

Observation of an Excited $B_c^{\pm}$ Meson State with the ATLAS Detector

G. Aad, S. Abdel Khalek, A. Bassalat, C. Becot, S. Binet, C. Bourdarios, D. Charfeddine, J.B. de Vivie de Regie, L. Duflot, M. Escalier, et al.

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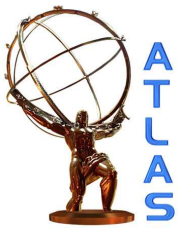
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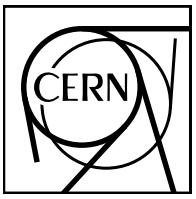


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The ATLAS Collaboration

Abstract

A search for excited states of the $B_c^{\pm}$ meson is performed using 4.9 fb^{-1} of 7 TeV and 19.2 fb^{-1} of 8 TeV pp collision data collected by the ATLAS experiment at the LHC. A new state is observed through its hadronic transition to the ground state, with the latter detected in the decay $B_c^{\pm} \to J/\psi\pi^{\pm}$. The state appears in the $m(B_c^{\pm}\pi^{+}\pi^{-}) - m(B_c^{\pm}) - 2m(\pi^{\pm})$ mass difference distribution with a significance of 5.2 standard deviations. The mass of the observed state is $6842 \pm 4 \pm 5$ MeV, where the first error is statistical and the second is systematic. The mass and decay of this state are consistent with expectations for the second S-wave state of the $B_c^{\pm}$ meson, $B_c^{\pm}(2S)$.

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A search for excited states of the $B_c^\pm$ meson is performed using 4.9 fb^{-1} of 7 TeV and 19.2 fb^{-1} of 8 TeV pp collision data collected by the ATLAS experiment at the LHC. A new state is observed through its hadronic transition to the ground state, with the latter detected in the decay $B_c^\pm \to J/\psi\pi^\pm$. The state appears in the $m(B_c^\pm\pi^+\pi^-) - m(B_c^\pm) - 2m(\pi^\pm)$ mass difference distribution with a significance of 5.2 standard deviations. The mass of the observed state is $6842 \pm 4 \pm 5$ MeV, where the first error is statistical and the second is systematic. The mass and decay of this state are consistent with expectations for the second S-wave state of the $B_c^\pm$ meson, $B_c^\pm(2S)$.

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The $B_c^\pm$ meson was first observed by the CDF experiment in the semileptonic decay mode [1], and its hadronic decay mode was observed later by both CDF [2] and D0 [3] experiments. The $B_c^\pm$ meson has also been observed by the LHCb experiment in various decay modes [4]. Excited states of the $B_c^\pm$ meson have not previously been observed. The spectrum and properties of the $B_c^\pm$ family are predicted by non-relativistic potential models, perturbative QCD, and lattice calculations [5]. Measurements of the ground and excited states through fully reconstructed channels will provide tests of the predictions of these models and ultimately the opportunity to extract information on the strong interaction potential.

The second S-wave state, $B_c^\pm(2S)$, is predicted to have a mass in the range 6835–6917 MeV [5]. The next S-wave state, $B_c^\pm(3S)$, is predicted to have a mass above the threshold for decay into a BD meson pair. Both the $1S$ and $2S$ states have pseudoscalar (0^-) and vector (1^-) spin states that are predicted to differ in mass by about 20–50 MeV. Transitions between the spin states occur through soft photon radiation that escapes identification in ATLAS; the spin states cannot be separated by this analysis.

This Letter presents the observation of a new state whose mass is consistent with predictions for the $B_c^\pm(2S)$, the second S-wave state of the $B_c^\pm$ meson. The $B_c^\pm(2S)$ state is reconstructed in the decay to the $B_c^\pm$ meson and two oppositely charged pions, with the $B_c^\pm$ reconstructed through its decay to $J/\psi\pi^\pm$, $J/\psi \to \mu^+\mu^-$.

The ATLAS collaboration at the Large Hadron Collider (LHC) uses a general-purpose particle detector [6], consisting of several subsystems including the inner detector (ID), the electromagnetic and hadronic calorimeters, and the muon spectrometer (MS). Muon reconstruction at ATLAS makes use of both the ID and the MS.

Muons pass through the calorimeters and reach the MS if their momentum is above approximately 3 GeV. The inner detector features a three-component tracking system, consisting of two silicon-based detectors, the pixel detector and the microstrip semiconductor tracker (SCT), and the transition radiation tracker (TRT). ID tracks are reconstructed if their transverse momentum, $p_{\rm T}$ [7], is greater than 400 MeV and the magnitude of their pseudorapidity, $|\eta|$, is less than 2.5. Muon candidates are formed from a stand-alone MS track that is matched to an ID track [8]. In this analysis the MS is only used to identify muons, while their momentum is measured using the ID information only.

