha_e} \approx 68.5, \tag{1}$$

where e is the unit electric charge and α_e is the fine structure constant. With the introduction of a magnetic monopole, the duality of Maxwell's equations implies a magnetic coupling [15]

$$\alpha_m = \frac{(g\beta)^2}{\hbar c} = \frac{1}{4\alpha_e}\beta^2, \tag{2}$$

where $\beta = v/c$ is the monopole velocity. For relativistic monopoles, α_m is very large, precluding any perturbative calculation of monopole production processes. Therefore, the main result of this analysis is a fiducial cross-section limit for Dirac monopoles of magnetic charge g derived without assuming a particular production mechanism. A cross-section limit assuming the kinematic distributions from Drell-Yan monopole pair production is also provided.

Monopoles are highly ionizing particles, interacting with matter like an ion of electric charge $68.5e$, according to Eq. 1. The high stopping power of the monopole ionization [16] results in the production of a large number of δ-rays. These energetic "knock-on" electrons emitted from the material carry away energy from the monopole trajectory and further ionize the medium. In the mass and energy regime of this study, the δ-rays have kinetic energies ranging from 1 MeV to a maximum of ~ 100 MeV. The secondary ionization by these δ-rays represents a significant fraction of the ionization energy loss of the magnetic monopole [16]. The dominant energy loss mechanism for magnetic monopoles in the mass and energy range considered herein is ionization [16–18]. Furthermore, the monopole ionization is independent of the monopole speed β to first order, in contrast to the ionization of electrically charged particles.

In the ATLAS detector [19, 20], the monopole signature can be easily distinguished using the transition radiation tracker (TRT) in the inner detector and the liquid argon (LAr) sampling electromagnetic (EM) calorimeter. The TRT is a straw-tube tracker that comprises a barrel ($|\eta| < 1.0$) with 4 mm diameter straws oriented parallel to the beam-line, and two endcaps ($0.8 < |\eta| < 2.0$) with straws orientated radially. A minimum ionizing particle deposits ~ 2 keV of energy in a TRT straw. Energy deposits in a TRT straw greater than 200 eV (called "low-threshold hits") are used for tracking, while those that exceed 6 keV (called "high-threshold hits") typically occur due to the transition radiation emitted by highly relativistic electrons when they penetrate the radiator layers between the straws. As a result, an electron of energy 5 GeV or above has a 20% probability of producing a high-threshold hit in any straw it traverses. The high-threshold hits can also indicate the presence of a highly ionizing particle. A 2 T superconducting solenoid magnet surrounds the inner detector. The LAr barrel EM calorimeter lies outside the solenoid in the $|\eta| < 1.5$ region. It is divided into three shower-depth layers and comprises accordion-shaped electrodes and lead absorbers. The cell granularity in the second layer is $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$. The characteristic signature of magnetic monopoles in ATLAS is a large localized energy deposit in the LAr EM calorimeter (EM cluster) in conjunction with a region of high ionization density in the TRT. A search for particles with large electric charge, which yield a similar signature, was performed previously [21] and production cross-section limits for such particles were set [22].

The trajectory of an electrically neutral magnetic monopole in the inner detector is straight in the r–ϕ plane and curved in r–z. The behavior of magnetic monopoles in the ATLAS detector is described by a GEANT4 [23] simulation [24], which includes the equations of motion, the ionization, the δ-ray production and a modified Birks' Law [25] to model recombination effects in LAr due to highly ionizing particles [26]. Equation 5.5 in Ref. [16] gives the δ-ray production cross section and Eq. 5.7 describes the derivation of the magnetic monopole ionization; both equations are implemented in GEANT4.

Simulated Monte Carlo (MC) single-monopole samples are used to determine the efficiency as a function of the transverse kinetic energy $E_{\mathrm{T}}^{\mathrm{kin}} = E^{\mathrm{kin}} \sin\theta$ and pseudorapidity η for various monopole masses. For the Drell-Yan process, it is assumed that spin-1/2 magnetic monopoles are produced in pairs from the initial pp state via quark-antiquark annihilation into a virtual photon. MadGraph [27] is used to model this process by assuming leading-order Drell-Yan heavy lepton pair production but making the replacement $e \to g\beta$ to reflect the magnetic coupling in Eq. 2. In the absence of a consistent theory describing the coupling of the monopole to the Z boson, such a coupling is set to zero in the MadGraph model. In the Drell-Yan samples, the CTEQ6L1 [28] parton distribution functions are used and PYTHIA version 6.425 [29] is used for the hadronization and the underlying event. Only Drell-Yan monopoles with transverse momentum $p_{\mathrm{T}} > 200$ GeV are processed by the simulation since lower p_{T} monopoles fail to reach the calorimeter. For all the simulated samples, both the monopoles and the antimonopoles are assumed to be stable and all final-state particles are processed by the simulation of the ATLAS detector. Additional pp collisions in each event are simulated according to the distribution of pp interactions per bunch crossing in the selected data period.

A simple algorithm is used to preselect events with monopole candidates for further study. Monopoles with $E_{\mathrm{T}}^{\mathrm{kin}}$ above approximately 500 GeV traverse the inner detector and penetrate to the LAr calorimeter, depositing most of their energy there. Only one third of the deposited energy is recorded due to the recombination effects in LAr [26]. Lacking a dedicated monopole trigger, only events collected with a single-electron trigger with transverse energy threshold $E_{\mathrm{T}} > 60$ GeV are considered. This trigger requires a track in the inner detector within $|\Delta\eta| < 0.01$ and $|\Delta\phi| < 0.02$ of the LAr energy deposit. Monopoles that fulfill the 60 GeV energy requirement travel fast enough to satisfy the tracking and timing requirements of the trigger. Very high energy monopoles (i.e., those with $E_{\mathrm{T}}^{\mathrm{kin}} \gtrsim$ 1400–1900 GeV, where the value of 1400 GeV is for monopoles of mass 1500 GeV and the value of 1900 GeV is for monopoles of mass 200 GeV) exit the EM calorimeter and are rejected by a veto on hadronic energy that is intrinsic to the single-electron trigger. This trigger was operational during the first six months of 2011 data-taking and recorded an integrated luminosity of 2.0 fb^{-1}, defining the dataset used for this search.

The reconstructed EM cluster is then required to have $E_{\mathrm{T}} > 65$ GeV and $|\eta| < 1.37$. The trigger efficiency is independent of E_T for $E_{\mathrm{T}} > 65$ GeV, motivating the former requirement. The η requirement ensures that the EM cluster is in the barrel region of the LAr calorimeter, where the two-dimensional spatial resolution is uniform. If two or more EM clusters in an event satisfy these criteria, only the cluster with the highest energy is considered as a monopole candidate.

In the barrel region, the monopole typically traverses 35 TRT straws and its high ionization ensures that most of these register high-threshold hits. Furthermore, as each δ-ray produced by the monopole ionization deposits ~ 2 keV in a straw, the combined energy deposited by multiple δ-rays crossing a single TRT straw gives rise to additional high-threshold hits. The large number of δ-rays bend in the 2 T magnetic field in the r–ϕ plane; therefore, the monopole trajectory appears as a $\sim$1-cm-wide swath of high-threshold TRT hits. The fraction of TRT hits that exceed the high threshold in the vicinity of the path of an ionizing particle is therefore a powerful discriminator between the monopole signal and the background. The ϕ position of the EM cluster is used to define a road of width $\Delta\phi = \pm 0.05$ rad from the beamline to the cluster. At least twenty high-threshold TRT hits must be present in the road. In addition, at least 20% of the TRT hits in the road must be high-threshold hits.