The trigger system [9] comprises three levels: the hardware-based Level-1 trigger and the High-Level Triggers (HLT), consisting of the Level-2 trigger and the Event Filter (EF). The Level-1 trigger uses resistive plate chambers (RPC) and thin gap chambers (TGC) to trigger muons in the pseudorapidity ranges of $|\eta| < 1.05$ and $1.05 < |\eta| < 2.5$, respectively. One or more regions of interest identified by the Level-1 muon trigger seed the HLT muon online reconstruction algorithms, where the responses from both the ID and the MS are combined. For this analysis the HLT selection for the J/ψ requires two muons, respectively μ_1 and μ_2, originating at a common vertex, with the invariant mass of the muon pair lying between 2.5 GeV and 4.3 GeV. The individual muon $p_{\rm T}$ thresholds are $p_{\rm T}(\mu_1) > 6$ GeV and $p_{\rm T}(\mu_2) > 4$ GeV.

This study uses pp collision data collected in the years 2011 ($\sqrt{s} = 7$ TeV) and 2012 ($\sqrt{s} = 8$ TeV) by the ATLAS experiment. The datasets used correspond to an integrated luminosity of 4.9 fb^{-1} and 19.2 fb^{-1}, respectively. The luminosity estimate has an uncertainty of 1.8% in 2011 [11] and 2.8% in 2012.

To improve the resolution, peaks are sought in the distribution of the variable $Q = m(B_c^\pm\pi\pi) - m(B_c^\pm) - 2m(\pi^\pm)$, where $m(B_c^\pm)$ is the offline reconstructed invariant mass of the $B_c^\pm$ candidate, $m(B_c^\pm\pi\pi)$ is the invariant mass of the $B_c^\pm$ candidate combined with two charged pion candidates, and $m(\pi^\pm)$ is the charged pion mass [10]. The $B_c^\pm$ candidates are reconstructed through the decay $B_c^\pm \to J/\psi(\mu^+\mu^-)\pi^\pm$. Since hadronic decays of excited B meson states have no observable displacement from the pp interaction point, these candidates are then combined with two charged pion candidates both originating at the corresponding pp interaction point. The mass difference (Q) distribution is formed and analyzed in the range $0 - 700$ MeV.

The $B_c^\pm$ selection criteria for the events are optimized

separately for 7 TeV and 8 TeV data using the corresponding Monte Carlo (MC) samples, produced in the ATLAS simulation framework [12, 13]. Differences between the 7 TeV and 8 TeV selection criteria are due to the higher $\sqrt{s}$ and the number of simultaneous pp interactions per bunch crossing hereafter called pile-up. The increase in the $B_c^{\pm}$ production cross section between the 7 TeV and 8 TeV MC samples is approximately 3%.

The PYTHIA 6 and 8 MC generators [14, 15], tuned for the LHC conditions [16], are used along with a dedicated PYTHIA extension for $B_c^{\pm}$ meson production, based on calculations from Ref. [17]. The following MC samples are used to optimize the event selection criteria (charge conjugates implied): B_c^+ decay modes $J/\psi\pi^+$, $J/\psi K^+$, $J/\psi\rho^+$ ($\rho^+ \to \pi^0\pi^+$), $J/\psi\mu^+\nu$, $J/\psi\pi^0\pi^+$, $J/\psi\pi^+\pi^-\pi^+$, as well as $J/\psi X$ produced inclusively or from $b\bar{b}$. The MC simulated events are treated in exactly the same way as the collision data, and the same analysis selections are always applied. The exclusive (B_c^+) channels are generated with PYTHIA 6, and inclusive ($J/\psi X$) channels are generated with PYTHIA 8.

This analysis involves several steps. First the J/ψ candidates are formed as described below. Then a pion track candidate from the same vertex is added to form a $B_c^{\pm}$ meson candidate. Finally, the $B_c^{\pm}(2S)$ candidates are formed by adding two pion candidates originating at the primary vertex (PV; the selection of the primary vertex is defined below).

The J/ψ candidates are reconstructed from pairs of oppositely charged muons. These pairs are fitted to a common vertex with the procedure described in Ref. [18]. The following requirements are applied to each J/ψ candidate:

- The p_{T} of the higher-p_{T} muon candidate to be above 6 GeV, and the p_{T} of the lower-p_{T} muon candidate to be above 4 GeV; these are approximately the p_{T} values for which the trigger is fully efficient.

- The J/ψ vertex fit chi-square per degree of freedom $\chi^2/NDOF < 15$ (this selection keeps more than 99.9% of the candidates, and is included only to remove spurious dimuon combinations).

- The invariant mass resolution of the J/ψ depends on the direction of the muons, with more forward candidates showing poorer resolutions. The sample is split into three categories and selection requirements are optimized for each of them: (1) both muons have $|\eta| < 1.05$, (2) one muon has $|\eta| < 1.05$ and the other one has $1.05 < |\eta| < 2.5$, (3) both muons have $1.05 < |\eta| < 2.5$. The invariant mass $m(\mu^+\mu^-)$ is calculated from the track parameters adjusted by the common-vertex fit to be in a three standard deviation $\pm 3\sigma$ mass window around the world average mass $m(J/\psi)$ [10], where the J/ψ reconstructed width σ varies in the range 40–90 MeV depending on muon reconstruction precision in different regions of pseudorapidity and on the data-taking period.

Selection requirements for the $B_c^{\pm}$ were chosen by maximizing $S/\sqrt{S+B}$, using MC events. Here S is the number of signal events and B refers to the number of background MC events scaled according to the production cross section. The production cross sections are taken from the MC generators' predictions. The optimization has been carried out separately for the two different datasets.

The pion candidate from the $B_c^{\pm}$ is required to have $p_{\mathrm{T}} > 4$ GeV. Hit requirements in the pixel detector and SCT are imposed on all tracks to ensure a reliable impact parameter reconstruction.

$B_c^{\pm}$ candidates are reconstructed by fitting two muon tracks from the J/ψ candidate together with a pion candidate track to a common vertex. The invariant mass of the two muons is constrained to the world average of $m(J/\psi)$. The yields per unit of integrated luminosity, and the central values of the dimuon invariant mass distributions are verified to be consistent within each dataset.

A significant part of the combinatorial background consists of real J/ψ candidates combined with candidate pions that are not associated with a $B_c^{\pm} \to J/\psi\pi^{\pm}$ decay. This background is reduced by imposing a lower cut on $d_0/\sigma(d_0)$; d_0 here represents the projection of the pion track impact parameter relative to the primary vertex onto the transverse plane, and $\sigma(d_0)$ is the track-by-track uncertainty on d_0. Pion candidates are required to have $d_0/\sigma(d_0) > 5$ for 7 TeV data and > 4.5 for 8 TeV data. In 7 TeV data the PV is defined as the collision vertex with the highest summed scalar p_{T}^2 of its constituent tracks. In 8 TeV data – the data collected with higher pile-up – the PV is identified as the vertex closest in three dimensions to the reconstructed decay vertex of the $B_c^{\pm}$ candidate. All reconstructed $B_c^{\pm}$ candidates are also required to satisfy the following selection criteria:

- the $J/\psi\pi$ vertex fit $\chi^2/NDOF < 2$ for 7 TeV and < 1.5 for 8 TeV data;

- the p_{T} of the $B_c^{\pm}$ candidate to be above 15 GeV for 7 TeV and above 18 GeV for 8 TeV data.

Figure 1 shows the invariant mass distributions for the $B_c^{\pm}$ candidates for 7 TeV data and 8 TeV data in the mass range 5620–6820 MeV. Both distributions are fitted separately using an extended unbinned maximum likelihood fit, with a Gaussian function modeling the signal and an exponential modeling the background shape. The various exclusive $B_c^{\pm}$ decay modes mentioned above are shown to have negligible contribution to the background shape. The results of the fits are summarized in Table

I. The fitted mass values are consistent with the world average for the $B_c^\pm$ mass [10]. The signal yield per fb^{-1} of the $B_c^\pm$ is lower in 8 TeV data due to the harder $p_{\rm T}$ requirements. The stability of the $B_c^\pm$ yield was checked through its normalization to $B^\pm \to J/\psi K^\pm$ decays that were reconstructed with similar requirements.

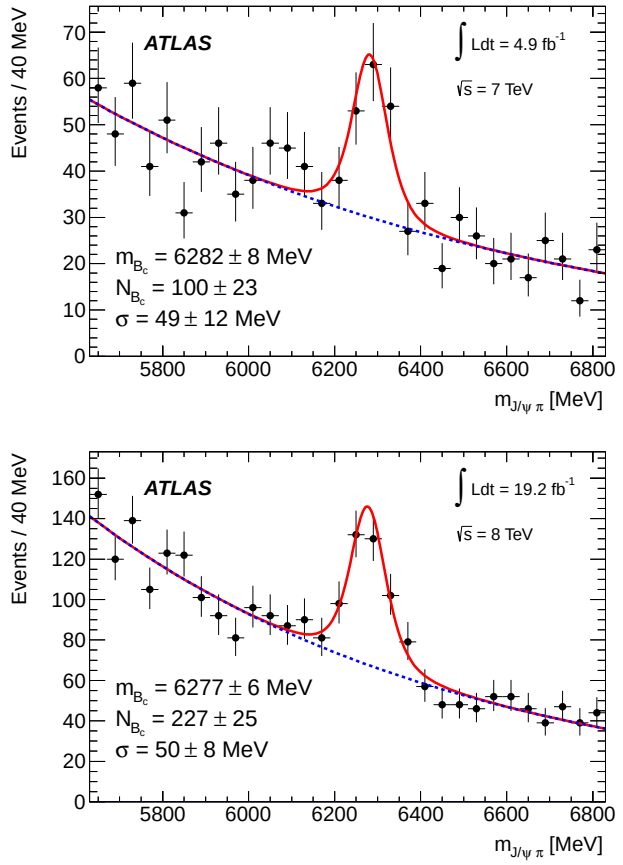


FIG. 1: Invariant mass distributions of the reconstructed $B_c^\pm \to J/\psi\pi^\pm$ candidates in 7 TeV data (top) and in 8 TeV data (bottom). The data are represented by the points with error bars (statistical only). The solid line is the projection of the results of the unbinned maximum likelihood fit to all candidates in the mass range 5620–6820 MeV. The dashed line is the projection of the background component of the same fit.