After the preselection, a more refined TRT hit counting algorithm is used to distinguish the signal from the backgrounds. A histogram with a bin width of 0.8 mrad is filled with the ϕ distribution of the high-threshold hits in the previously defined road. The location of the highest bin is used to calculate the center of a new road. In the TRT barrel, a rectangular road of ± 4 mm in the r–ϕ plane is used and the hits are counted. In the TRT endcap, a wedge-shaped road of width $\Delta\phi = \pm 0.006$ rad is used. These roads are wide enough to encompass two neighboring straws, taking into account the monopole trajectory and the associated δ-rays, but sufficiently narrow to ensure that the fraction of hits that exceed the high threshold, $f_{\rm HT}$, is insensitive to the presence of neighboring tracks. In the barrel region, the number of hits in the road is required to be greater than 54. An η-dependent requirement on the number of hits in the road is applied in the endcap and barrel–endcap transition region to account for the TRT geometry.

Energy loss by bremsstrahlung and e^+e^- pair production is negligible for magnetic monopoles in the mass and energy range considered herein. Therefore, magnetic monopoles give rise to a narrow ionization energy deposit in the LAr calorimeter, the size of which provides another powerful discriminator of the monopole signal from backgrounds such as electrons and photons, which induce an EM shower via bremsstrahlung and e^+e^- pair production. The variable used is $\sigma_{\rm R}$, the energy-weighted two-dimensional η–ϕ cluster dispersion in the second layer of the EM calorimeter, which has the highest two-dimensional spatial resolution. The dispersion $\sigma_{\rm R}$ is calculated from the energies deposited in a 3×7 array of cells centered around the most energetic cell of the EM cluster: $\sigma_{\rm R} = \sqrt{\sigma_\phi^2 + \sigma_\eta^2}$, where $\sigma_\phi^2 = \Sigma\left(E_i \delta\phi_i^2\right)/\Sigma E_i - \left[\Sigma\left(E_i\delta\phi_i\right)/\Sigma E_i\right]^2$, $\delta\phi_i$ is the deviation in ϕ between cell i and the most energetic cell and E_i is the energy of cell i; σ_η^2 is defined similarly.

The high-threshold TRT hit fraction, $f_{\rm HT}$, and the cluster dispersion, $\sigma_{\rm R}$, are thus chosen as the distinguishing variables between the signal and background, and are shown in Fig. 1. The main physics background sources are high-energy electrons, photons and jets, which exhibit no correlation between these variables in simulated processes. The background and monopole MC samples are used to define an approximate signal region. Then ($\sigma_{\rm R}$, $f_{\rm HT}$) parameter pairs are generated by randomly sampling the one-dimensional $\sigma_{\rm R}$ and $f_{\rm HT}$ distributions for data outside this approximate signal region. The borders of the signal region are tuned for maximal significance of observation of three signal events by replacing the background MC events with these parameter pairs. The final signal region A is defined by $\sigma_{\rm R} \leq 0.017$ and $f_{\rm HT} > 0.7$.

The efficiencies, which include trigger, reconstruction and selection effects, in the two-dimensional $E_{\rm T}^{\rm kin}$ versus η plane are obtained from the simulated single-monopole samples. A fiducial region for each monopole mass is defined by the $E_{\rm T}^{\rm kin}$ range in which the efficiency is 0.80 or higher in the $|\eta| < 1.37$ region. Figure 2 shows the efficiency versus $E_{\rm T}^{\rm kin}$, averaged over $|\eta| < 1.37$. For monopoles with a mass of 200 GeV, the minimum transverse kinetic energy $(E_{\rm T}^{\rm kin})_{\rm min}$ where the efficiency rises above 0.80 is 700 GeV. For monopoles with a mass between 500 GeV and 1500 GeV, $(E_{\rm T}^{\rm kin})_{\rm min}$ is 600 GeV. Monopoles with lower $E_{\rm T}^{\rm kin}$ fail to penetrate to the EM calorimeter and therefore do not satisfy the trigger requirements. Monopoles with very high $E_{\rm T}^{\rm kin}$ exit the EM calorimeter and are rejected by the hadronic veto

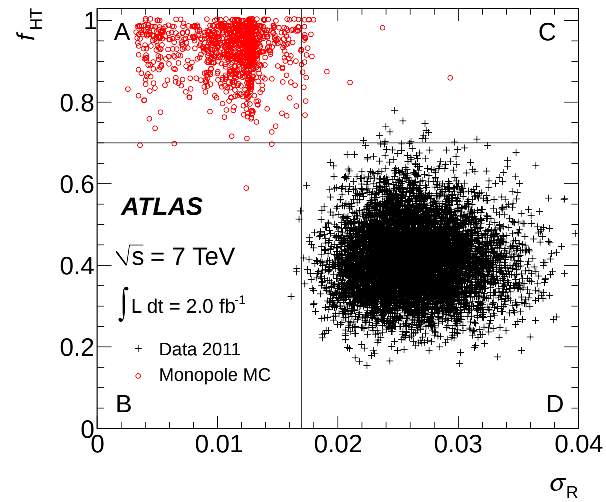

FIG. 1. High-threshold TRT hit fraction, $f_{\rm HT}$, versus EM cluster dispersion, $\sigma_{\rm R}$. The circles represent 1000 simulated single monopoles with mass 800 GeV. The crosses represent ATLAS data. The regions marked A-D are discussed in the text.

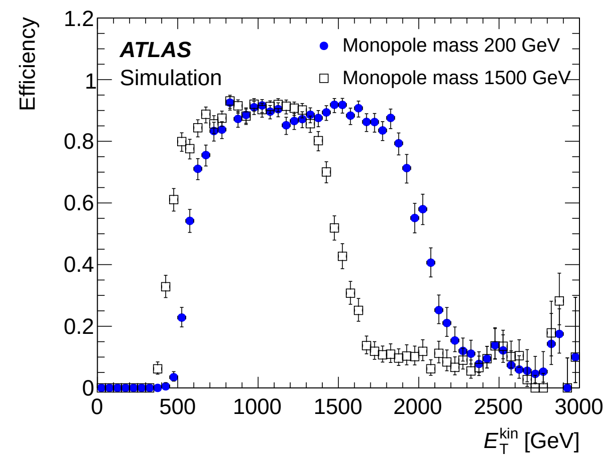

FIG. 2. Efficiency versus $E_{\rm T}^{\rm kin}$, averaged over $|\eta| < 1.37$, for single monopoles of mass 200 GeV and mass 1500 GeV.

of the electron trigger. A common upper value of $E_{\rm T}^{\rm kin} =$ 1400 GeV is used for the fiducial region of all monopole masses. As the minimum efficiency is 0.80 in the fiducial region, a common value of 0.80 is used in the determination of the upper cross-section limit.