Data	Signal events	Peak mean [MeV]	Peak width [MeV]
7 TeV	100±23	6282±8	49±12
8 TeV	227±25	6277±6	50±8

TABLE I: The results of the unbinned maximum likelihood fits of the invariant mass distribution of the $B_c^\pm$ candidates. Systematic uncertainties are not included.

The reconstruction of the excited state candidates uses the $B_c^\pm$ ground state candidates within $\pm 3\sigma$ of the fitted mass value of the corresponding dataset. These candidates are combined as described below with two pion candidate tracks associated with the corresponding primary vertex. The $p_{\rm T}$ threshold of the pion candidates is 400 MeV. No additional selection requirement is applied to the $B_c^\pm(2S)$ pion candidates. The three tracks from the secondary vertex and the two tracks from the primary vertex are refitted simultaneously with the following constraints given by the decay topology: the refitted triplet of the $B_c^\pm$ tracks and the pair of PV pion tracks must intersect in two separate $B_c^\pm$ and $B_c^\pm(2S)$ vertices. The invariant mass of the refitted muon tracks is constrained to the J/ψ world average mass, and the combined momentum of the refitted $B_c^\pm$ tracks must point to the $B_c^\pm(2S)$ vertex. When multiple $B_c^\pm(2S)$ candidates are found in the same event, the one with the best χ^2 value returned by the fitter is kept as an excited state candidate. Wrong-charge combinations ($B_c^\pm\pi^+\pi^+$ and $B_c^\pm\pi^-\pi^-$) are kept separately for comparison with the combinatorial background shape in the right-charge combinations (oppositely charged pion pairs).

Figure 2 shows the mass difference distribution $m(B_c^\pm\pi\pi) - m(B_c^\pm) - 2m(\pi)$ for the right-charge combinations $B_c^\pm\pi^+\pi^-$ as well as the wrong-charge combinations.

A structure is observed in the mass difference distribution. In order to characterize it, an unbinned maximum likelihood fit to the right-charge combinations is performed. The fit includes a third-order polynomial to model the background and a Gaussian function for the structure. The background shape resulting from the fit is verified to be consistent with the wrong-charge combinations (which are not used to constrain the model in the right-charge fit) by fitting the same shape to them, with the normalization as the only free parameter. Alternative models for the signal and the background parameterizations are studied as sources of systematic uncertainty. A Breit–Wigner contribution was tested in convolution with the Gaussian function and was found to be negligible, implying that the natural width of the structure is small relative to the detector resolution. The resulting fit parameters (with statistical uncertainties only), as well as the distributions of the wrong-charge ($B_c^\pm\pi^+\pi^+$, $B_c^\pm\pi^-\pi^-$) combinations are shown in figure 2. The wrong-charge combinations are normalized to the same yield as the right-charge background.

The relative $B_c^\pm(2S)/B_c^\pm$ yield ratio is verified to be statistically consistent between the 7 TeV and 8 TeV data.

The fit finds the peak at a mass difference (Q) value of 288.2 ± 5.1 MeV in the 7 TeV data and 288.4 ± 4.8 MeV in the 8 TeV data. The fit yields 22 ± 6 signal events in the 7 TeV data and 35 ± 13 events in the 8 TeV data. The Gaussian width of the structure is found to be 18.2 ± 3.8 MeV in the 7 TeV data and 17.6 ± 4.0 MeV in the 8 TeV data. All uncertainties mentioned in this