The efficiencies can be under- or over-estimated for several reasons. These effects are described below and the relative systematic uncertainties for each effect are given. 1) Cross-talk in the second EM layer in the ϕ direction is not modeled in the simulation. The energy is reweighted assuming 1.8% cross-talk [30] and the cluster dispersion, $\sigma_{\rm R}$, recomputed. The efficiency is reduced and the resulting relative shift of -1.7% for single monopoles is taken as a one-sided uncertainty. 2) The simulation underestimates the TRT occupancy in the data by up to 20%; therefore, the number of low-threshold hits (those unlikely to come from the monopole or related δ-rays) is increased by 20%. The resulting relative uncertainty is -1.3%. 3) The modification to Birks' Law is varied between its upper and lower systematic uncertainties [26], yielding a relative uncertainty of $+1.8\%$ and $+1.5\%$, respectively. 4) The production of δ-rays is varied by 3% [16] and the resulting uncertainty is negligible. 5) The GEANT4 "range cut" [23] controls the minimum kinetic energy threshold below which δ-rays are not propagated explicitly. This parameter is reduced from 50 μm to 25 μm in the TRT simulation. The resulting relative uncertainty is $+0.14\%$. 6) The material in the inner detector, in the barrel cryostat and in between the cryostat and the first layer of the EM calorimeter is increased by 5%, 10% and 5%, respectively, in the simulation [31]. The resulting -0.74% relative uncertainty is taken as symmetric. Including an uncertainty of $\sim$1.7% to account for the limited number of MC events, the total upper and lower relative uncertainties on the efficiency for single monopoles are $+2.6\%$ and -2.8%, respectively.

The efficiencies to reconstruct at least one of the monopoles in the pairs produced with Drell-Yan kinematic distributions are given in Table I for each mass. Only masses up to 1200 GeV are considered, taking into account the phase space limitations for pair production. The total relative uncertainties, which reflect the same systematic variations described above, are also given. The efficiencies and their associated systematic uncertainties reflect large losses due to acceptance, since many Drell-Yan monopoles have insufficient energy to reach the calorimeter.

TABLE I. Efficiencies and their relative uncertainties in percent for Drell-Yan pair-produced monopoles of various masses.

Mass (GeV)	200	500	800	1000	1200
Efficiency	0.011	0.048	0.081	0.095	0.095
Relative uncertainty					
Upper (%)	+32	+24	+22	+23	+20
Lower (%)	−36	−23	−22	−25	−25

The background in the signal region is predicted directly from the data. The two-dimensional plane in Fig. 1 is divided into quadrants, one of which is dominated by signal (region A), and three others that are occupied mainly by background (regions B, C and D). The ratio of background events in signal region A to events in background region B is expected to be the same as the ratio of background events in regions C to D. This assumption is incorporated into a maximum likelihood fit to determine the estimated numbers of signal and background events in signal region A. The inputs to the fit include the observed event yields in quadrants A through D, which are 0, 5, 16 and 7001, respectively, the efficiencies and associated systematic uncertainties that have already been discussed, and the integrated luminosity and its 3.7% uncertainty [32]. For each monopole mass, the rate of appearance of signal events in quadrants B and C, as predicted by the simulation, is also taken into account. According to the simulation, no signal event appears in quadrant D for any monopole mass. The fit predicts 0.011 ± 0.007 background events in the signal region.

Using the results of the maximum likelihood fit, the upper limits on the production cross sections at 95% confidence level are calculated using the profile likelihood ratio as a test statistic [33]. The results are extracted using the CL_s method [34]. The cross section limits can be expressed as a function of the efficiency, ϵ, which is shown in Fig. 2 for single monopoles and given in Table I for Drell-Yan pair-produced monopoles. The upper limit on the production cross section at 95% confidence level is found to be $1.6/\epsilon$ fb for Dirac magnetic monopoles with the minimum unit magnetic charge and with mass between 200 GeV and 1500 GeV. Assuming the kinematic distributions from Drell-Yan pair production of spin-1/2 Dirac magnetic monopoles, this translates to an upper limit on the cross section at 95% confidence level that varies from 145 fb to 16 fb for monopoles with mass between 200 GeV and 1200 GeV, as shown in Fig. 3. Since the number of expected background events is very small and no event is observed in the signal region, only the observed limits are shown. To compare with previous experiments that have provided lower mass limits on spin-1/2 Dirac magnetic monopoles by assuming Drell-Yan pair production, such an approach would yield a lower mass limit of 862 GeV in the present search [35].

The monopole reconstruction efficiency is high and uniform in the fiducial region given by pseudorapidity $|\eta| < 1.37$ and transverse kinetic energy $(E_{\mathrm{T}}^{\mathrm{kin}})_{\mathrm{min}} < E^{\mathrm{kin}} \sin\theta < 1400$ GeV, where $(E_{\mathrm{T}}^{\mathrm{kin}})_{\mathrm{min}}$ is 600 GeV for monopoles with a mass between 500 GeV and 1500 GeV. For monopoles with a mass of 200 GeV, $(E_{\mathrm{T}}^{\mathrm{kin}})_{\mathrm{min}} =$ 700 GeV. Therefore, the upper limit on the production cross section at 95% confidence level is 2 fb, as shown in Fig. 3, for Dirac magnetic monopoles with the minimum unit magnetic charge and with mass between 200 GeV and 1500 GeV in this fiducial region. The fluctuations of the observed limit in the fiducial region originate from variations of the nuisance parameters used in the profile likelihood ratio.

These results extend the upper limits on the production cross section for monopoles in this mass region established by preceding experiments. This is the first direct collider search that yields cross-section constraints on magnetic monopoles with masses greater than 900 GeV.

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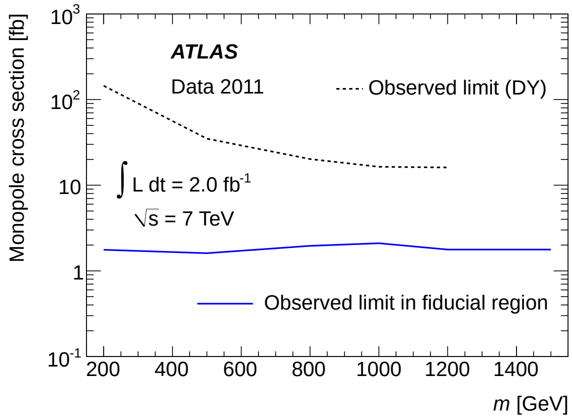

FIG. 3. Upper limits on the monopole production cross sections at 95% confidence level. The solid line is the limit for single monopoles in the fiducial region and the dashed line is the limit assuming the kinematic distributions from Drell-Yan (DY) monopole pair production.

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[35] Over the range of monopole masses from 200 GeV to 1200 GeV, the leading-order Drell-Yan production cross section drops from 10^5 fb to 1 fb, but has large theoretical uncertainties, due to the non-perturbative nature of the magnetic coupling.

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G. Aad[47], T. Abajyan[20], B. Abbott[110], J. Abdallah[11], S. Abdel Khalek[114], A.A. Abdelalim[48], O. Abdinov[10], R. Aben[104], B. Abi[111], M. Abolins[87], O.S. AbouZeid[157], H. Abramowicz[152], H. Abreu[135], E. Acerbi[88a,88b], B.S. Acharya[163a,163b], L. Adamczyk[37], D.L. Adams[24], T.N. Addy[55], J. Adelman[175], S. Adomeit[97], P. Adragna[74], T. Adye[128], S. Aefsky[22], J.A. Aguilar-Saavedra[123b,a], M. Agustoni[16], M. Aharrouche[80], S.P. Ahlen[21], F. Ahles[47], A. Ahmad[147], M. Ahsan[40], G. Aielli[132a,132b], T. Akdogan[18a], T.P.A. Åkesson[78], G. Akimoto[154], A.V. Akimov[93], M.S. Alam[1], M.A. Alam[75], J. Albert[168], S. Albrand[54], M. Aleksa[29], I.N. Aleksandrov[63], F. Alessandria[88a], C. Alexa[25a], G. Alexander[152], G. Alexandre[48], T. Alexopoulos[9], M. Alhroob[163a,163c], M. Aliev[15], G. Alimonti[88a], J. Alison[119], B.M.M. Allbrooke[17], P.P. Allport[72], S.E. Allwood-Spiers[52], J. Almond[81], A. Aloisio[101a,101b], R. Alon[171], A. Alonso[78], F. Alonso[69], B. Alvarez Gonzalez[87], M.G. Alviggi[101a,101b], K. Amako[64], C. Amelung[22], V.V. Ammosov[127,*], A. Amorim[123a,b], N. Amram[152], C. Anastopoulos[29], L.S. Ancu[16], N. Andari[114], T. Andeen[34], C.F. Anders[57b], G. Anders[57a], K.J. Anderson[30], A. Andreazza[88a,88b], V. Andrei[57a], X.S. Anduaga[69], P. Anger[43], A. Angerami[34], F. Anghinolfi[29], A. Anisenkov[106], N. Anjos[123a], A. Annovi[46], A. Antonaki[8], M. Antonelli[46], A. Antonov[95], J. Antos[143b], F. Anulli[131a], M. Aoki[100], S. Aoun[82], L. Aperio Bella[4], R. Apolle[117,c], G. Arabidze[87], I. Aracena[142], Y. Arai[64], A.T.H. Arce[44], S. Arfaoui[147], J-F. Arguin[14], E. Arik[18a,*], M. Arik[18a], A.J. Armbruster[86], O. Arnaez[80], V. Arnal[79], C. Arnault[114], A. Artamonov[94], G. Artoni[131a,131b], D. Arutinov[20], S. Asai[154], R. Asfandiyarov[172], S. Ask[27], B. Åsman[145a,145b], L. Asquith[5], K. Assamagan[24], A. Astbury[168], M. Atkinson[164], B. Aubert[4], E. Auge[114], K. Augsten[126], M. Aurousseau[144a], G. Avolio[162], R. Avramidou[9], D. Axen[167], G. Azuelos[92,d], Y. Azuma[154], M.A. Baak[29], G. Baccaglioni[88a], C. Bacci[133a,133b], A.M. Bach[14], H. Bachacou[135], K. Bachas[29], M. Backes[48], M. Backhaus[20], E. Badescu[25a], P. Bagnaia[131a,131b], S. Bahinipati[2], Y. Bai[32a], D.C. Bailey[157], T. Bain[157], J.T. Baines[128], O.K. Baker[175], M.D. Baker[24], S. Baker[76], E. Banas[38], P. Banerjee[92], Sw. Banerjee[172], D. Banfi[29], A. Bangert[149], V. Bansal[168], H.S. Bansil[17], L. Barak[171], S.P. Baranov[93], A. Barbaro Galtieri[14], T. Barber[47], E.L. Barberio[85], D. Barberis[49a,49b], M. Barbero[20], D.Y. Bardin[63], T. Barillari[98], M. Barisonzi[174], T. Barklow[142], N. Barlow[27], B.M. Barnett[128], R.M. Barnett[14], A. Baroncelli[133a], G. Barone[48], A.J. Barr[117], F. Barreiro[79], J. Barreiro Guimarães da Costa[56], P. Barrillon[114], R. Bartoldus[142], A.E. Barton[70], V. Bartsch[148], R.L. Bates[52], L. Batkova[143a], J.R. Batley[27], A. Battaglia[16], M. Battistin[29], F. Bauer[135], H.S. Bawa[142,e], S. Beale[97], T. Beau[77], P.H. Beauchemin[160], R. Beccherle[49a], P. Bechtle[20], H.P. Beck[16], A.K. Becker[174], S. Becker[97], M. Beckingham[137], K.H. Becks[174], A.J. Beddall[18c], A. Beddall[18c], S. Bedikian[175], V.A. Bednyakov[63], C.P. Bee[82], L.J. Beemster[104], M. Begel[24], S. Behar Harpaz[151], M. Beimforde[98], C. Belanger-Champagne[84], P.J. Bell[48], W.H. Bell[48], G. Bella[152], L. Bellagamba[19a], F. Bellina[29], M. Bellomo[29], A. Belloni[56], O. Beloborodova[106,f], K. Belotskiy[95], O. Beltramello[29], O. Benary[152], D. Benchekroun[134a], K. Bendtz[145a,145b], N. Benekos[164], Y. Benhammou[152], E. Benhar Noccioli[48], J.A. Benitez Garcia[158b], D.P. Benjamin[44], M. Benoit[114], J.R. Bensinger[22], K. Benslama[129], S. Bentvelsen[104], D. Berge[29], E. Bergeaas Kuutmann[41], N. Berger[4], F. Berghaus[168], E. Berglund[104], J. Beringer[14], P. Bernat[76], R. Bernhard[47], C. Bernius[24], T. Berry[75], C. Bertella[82], A. Bertin[19a,19b], F. Bertolucci[121a,121b], M.I. Besana[88a,88b], G.J. Besjes[103], N. Besson[135], S. Bethke[98], W. Bhimji[45], R.M. Bianchi[29], M. Bianco[71a,71b], O. Biebel[97], S.P. Bieniek[76], K. Bierwagen[53], J. Biesiada[14], M. Biglietti[133a], H. Bilokon[46], M. Bindi[19a,19b], S. Binet[114], A. Bingul[18c], C. Bini[131a,131b], C. Biscarat[177], U. Bitenc[47], K.M. Black[21], R.E. Blair[5], J.-B. Blanchard[135], G. Blanchot[29], T. Blazek[143a], C. Blocker[22], J. Blocki[38], A. Blondel[48], W. Blum[80], U. Blumenschein[53], G.J. Bobbink[104], V.B. Bobrovnikov[106], S.S. Bocchetta[78], A. Bocci[44], C.R. Boddy[117], M. Boehler[47], J. Boek[174], N. Boelaert[35], J.A. Bogaerts[29], A. Bogdanchikov[106], A. Bogouch[89,*], C. Bohm[145a], J. Bohm[124], V. Boisvert[75], T. Bold[37], V. Boldea[25a], N.M. Bolnet[135], M. Bomben[77], M. Bona[74], M. Boonekamp[135], C.N. Booth[138], S. Bordoni[77], C. Borer[16], A. Borisov[127], G. Borissov[70], I. Borjanovic[12a], M. Borri[81], S. Borroni[86], V. Bortolotto[133a,133b], K. Bos[104], D. Boscherini[19a], M. Bosman[11], H. Boterenbrood[104], J. Bouchami[92], J. Boudreau[122], E.V. Bouhova-Thacker[70], D. Boumediene[33], C. Bourdarios[114], N. Bousson[82], A. Boveia[30], J. Boyd[29], I.R. Boyko[63], I. Bozovic-Jelisavcic[12b], J. Bracinik[17], P. Branchini[133a], A. Brandt[7], G. Brandt[117], O. Brandt[53], U. Bratzler[155], B. Brau[83], J.E. Brau[113], H.M. Braun[174,*], S.F. Brazzale[163a,163c], B. Brelier[157], J. Bremer[29], K. Brendlinger[119], R. Brenner[165], S. Bressler[171], D. Britton[52], F.M. Brochu[27], I. Brock[20], R. Brock[87], F. Broggi[88a], C. Bromberg[87], J. Bronner[98], G. Brooijmans[34], T. Brooks[75], W.K. Brooks[31b], G. Brown[81], H. Brown[7], P.A. Bruckman de Renstrom[38], D. Bruncko[143b], R. Bruneliere[47], S. Brunet[59], A. Bruni[19a], G. Bruni[19a], M. Bruschi[19a], T. Buanes[13], Q. Buat[54], F. Bucci[48], J. Buchanan[117], P. Buchholz[140], R.M. Buckingham[117], A.G. Buckley[45], S.I. Buda[25a], I.A. Budagov[63], B. Budick[107], V. Büscher[80], L. Bugge[116], O. Bulekov[95], A.C. Bundock[72], M. Bunse[42], T. Buran[116], H. Burckhart[29], S. Burdin[72], T. Burgess[13], S. Burke[128], E. Busato[33], P. Bussey[52], C.P. Buszello[165], B. Butler[142], J.M. Butler[21], C.M. Buttar[52], J.M. Butterworth[76], W. Buttinger[27], S. Cabrera Urbán[166], D. Caforio[19a,19b], O. Cakir[3a], P. Calafiura[14], G. Calderini[77], P. Calfayan[97], R. Calkins[105], L.P. Caloba[23a], R. Caloi[131a,131b], D. Calvet[33], S. Calvet[33], R. Camacho Toro[33], P. Camarri[132a,132b], D. Cameron[116], L.M. Caminada[14], S. Campana[29], M. Campanelli[76], V. Canale[101a,101b], F. Canelli[30,g], A. Canepa[158a], J. Cantero[79], R. Cantrill[75], L. Capasso[101a,101b], M.D.M. Capeans Garrido[29], I. Caprini[25a], M. Caprini[25a], D. Capriotti[98], M. Capua[36a,36b], R. Caputo[80], R. Cardarelli[132a], T. Carli[29], G. Carlino[101a], L. Carminati[88a,88b], B. Caron[84], S. Caron[103], E. Carquin[31b], G.D. Carrillo Montoya[172], A.A. Carter[74], J.R. Carter[27], J. Carvalho[123a,h], D. Casadei[107], M.P. Casado[11], M. Cascella[121a,121b], C. Caso[49a,49b,*], A.M. Castaneda Hernandez[172,i], E. Castaneda-Miranda[172], V. Castillo Gimenez[166], N.F. Castro[123a], G. Cataldi[71a], P. Catastini[56], A. Catinaccio[29], J.R. Catmore[29], A. Cattai[29], G. Cattani[132a,132b], S. Caughron[87], V. Cavaliere[164], P. Cavalleri[77], D. Cavalli[88a], M. Cavalli-Sforza[11], V. Cavasinni[121a,121b], F. Ceradini[133a,133b], A.S. Cerqueira[23b], A. Cerri[29], L. Cerrito[74], F. Cerutti[46], S.A. Cetin[18b], A. Chafaq[134a], D. Chakraborty[105], I. Chalupkova[125], K. Chan[2], B. Chapleau[84], J.D. Chapman[27], J.W. Chapman[86], E. Chareyre[77], D.G. Charlton[17], V. Chavda[81], C.A. Chavez Barajas[29], S. Cheatham[84], S. Chekanov[5], S.V. Chekulaev[158a], G.A. Chelkov[63], M.A. Chelstowska[103], C. Chen[62], H. Chen[24], S. Chen[32c], X. Chen[172], Y. Chen[34], A. Cheplakov[63], R. Cherkaoui El Moursli[134e], V. Chernyatin[24], E. Cheu[6], S.L. Cheung[157], L. Chevalier[135], G. Chiefari[101a,101b], L. Chikovani[50a,*], J.T. Childers[29], A. Chilingarov[70], G. Chiodini[71a], A.S. Chisholm[17], R.T. Chislett[76], A. Chitan[25a], M.V. Chizhov[63], G. Choudalakis[30], S. Chouridou[136], I.A. Christidi[76], A. Christov[47], D. Chromek-Burckhart[29], M.L. Chu[150], J. Chudoba[124], G. Ciapetti[131a,131b], A.K. Ciftci[3a], R. Ciftci[3a], D. Cinca[33], V. Cindro[73], C. Ciocca[19a,19b], A. Ciocio[14], M. Cirilli[86], P. Cirkovic[12b], M. Citterio[88a], M. Ciubancan[25a], A. Clark[48], P.J. Clark[45], R.N. Clarke[14], W. Cleland[122], J.C. Clemens[82], B. Clement[54], C. Clement[145a,145b], Y. Coadou[82], M. Cobal[163a,163c], A. Coccaro[137], J. Cochran[62], J.G. Cogan[142], J. Coggeshall[164], E. Cogneras[177], J. Colas[4], S. Cole[105], A.P. Colijn[104], N.J. Collins[17], C. Collins-Tooth[52], J. Collot[54], T. Colombo[118a,118b], G. Colon[83], P. Conde Muiño[123a], E. Coniavitis[117], M.C. Conidi[11], S.M. Consonni[88a,88b], V. Consorti[47], S. Constantinescu[25a], C. Conta[118a,118b], G. Conti[56], F. Conventi[101a,j], M. Cooke[14], B.D. Cooper[76], A.M. Cooper-Sarkar[117], K. Copic[14], T. Cornelissen[174], M. Corradi[19a], F. Corriveau[84,k], A. Cortes-Gonzalez[164], G. Cortiana[98], G. Costa[88a], M.J. Costa[166], D. Costanzo[138], T. Costin[30], D. Côté[29], L. Courneyea[168], G. Cowan[75], C. Cowden[27], B.E. Cox[81], K. Cranmer[107], F. Crescioli[121a,121b], M. Cristinziani[20], G. Crosetti[36a,36b], S. Crépé-Renaudin[54], C.-M. Cuciuc[25a], C. Cuenca Almenar[175], T. Cuhadar Donszelmann[138], M. Curatolo[46], C.J. Curtis[17], C. Cuthbert[149], P. Cwetanski[59], H. Czirr[140], P. Czodrowski[43], Z. Czyczula[175], S. D'Auria[52], M. D'Onofrio[72], A. D'Orazio[131a,131b], M.J. Da Cunha Sargedas De Sousa[123a], C. Da Via[81], W. Dabrowski[37], A. Dafinca[117], T. Dai[86], C. Dallapiccola[83], M. Dam[35], M. Dameri[49a,49b], D.S. Damiani[136], H.O. Danielsson[29], V. Dao[48], G. Darbo[49a], G.L. Darlea[25b], J.A. Dassoulas[41], W. Davey[20], T. Davidek[125], N. Davidson[85], R. Davidson[70], E. Davies[117,c], M. Davies[92], O. Davignon[77], A.R. Davison[76], Y. Davygora[57a], E. Dawe[141], I. Dawson[138], R.K. Daya-Ishmukhametova[22], K. De[7], R. de Asmundis[101a], S. De Castro[19a,19b], S. De Cecco[77], J. de Graat[97], N. De Groot[103], P. de Jong[104], C. De La Taille[114], H. De la Torre[79], F. De Lorenzi[62], L. de Mora[70], L. De Nooij[104], D. De Pedis[131a], A. De Salvo[131a], U. De Sanctis[163a,163c], A. De Santo[148], J.B. De Vivie De Regie[114], G. De Zorzi[131a,131b], W.J. Dearnaley[70], R. Debbe[24], C. Debenedetti[45], B. Dechenaux[54], D.V. Dedovich[63], J. Degenhardt[119], C. Del Papa[163a,163c], J. Del Peso[79], T. Del Prete[121a,121b], T. Delemontex[54], M. Deliyergiyev[73], A. Dell'Acqua[29], L. Dell'Asta[21], M. Della Pietra[101a,j], D. della Volpe[101a,101b], M. Delmastro[4], P.A. Delsart[54], C. Deluca[104], S. Demers[175], M. Demichev[63], B. Demirkoz[11,l], J. Deng[162], S.P. Denisov[127], D. Derendarz[38], J.E. Derkaoui[134d], F. Derue[77], P. Dervan[72], K. Desch[20], E. Devetak[147], P.O. Deviveiros[104], A. Dewhurst[128], B. DeWilde[147], S. Dhaliwal[157], R. Dhullipudi[24,m], A. Di Ciaccio[132a,132b], L. Di Ciaccio[4], A. Di Girolamo[29], B. Di Girolamo[29], S. Di Luise[133a,133b], A. Di Mattia[172], B. Di Micco[29], R. Di Nardo[46], A. Di Simone[132a,132b], R. Di Sipio[19a,19b], M.A. Diaz[31a], E.B. Diehl[86], J. Dietrich[41], T.A. Dietzsch[57a], S. Diglio[85], K. Dindar Yagci[39], J. Dingfelder[20], F. Dinut[25a], C. Dionisi[131a,131b], P. Dita[25a], S. Dita[25a], F. Dittus[29], F. Djama[82], T. Djobava[50b], M.A.B. do Vale[23c], A. Do Valle Wemans[123a,n], T.K.O. Doan[4], M. Dobbs[84], R. Dobinson[29,*], D. Dobos[29], E. Dobson[29,o], J. Dodd[34], C. Doglioni[48], T. Doherty[52], Y. Doi[64,*], J. Dolejsi[125], I. Dolenc[73], Z. Dolezal[125], B.A. Dolgoshein[95,*], T. Dohmae[154], M. Donadelli[23d], J. Donini[33], J. Dopke[29], A. Doria[101a], A. Dos Anjos[172], A. Dotti[121a,121b], M.T. Dova[69], A.D. Doxiadis[104], A.T. Doyle[52], M. Dris[9], J. Dubbert[98], S. Dube[14], E. Duchovni[171], G. Duckeck[97], A. Dudarev[29], F. Dudziak[62], M. Dührssen[29], I.P. Duerdoth[81], L. Duflot[114], M-A. Dufour[84], L. Duguid[75], M. Dunford[29], H. Duran Yildiz[3a], R. Duxfield[138], M. Dwuznik[37], F. Dydak[29], M. Düren[51], J. Ebke[97], S. Eckweiler[80], K. Edmonds[80], W. Edson[1], C.A. Edwards[75], N.C. Edwards[52], W. Ehrenfeld[41], T. Eifert[142], G. Eigen[13], K. Einsweiler[14], E. Eisenhandler[74], T. Ekelof[165], M. El Kacimi[134c], M. Ellert[165], S. Elles[4], F. Ellinghaus[80], K. Ellis[74], N. Ellis[29], J. Elmsheuser[97], M. Elsing[29], D. Emeliyanov[128], R. Engelmann[147], A. Engl[97], B. Epp[60], J. Erdmann[53], A. Ereditato[16], D. Eriksson[145a], J. Ernst[1], M. Ernst[24], J. Ernwein[135], D. Errede[164], S. Errede[164], E. Ertel[80], M. Escalier[114], H. Esch[42], C. Escobar[122], X. Espinal Curull[11], B. Esposito[46], F. Etienne[82], A.I. Etienvre[135], E. Etzion[152], D. Evangelakou[53], H. Evans[59], L. Fabbri[19a,19b], C. Fabre[29], R.M. Fakhrutdinov[127], S. Falciano[131a], Y. Fang[172], M. Fanti[88a,88b], A. Farbin[7], A. Farilla[133a], J. Farley[147], T. Farooque[157], S. Farrell[162], S.M. Farrington[169], P. Farthouat[29], P. Fassnacht[29], D. Fassouliotis[8], B. Fatholahzadeh[157], A. Favareto[88a,88b], L. Fayard[114], S. Fazio[36a,36b], R. Febbraro[33], P. Federic[143a], O.L. Fedin[120], W. Fedorko[87], M. Fehling-Kaschek[47], L. Feligioni[82], D. Fellmann[5], C. Feng[32d], E.J. Feng[5], A.B. Fenyuk[127], J. Ferencei[143b], W. Fernando[5], S. Ferrag[52], J. Ferrando[52], V. Ferrara[41], A. Ferrari[165], P. Ferrari[104], R. Ferrari[118a], D.E. Ferreira de Lima[52], A. Ferrer[166], D. Ferrere[48], C. 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Troncon[88a], M. Trottier-McDonald[141], M. Trzebinski[38], A. Trzupek[38], C. Tsarouchas[29], J.C-L. Tseng[117], M. Tsiakiris[104], P.V. Tsiareshka[89], D. Tsionou[4,ai], G. Tsipolitis[9], S. Tsiskaridze[11], V. Tsiskaridze[47], E.G. Tskhadadze[50a], I.I. Tsukerman[94], V. Tsulaia[14], J.-W. Tsung[20], S. Tsuno[64], D. Tsybychev[147], A. Tua[138], A. Tudorache[25a], V. Tudorache[25a], J.M. Tuggle[30], M. Turala[38], D. Turecek[126], I. Turk Cakir[3e], E. Turlay[104], R. Turra[88a,88b], P.M. Tuts[34], A. Tykhonov[73], M. Tylmad[145a,145b], M. Tyndel[128], G. Tzanakos[8], K. Uchida[20], I. Ueda[154], R. Ueno[28], M. Ugland[13], M. Uhlenbrock[20], M. Uhrmacher[53], F. Ukegawa[159], G. Unal[29], A. Undrus[24], G. Unel[162], Y. Unno[64], D. Urbaniec[34], G. Usai[7], M. Uslenghi[118a,118b], L. Vacavant[82], V. Vacek[126], B. Vachon[84], S. Vahsen[14], J. Valenta[124], S. Valentinetti[19a,19b], A. Valero[166], S. Valkar[125], E. Valladolid Gallego[166], S. Vallecorsa[151], J.A. Valls Ferrer[166], P.C. Van Der Deijl[104], R. van der Geer[104], H. van der Graaf[104], R. Van Der Leeuw[104], E. van der Poel[104], D. van der Ster[29], N. van Eldik[29], P. van Gemmeren[5], I. van Vulpen[104], M. Vanadia[98], W. Vandelli[29], A. Vaniachine[5], P. Vankov[41], F. Vannucci[77], R. Vari[131a], T. Varol[83], D. Varouchas[14], A. Vartapetian[7], K.E. Varvell[149], V.I. Vassilakopoulos[55], F. Vazeille[33], T. Vazquez Schroeder[53], G. Vegni[88a,88b], J.J. Veillet[114], F. Veloso[123a], R. Veness[29], S. Veneziano[131a], A. Ventura[71a,71b], D. Ventura[83], M. Venturi[47], N. Venturi[157], V. Vercesi[118a], M. Verducci[137], W. Verkerke[104], J.C. Vermeulen[104], A. Vest[43], M.C. Vetterli[141,d], I. Vichou[164], T. Vickey[144b,aj], O.E. Vickey Boeriu[144b], G.H.A. Viehhauser[117], S. Viel[167], M. Villa[19a,19b], M. Villaplana Perez[166], E. Vilucchi[46], M.G. Vincter[28], E. Vinek[29], V.B. Vinogradov[63], M. Virchaux[135,*], J. Virzi[14], O. Vitells[171], M. Viti[41], I. Vivarelli[47], F. Vives Vaque[2], S. Vlachos[9], D. Vladoiu[97], M. Vlasak[126], A. Vogel[20], P. Vokac[126], G. Volpi[46], M. Volpi[85], G. Volpini[88a], H. von der Schmitt[98], H. von Radziewski[47], E. von Toerne[20], V. Vorobel[125], V. Vorwerk[11], M. Vos[166], R. Voss[29], T.T. Voss[174], J.H. Vossebeld[72], N. Vranjes[135], M. Vranjes Milosavljevic[104], V. Vrba[124], M. Vreeswijk[104], T. Vu Anh[47], R. Vuillermet[29], I. Vukotic[30], W. Wagner[174], P. Wagner[119], H. Wahlen[174], S. Wahrmund[43], J. Wakabayashi[100], S. Walch[86], J. Walder[70], R. Walker[97], W. Walkowiak[140], R. Wall[175], P. Waller[72], B. Walsh[175], C. Wang[44], H. Wang[172], H. Wang[32b,ak], J. Wang[150], J. Wang[54], R. Wang[102], S.M. Wang[150], T. Wang[20], A. Warburton[84], C.P. Ward[27], M. Warsinsky[47], A. Washbrook[45], C. Wasicki[41],