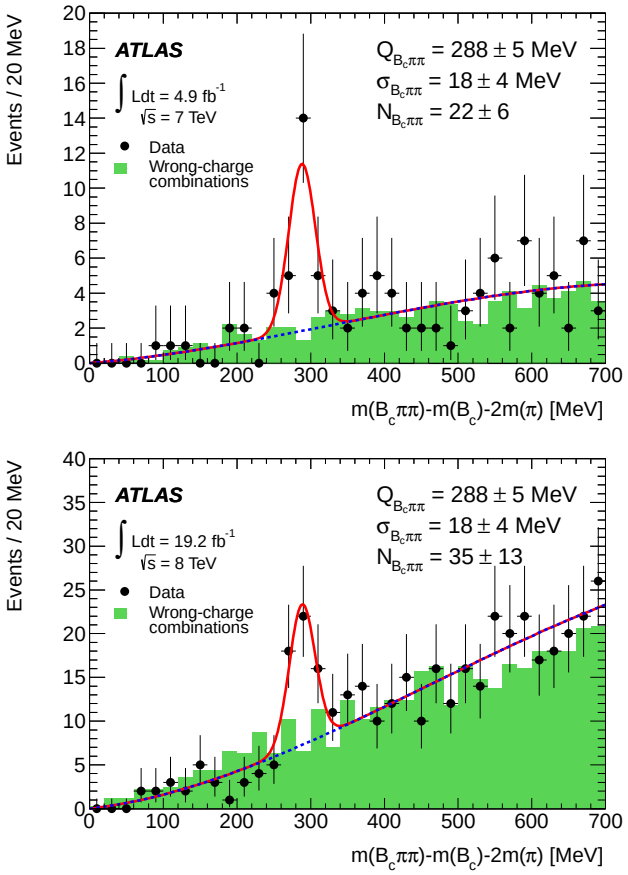


FIG. 2: The $Q = m(B_c^{\pm}\pi\pi) - m(B_c^{\pm}) - 2m(\pi^{\pm})$ distribution for the right-charge combinations (points with error bars) and for the same (wrong) pion charge combinations (shaded histogram) in 7 TeV data (top) and in 8 TeV data (bottom). The wrong-charge combinations are normalized to the same yield as the right-charge background. The solid line is the projection of the results of the unbinned maximum likelihood fit to all candidates in the range 0–700 MeV. The dashed line is the projection of the background component of the same fit.

paragraph do not include systematic uncertainties.

There are two dominant sources of systematic uncertainty on the position of the peak. One comes from the uncertainty on the mass of the $B_c^{\pm}$ ground state candidate and is largely canceled in the mass difference distribution. The other involves systematic uncertainties in the fit of the mass difference distribution itself. The uncertainty on the mass of the $B_c^{\pm}(2S)$ candidate is dominated by the fitting procedure and estimated below to be about 3.6 MeV. The contribution from the uncertainty on the pion momentum scale to the $B_c^{\pm}$ mass is 1.2 MeV. The residual uncertainty from the $B_c^{\pm}$ candidate mass in the mass difference distribution, $\delta m_{B_c^{\pm}(2S)} = \delta m_{B_c^{\pm}} \times (m_{B_c^{\pm}})/m_{B_c^{\pm}(2S)}$, where the $\delta m_{B_c^{\pm}}$ is the world average uncertainty on the $B_c^{\pm}$ mass [10], is about 1.7 MeV. The systematic uncertainty on the mass difference introduced by the fitting procedure is estimated by:

- varying the background model. An exponential threshold function ($f(Q) \backsim Q^a e^{-bQ}$, where a and b are free parameters) and second- and fourth-order polynomials were considered as alternatives, resulting in a 3.4 MeV systematic uncertainty;
- varying the fit mass range from 0–700 MeV to 0–1500 MeV, results in a 1.2 MeV contribution to the systematic uncertainty;
- using different models for the signal. A single Breit–Wigner function, a Breit–Wigner function convolved with a Gaussian function, and a double Gaussian function were considered. This results in a negligible systematic uncertainty, compared to the above two;

In each case the largest difference between any of the variations mentioned and the default fit model is used as the systematic uncertainty. The values are calculated as the weighted mean of the 7 and 8 TeV mass values.

An additional systematic uncertainty of 2 MeV is obtained from the study of the mass bias in the selection of the candidate with the best χ^2 of the vertex fit.

The various sources of systematic uncertainty are treated as uncorrelated. The total averaged systematic uncertainty propagated to the mass value of the new structure is approximately 4.1 MeV.

The significance of the new structure is evaluated with pseudo-experiments. A large number of background-only mass difference distributions are generated. Parameters of the generation are taken from the fit with their uncertainties to account for systematic effects. The background shape is scaled to the observed number of events. The mean mass value of the signal contribution is left free to vary within the theoretically motivated range (6835–6917 MeV) to evaluate the "look-elsewhere effect" [19]. The significance is calculated as the fraction of the pseudo-experiments in which the difference of the logarithms of fit likelihoods $\Delta\ln L$ with and without signal is larger than in the data. In terms of standard deviations the significance of the observation is 3.7σ in the 7 TeV data and 4.5σ in the 8 TeV data. For the combined 7 TeV and 8 TeV dataset the total significance of the observation is found to be 5.2σ. The local significance of the observation, obtained by fixing the mean value of the signal component, is 5.4σ.

In conclusion, the distribution of the mass difference $Q = m(B_c^{\pm}\pi^+\pi^-) - m(B_c^{\pm}) - 2m(\pi^{\pm})$ for events with the $B_c^{\pm}$ meson reconstructed in its decay to $J/\psi\pi^{\pm}$ has been investigated in pp collisions at the LHC using the ATLAS detector. The analysis is based on an integrated luminosity of 4.9 (19.2) fb^{-1} of pp collisions at a center-of-mass energy of 7 (8) TeV. A new state is observed

at $Q = 288.3 \pm 3.5 \pm 4.1$ MeV (calculated as the error weighted mean of the 7 TeV and 8 TeV mass values) corresponding to a mass of $6842 \pm 4 \pm 5$ MeV, where the first error is statistical and the second is systematic. The significance of the observation is 5.2σ with the "look elsewhere effect" taken into account, and the local significance is 5.4σ. Within the uncertainties, the mass of the resonance corresponding to the observed structure is consistent with the predicted mass of the $B_c^{\pm}(2S)$ state.