I. Watanabe[65], P.M. Watkins[17], A.T. Watson[17], I.J. Watson[149], M.F. Watson[17], G. Watts[137], S. Watts[81], A.T. Waugh[149], B.M. Waugh[76], M.S. Weber[16], P. Weber[53], A.R. Weidberg[117], P. Weigell[98], J. Weingarten[53], C. Weiser[47], H. Wellenstein[22], P.S. Wells[29], T. Wenaus[24], D. Wendland[15], Z. Weng[150,w], T. Wengler[29], S. Wenig[29], N. Wermes[20], M. Werner[47], P. Werner[29], M. Werth[162], M. Wessels[57a], J. Wetter[160], C. Weydert[54], K. Whalen[28], S.J. Wheeler-Ellis[162], A. White[7], M.J. White[85], S. White[121a,121b], S.R. Whitehead[117], D. Whiteson[162], D. Whittington[59], F. Wicek[114], D. Wicke[174], F.J. Wickens[128], W. Wiedenmann[172], M. Wielers[128], P. Wienemann[20], C. Wiglesworth[74], L.A.M. Wiik-Fuchs[47], P.A. Wijeratne[76], A. Wildauer[98], M.A. Wildt[41,s], I. Wilhelm[125], H.G. Wilkens[29], J.Z. Will[97], E. Williams[34], H.H. Williams[119], W. Willis[34], S. Willocq[83], J.A. Wilson[17], M.G. Wilson[142], A. Wilson[86], I. Wingerter-Seez[4], S. Winkelmann[47], F. Winklmeier[29], M. Wittgen[142], S.J. Wollstadt[80], M.W. Wolter[38], H. Wolters[123a,h], W.C. Wong[40], G. Wooden[86], B.K. Wosiek[38], J. Wotschack[29], M.J. Woudstra[81], K.W. Wozniak[38], K. Wraight[52], M. Wright[52], B. Wrona[72], S.L. Wu[172], X. Wu[48], Y. Wu[32b,al], E. Wulf[34], B.M. Wynne[45], S. Xella[35], M. Xiao[135], S. Xie[47], C. Xu[32b,z], D. Xu[138], B. Yabsley[149], S. Yacoob[144b], M. Yamada[64], H. Yamaguchi[154], A. Yamamoto[64], K. Yamamoto[62], S. Yamamoto[154], T. Yamamura[154], T. Yamanaka[154], J. Yamaoka[44], T. Yamazaki[154], Y. Yamazaki[65], Z. Yan[21], H. Yang[86], U.K. Yang[81], Y. Yang[59], Z. Yang[145a,145b], S. Yanush[90], L. Yao[32a], Y. Yao[14], Y. Yasu[64], G.V. Ybeles Smit[129], J. Ye[39], S. Ye[24], M. Yilmaz[3c], R. Yoosoofmiya[122], K. Yorita[170], R. Yoshida[5], C. Young[142], C.J. Young[117], S. Youssef[21], D. Yu[24], J. Yu[7], J. Yu[111], L. Yuan[65], A. Yurkewicz[105], M. Byszewski[29], B. Zabinski[38], R. Zaidan[61], A.M. Zaitsev[127], Z. Zajacova[29], L. Zanello[131a,131b], A. Zaytsev[106], C. Zeitnitz[174], M. Zeman[124], A. Zemla[38], C. Zendler[20], O. Zenin[127], T. Ženiš[143a], Z. Zinonos[121a,121b], S. Zenz[14], D. Zerwas[114], G. Zevi della Porta[56], Z. Zhan[32d], D. Zhang[32b,ak], H. Zhang[87], J. Zhang[5], X. Zhang[32d], Z. Zhang[114], L. Zhao[107], T. Zhao[137], Z. Zhao[32b], A. Zhemchugov[63], J. Zhong[117], B. Zhou[86], N. Zhou[162], Y. Zhou[150], C.G. Zhu[32d], H. Zhu[41], J. Zhu[86], Y. Zhu[32b], X. Zhuang[97], V. Zhuravlov[98], D. Zieminska[59], N.I. Zimin[63], R. Zimmermann[20], S. Zimmermann[20], S. Zimmermann[47], M. Ziolkowski[140], R. Zitoun[4], L. Živković[34], V.V. Zmouchko[127,*], G. Zobernig[172], A. Zoccoli[19a,19b], M. zur Nedden[15], V. Zutshi[105], L. Zwalinski[29].