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Stewart[53], J.A. Stillings[21], M.C. Stockton[86], M. Stoebe[86], G. Stoicea[26a], P. Stolte[54], S. Stonjek[100], A.R. Stradling[8], A. Straessner[44], M.E. Stramaglia[17], J. Strandberg[148], S. Strandberg[147a,147b], A. Strandlie[118], E. Strauss[144], M. Strauss[112], P. Strizenec[145b], R. Ströhmer[175], D.M. Strom[115], R. Stroynowski[40], S.A. Stucci[17], B. Stugu[14], N.A. Styles[42], D. Su[144], J. Su[124], HS. Subramania[3], R. Subramaniam[78], A. Succurro[12], Y. Sugaya[117], C. Suhr[107], M. Suk[127], V.V. Sulin[95], S. Sultansoy[4c], T. Sumida[67], X. Sun[33a], J.E. Sundermann[48], K. Suruliz[140], G. Susinno[37a,37b], M.R. Sutton[150], Y. Suzuki[65], M. Svatos[126], S. Swedish[169], M. Swiatlowski[144], I. Sykora[145a], T. Sykora[128], D. Ta[89], C. Taccini[135a,135b], K. Tackmann[42], J. Taenzer[159], A. Taffard[164], R. Tafirout[160a], N. Taiblum[154], Y. Takahashi[102], H. Takai[25], R. Takashima[68], H. Takeda[66], T. Takeshita[141], Y. Takubo[65], M. Talby[84], A.A. Talyshev[108,t], J.Y.C. Tam[175], K.G. Tan[87], J. Tanaka[156], R. Tanaka[116], S. Tanaka[132], S. Tanaka[65], A.J. Tanasijczuk[143], B.B. Tannenwald[110], N. Tannoury[21], S. Tapprogge[82], S. Tarem[153], F. Tarrade[29], G.F. Tartarelli[90a], P. Tas[128], M. Tasevsky[126], T. Tashiro[67], E. Tassi[37a,37b], A. Tavares Delgado[125a,125b], Y. Tayalati[136d], F.E. Taylor[93], G.N. Taylor[87], W. Taylor[160b], F.A. Teischinger[30], M. Teixeira Dias Castanheira[75], P. Teixeira-Dias[76], K.K. Temming[48], H. Ten Kate[30], P.K. Teng[152], J.J. Teoh[117], S. Terada[65], K. Terashi[156], J. Terron[81], S. Terzo[100], M. Testa[47], R.J. Teuscher[159,i], J. Therhaag[21], T. Theveneaux-Pelzer[34], J.P. Thomas[18], J. Thomas-Wilsker[76], E.N. Thompson[35], P.D. Thompson[18], P.D. Thompson[159], A.S. Thompson[53], L.A. Thomsen[36], E. Thomson[121], M. Thomson[28], W.M. Thong[87], R.P. Thun[88,*], F. Tian[35], M.J. Tibbetts[15], V.O. Tikhomirov[95,ag], Yu.A. Tikhonov[108,t], S. Timoshenko[97], E. Tiouchichine[84], P. Tipton[177], S. Tisserant[84], T. Todorov[5], S. Todorova-Nova[128], B. Toggerson[7], J. Tojo[69], S. Tokár[145a], K. Tokushuku[65], K. Tollefson[89], L. Tomlinson[83], M. Tomoto[102], L. Tompkins[31], K. Toms[104], N.D. Topilin[64], E. Torrence[115], H. Torres[143], E. Torró Pastor[168], J. Toth[84,ah], F. Touchard[84], D.R. Tovey[140], H.L. Tran[116], T. Trefzger[175], L. Tremblet[30], A. Tricoli[30], I.M. Trigger[160a], S. Trincaz-Duvoid[79], M.F. Tripiana[12], N. Triplett[25], W. Trischuk[159], B. Trocmé[55], C. Troncon[90a], M. Trottier-McDonald[143], M. Trovatelli[135a,135b], P. True[89], M. Trzebinski[39], A. Trzupek[39], C. Tsarouchas[30], J.C-L. Tseng[119], P.V. Tsiareshka[91], D. Tsionou[137], G. Tsipolitis[10], N. Tsirintanis[9], S. Tsiskaridze[12], V. Tsiskaridze[48], E.G. Tskhadadze[51a], I.I. Tsukerman[96], V. Tsulaia[15], S. Tsuno[65], D. Tsybychev[149], A. Tudorache[26a], V. Tudorache[26a], A.N. Tuna[121], S.A. Tupputi[20a,20b], S. Turchikhin[98,af], D. Turecek[127], I. Turk Cakir[4d], R. Turra[90a,90b], P.M. Tuts[35], A. Tykhonov[49], M. Tylmad[147a,147b], M. Tyndel[130], K. Uchida[21], I. Ueda[156], R. Ueno[29], M. Ughetto[84], M. Ugland[14], M. Uhlenbrock[21], F. Ukegawa[161], G. Unal[30], A. Undrus[25], G. Unel[164], F.C. Ungaro[48], Y. Unno[65], C. Unverdorben[99], D. Urbaniec[35], P. Urquijo[87], G. Usai[8], A. Usanova[61], L. Vacavant[84], V. Vacek[127], B. Vachon[86], N. Valencic[106], S. Valentinetti[20a,20b], A. Valero[168], L. Valery[34], S. Valkar[128], E. Valladolid Gallego[168], S. Vallecorsa[49], J.A. Valls Ferrer[168], W. Van Den Wollenberg[106], P.C. Van Der Deijl[106], R. van der Geer[106], H. van der Graaf[106], R. Van Der Leeuw[106], D. van der Ster[30], N. van Eldik[30], P. van Gemmeren[6], J. Van Nieuwkoop[143], I. van Vulpen[106], M.C. van Woerden[30], M. Vanadia[133a,133b], W. Vandelli[30], R. Vanguri[121], A. Vaniachine[6], P. Vankov[42], F. Vannucci[79], G. Vardanyan[178], R. Vari[133a], E.W. Varnes[7], T. Varol[85], D. Varouchas[79], A. Vartapetian[8], K.E. Varvell[151], F. Vazeille[34], T. Vazquez Schroeder[54], J. Veatch[7], F. Veloso[125a,125c], S. Veneziano[133a], A. Ventura[72a,72b], D. Ventura[85], M. Venturi[170], N. Venturi[159], A. Venturini[23], V. Vercesi[120a], M. Verducci[133a,133b], W. Verkerke[106], J.C. Vermeulen[106], A. Vest[44], M.C. Vetterli[143,d], O. Viazlo[80], I. Vichou[166], T. Vickey[146c,ai], O.E. Vickey Boeriu[146c], G.H.A. Viehhauser[119], S. Viel[169], R. Vigne[30], M. Villa[20a,20b], M. Villaplana Perez[90a,90b], E. Vilucchi[47], M.G. Vincter[29], V.B. Vinogradov[64], J. Virzi[15], I. Vivarelli[150], F. Vives Vaque[3], S. Vlachos[10], D. Vladoiu[99], M. Vlasak[127], A. Vogel[21], M. Vogel[32a], P. Vokac[127], G. Volpi[123a,123b], M. Volpi[87], H. von der Schmitt[100],