[1] Physics Department, SUNY Albany, Albany NY, United States of America
[2] Department of Physics, University of Alberta, Edmonton AB, Canada
[3] [(a)]Department of Physics, Ankara University, Ankara; [(b)]Department of Physics, Dumlupinar University, Kutahya; [(c)]Department of Physics, Gazi University, Ankara; [(d)]Division of Physics, TOBB University of Economics and Technology, Ankara; [(e)]Turkish Atomic Energy Authority, Ankara, Turkey
[4] LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
[5] High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
[6] Department of Physics, University of Arizona, Tucson AZ, United States of America
[7] Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
[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 Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
[12] [(a)]Institute of Physics, University of Belgrade, Belgrade; [(b)]Vinca Institute of Nuclear Sciences, University of Belgrade, 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 CA, United States of America
[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
[18] [(a)]Department of Physics, Bogazici University, Istanbul; [(b)]Division of Physics, Dogus University, Istanbul; [(c)]Department of Physics Engineering, Gaziantep University, Gaziantep; [(d)]Department of Physics, Istanbul Technical University, Istanbul, Turkey
[19] [(a)]INFN Sezione di Bologna; [(b)]Dipartimento di Fisica, Università di Bologna, Bologna, Italy
[20] Physikalisches Institut, University of Bonn, Bonn, Germany
[21] Department of Physics, Boston University, Boston MA, United States of America
[22] Department of Physics, Brandeis University, Waltham MA, United States of America
[23] [(a)]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; [(b)]Federal University of Juiz de Fora (UFJF), Juiz de Fora; [(c)]Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; [(d)]Instituto de Fisica,