H. von Radziewski[48], E. von Toerne[21], V. Vorobel[128], K. Vorobev[97], M. Vos[168], R. Voss[30], J.H. Vossebeld[73], N. Vranjes[137], M. Vranjes Milosavljevic[106], V. Vrba[126], M. Vreeswijk[106], T. Vu Anh[48], R. Vuillermet[30], I. Vukotic[31], Z. Vykydal[127], P. Wagner[21], W. Wagner[176], H. Wahlberg[70], S. Wahrmund[44], J. Wakabayashi[102], J. Walder[71], R. Walker[99], W. Walkowiak[142], R. Wall[177], P. Waller[73], B. Walsh[177], C. Wang[152,aj], C. Wang[45], F. Wang[174], H. Wang[15], H. Wang[40], J. Wang[42], J. Wang[33a], K. Wang[86], R. Wang[104], S.M. Wang[152], T. Wang[21], X. Wang[177], C. Wanotayaroj[115], A. Warburton[86], C.P. Ward[28], D.R. Wardrope[77], M. Warsinsky[48], A. Washbrook[46], C. Wasicki[42], P.M. Watkins[18], A.T. Watson[18], I.J. Watson[151], M.F. Watson[18], G. Watts[139], S. Watts[83], B.M. Waugh[77], S. Webb[83], M.S. Weber[17], S.W. Weber[175], J.S. Webster[31], A.R. Weidberg[119], P. Weigell[100], B. Weinert[60], J. Weingarten[54], C. Weiser[48], H. Weits[106], P.S. Wells[30], T. Wenaus[25], D. Wendland[16], Z. Weng[152,ae], T. Wengler[30], S. Wenig[30], N. Wermes[21], M. Werner[48], P. Werner[30], M. Wessels[58a], J. Wetter[162], K. Whalen[29], A. White[8], M.J. White[1], R. White[32b], S. White[123a,123b], D. Whiteson[164], D. Wicke[176], F.J. Wickens[130], W. Wiedenmann[174], M. Wielers[130], P. Wienemann[21], C. Wiglesworth[36], L.A.M. Wiik-Fuchs[21], P.A. Wijeratne[77], A. Wildauer[100], M.A. Wildt[42,ak], H.G. Wilkens[30], J.Z. Will[99], H.H. Williams[121], S. Williams[28], C. Willis[89], S. Willocq[85], A. Wilson[88], J.A. Wilson[18], I. Wingerter-Seez[5], F. Winklmeier[115], B.T. Winter[21], M. Wittgen[144], T. Wittig[43], J. Wittkowski[99], S.J. Wollstadt[82], M.W. Wolter[39], H. Wolters[125a,125c], B.K. Wosiek[39], J. Wotschack[30], M.J. Woudstra[83], K.W. Wozniak[39], M. Wright[53], M. Wu[55], S.L. Wu[174], X. Wu[49], Y. Wu[88], E. Wulf[35], T.R. Wyatt[83], B.M. Wynne[46], S. Xella[36], M. Xiao[137], D. Xu[33a], L. Xu[33b,al], B. Yabsley[151], S. Yacoob[146b,am], M. Yamada[65], H. Yamaguchi[156], Y. Yamaguchi[117], A. Yamamoto[65], K. Yamamoto[63], S. Yamamoto[156], T. Yamamura[156], T. Yamanaka[156], K. Yamauchi[102], Y. Yamazaki[66], Z. Yan[22], H. Yang[33e], H. Yang[174], U.K. Yang[83], Y. Yang[110], S. Yanush[92], L. Yao[33a], W-M. Yao[15], Y. Yasu[65], E. Yatsenko[42], K.H. Yau Wong[21], J. Ye[40], S. Ye[25], A.L. Yen[57], E. Yildirim[42], M. Yilmaz[4b], R. Yoosoofmiya[124], K. Yorita[172], R. Yoshida[6], K. Yoshihara[156], C. Young[144], C.J.S. Young[30], S. Youssef[22], D.R. Yu[15], J. Yu[8], J.M. Yu[88], J. Yu[113], L. Yuan[66], A. Yurkewicz[107], I. Yusuff[28,an], B. Zabinski[39], R. Zaidan[62], A.M. Zaitsev[129,aa], A. Zaman[149], S. Zambito[23], L. Zanello[133a,133b], D. Zanzi[100], C. Zeitnitz[176], M. Zeman[127], A. Zemla[38a], K. Zengel[23], O. Zenin[129], T. Ženiš[145a], D. Zerwas[116], G. Zevi della Porta[57], D. Zhang[88], F. Zhang[174], H. Zhang[89], J. Zhang[6], L. Zhang[152], X. Zhang[33d], Z. Zhang[116], Z. Zhao[33b], A. Zhemchugov[64], J. Zhong[119], B. Zhou[88], L. Zhou[35], N. Zhou[164], C.G. Zhu[33d], H. Zhu[33a], J. Zhu[88], Y. Zhu[33b], X. Zhuang[33a], K. Zhukov[95], A. Zibell[175], D. Zieminska[60], N.I. Zimine[64], C. Zimmermann[82], R. Zimmermann[21], S. Zimmermann[21], S. Zimmermann[48], Z. Zinonos[54], M. Ziolkowski[142], G. Zobernig[174], A. Zoccoli[20a,20b], M. zur Nedden[16], G. Zurzolo[103a,103b], V. Zutshi[107], L. Zwalinski[30].