Universidade de Sao Paulo, Sao Paulo, Brazil
[24] Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
[25] [(a)]National Institute of Physics and Nuclear Engineering, Bucharest; [(b)]University Politehnica Bucharest, Bucharest; [(c)]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 ON, Canada
[29] CERN, Geneva, Switzerland
[30] Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
[31] [(a)]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; [(b)]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[32] [(a)]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; [(b)]Department of Modern Physics, University of Science and Technology of China, Anhui; [(c)]Department of Physics, Nanjing University, Jiangsu; [(d)]School of Physics, Shandong University, Shandong, China
[33] Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
[34] Nevis Laboratory, Columbia University, Irvington NY, United States of America
[35] Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
[36] [(a)]INFN Gruppo Collegato di Cosenza; [(b)]Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
[37] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
[38] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
[39] Physics Department, Southern Methodist University, Dallas TX, United States of America
[40] Physics Department, University of Texas at Dallas, Richardson TX, United States of America
[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 NC, United States of America
[45] SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[46] INFN Laboratori Nazionali di Frascati, Frascati, Italy
[47] Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
[48] Section de Physique, Université de Genève, Geneva, Switzerland
[49] [(a)]INFN Sezione di Genova; [(b)]Dipartimento di Fisica, Università di Genova, Genova, Italy
[50] [(a)]E. Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; [(b)]High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[51] II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[52] SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[53] II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
[54] Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
[55] Department of Physics, Hampton University, Hampton VA, United States of America
[56] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
[57] [(a)]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(c)]ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
[58] Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[59] Department of Physics, Indiana University, Bloomington IN, United States of America
[60] Institut für Astro-und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[61] University of Iowa, Iowa City IA, United States of America
[62] Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
[63] Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
[64] KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[65] Graduate School of Science, Kobe University, Kobe, Japan
[66] Faculty of Science, Kyoto University, Kyoto, Japan
[67] Kyoto University of Education, Kyoto, Japan
[68] Department of Physics, Kyushu University, Fukuoka, Japan

[69] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[70] Physics Department, Lancaster University, Lancaster, United Kingdom
[71] [(a)]INFN Sezione di Lecce; [(b)]Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[72] Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[73] Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
[74] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[75] Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
[76] Department of Physics and Astronomy, University College London, London, United Kingdom
[77] Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[78] Fysiska institutionen, Lunds universitet, Lund, Sweden
[79] Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
[80] Institut für Physik, Universität Mainz, Mainz, Germany
[81] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[82] CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[83] Department of Physics, University of Massachusetts, Amherst MA, United States of America
[84] Department of Physics, McGill University, Montreal QC, Canada
[85] School of Physics, University of Melbourne, Victoria, Australia
[86] Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
[87] Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
[88] [(a)]INFN Sezione di Milano; [(b)]Dipartimento di Fisica, Università di Milano, Milano, Italy
[89] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
[90] National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
[91] Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
[92] Group of Particle Physics, University of Montreal, Montreal QC, Canada
[93] P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
[94] Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
[95] Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
[96] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
[97] Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[98] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[99] Nagasaki Institute of Applied Science, Nagasaki, Japan
[100] Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[101] [(a)]INFN Sezione di Napoli; [(b)]Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
[102] Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
[103] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
[104] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[105] Department of Physics, Northern Illinois University, DeKalb IL, United States of America
[106] Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
[107] Department of Physics, New York University, New York NY, United States of America
[108] Ohio State University, Columbus OH, United States of America
[109] Faculty of Science, Okayama University, Okayama, Japan
[110] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
[111] Department of Physics, Oklahoma State University, Stillwater OK, United States of America
[112] Palacký University, RCPTM, Olomouc, Czech Republic
[113] Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
[114] LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[115] Graduate School of Science, Osaka University, Osaka, Japan
[116] Department of Physics, University of Oslo, Oslo, Norway
[117] Department of Physics, Oxford University, Oxford, United Kingdom
[118] [(a)]INFN Sezione di Pavia; [(b)]Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[119] Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
[120] Petersburg Nuclear Physics Institute, Gatchina, Russia
[121] [(a)]INFN Sezione di Pisa; [(b)]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

[122] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
[123] [(a)]Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; [(b)]Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
[124] Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
[125] Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
[126] Czech Technical University in Prague, Praha, Czech Republic
[127] State Research Center Institute for High Energy Physics, Protvino, Russia
[128] Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[129] Physics Department, University of Regina, Regina SK, Canada
[130] Ritsumeikan University, Kusatsu, Shiga, Japan
[131] [(a)]INFN Sezione di Roma I; [(b)]Dipartimento di Fisica, Università La Sapienza, Roma, Italy
[132] [(a)]INFN Sezione di Roma Tor Vergata; [(b)]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[133] [(a)]INFN Sezione di Roma Tre; [(b)]Dipartimento di Fisica, Università Roma Tre, Roma, Italy
[134] [(a)]Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; [(b)]Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; [(c)]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; [(d)]Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; [(e)]Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
[135] DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
[136] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
[137] Department of Physics, University of Washington, Seattle WA, United States of America
[138] Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[139] Department of Physics, Shinshu University, Nagano, Japan
[140] Fachbereich Physik, Universität Siegen, Siegen, Germany
[141] Department of Physics, Simon Fraser University, Burnaby BC, Canada
[142] SLAC National Accelerator Laboratory, Stanford CA, United States of America
[143] [(a)]Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; [(b)]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[144] [(a)]Department of Physics, University of Johannesburg, Johannesburg; [(b)]School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[145] [(a)]Department of Physics, Stockholm University; [(b)]The Oskar Klein Centre, Stockholm, Sweden
[146] Physics Department, Royal Institute of Technology, Stockholm, Sweden
[147] Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
[148] Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[149] School of Physics, University of Sydney, Sydney, Australia
[150] Institute of Physics, Academia Sinica, Taipei, Taiwan
[151] Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
[152] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[153] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[154] International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
[155] Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[156] Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[157] Department of Physics, University of Toronto, Toronto ON, Canada
[158] [(a)]TRIUMF, Vancouver BC; [(b)]Department of Physics and Astronomy, York University, Toronto ON, Canada
[159] Institute of Pure and Applied Sciences, University of Tsukuba,1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan
[160] Science and Technology Center, Tufts University, Medford MA, United States of America
[161] Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[162] Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
[163] [(a)]INFN Gruppo Collegato di Udine; [(b)]ICTP, Trieste; [(c)]Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
[164] Department of Physics, University of Illinois, Urbana IL, United States of America
[165] Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[166] Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and

Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
[167] Department of Physics, University of British Columbia, Vancouver BC, Canada
[168] Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
[169] Department of Physics, University of Warwick, Coventry, United Kingdom
[170] Waseda University, Tokyo, Japan
[171] Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[172] Department of Physics, University of Wisconsin, Madison WI, United States of America
[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 CT, United States of America
[176] Yerevan Physics Institute, Yerevan, Armenia
[177] Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France
[a] Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
[b] Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
[c] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[d] Also at TRIUMF, Vancouver BC, Canada
[e] Also at Department of Physics, California State University, Fresno CA, United States of America
[f] Also at Novosibirsk State University, Novosibirsk, Russia
[g] Also at Fermilab, Batavia IL, United States of America
[h] Also at Department of Physics, University of Coimbra, Coimbra, Portugal
[i] Also at Department of Physics, UASLP, San Luis Potosi, Mexico
[j] Also at Università di Napoli Parthenope, Napoli, Italy
[k] Also at Institute of Particle Physics (IPP), Canada
[l] Also at Department of Physics, Middle East Technical University, Ankara, Turkey
[m] Also at Louisiana Tech University, Ruston LA, United States of America
[n] Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
[o] Also at Department of Physics and Astronomy, University College London, London, United Kingdom
[p] Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada
[q] Also at Department of Physics, University of Cape Town, Cape Town, South Africa
[r] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[s] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
[t] Also at Manhattan College, New York NY, United States of America
[u] Also at School of Physics, Shandong University, Shandong, China
[v] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[w] Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
[x] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
[y] Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy
[z] Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
[aa] Also at Section de Physique, Université de Genève, Geneva, Switzerland
[ab] Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal
[ac] Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
[ad] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
[ae] Also at California Institute of Technology, Pasadena CA, United States of America
[af] Also at Institute of Physics, Jagiellonian University, Krakow, Poland
[ag] Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[ah] Also at Nevis Laboratory, Columbia University, Irvington NY, United States of America
[ai] Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[aj] Also at Department of Physics, Oxford University, Oxford, United Kingdom
[ak] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
[al] Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
* Deceased