[1] Department of Physics, University of Adelaide, Adelaide, Australia
[2] Physics Department, SUNY Albany, Albany NY, United States of America
[3] Department of Physics, University of Alberta, Edmonton AB, Canada
[4] [(a)] Department of Physics, Ankara University, Ankara; [(b)] Department of Physics, Gazi University, Ankara; [(c)] Division of Physics, TOBB University of Economics and Technology, Ankara; [(d)] Turkish Atomic Energy Authority, Ankara, Turkey
[5] LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
[6] High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
[7] Department of Physics, University of Arizona, Tucson AZ, United States of America
[8] Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
[9] Physics Department, University of Athens, Athens, Greece
[10] Physics Department, National Technical University of Athens, Zografou, Greece
[11] Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[12] Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
[13] [(a)] Institute of Physics, University of Belgrade, Belgrade; [(b)] Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
[14] Department for Physics and Technology, University of Bergen, Bergen, Norway
[15] Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
[16] Department of Physics, Humboldt University, Berlin, Germany
[17] Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[18] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[19] [(a)] Department of Physics, Bogazici University, Istanbul; [(b)] Department of Physics, Dogus University, Istanbul; [(c)] Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

[20] [(a)] INFN Sezione di Bologna; [(b)] Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
[21] Physikalisches Institut, University of Bonn, Bonn, Germany
[22] Department of Physics, Boston University, Boston MA, United States of America
[23] Department of Physics, Brandeis University, Waltham MA, United States of America
[24] [(a)] Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; [(b)] Federal University of Juiz de Fora (UFJF), Juiz de Fora; [(c)] Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; [(d)] Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
[25] Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
[26] [(a)] National Institute of Physics and Nuclear Engineering, Bucharest; [(b)] National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; [(c)] University Politehnica Bucharest, Bucharest; [(d)] West University in Timisoara, Timisoara, Romania
[27] Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
[28] Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[29] Department of Physics, Carleton University, Ottawa ON, Canada
[30] CERN, Geneva, Switzerland
[31] Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
[32] [(a)] Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; [(b)] Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[33] [(a)] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; [(b)] Department of Modern Physics, University of Science and Technology of China, Anhui; [(c)] Department of Physics, Nanjing University, Jiangsu; [(d)] School of Physics, Shandong University, Shandong; [(e)] Physics Department, Shanghai Jiao Tong University, Shanghai, China
[34] Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
[35] Nevis Laboratory, Columbia University, Irvington NY, United States of America
[36] Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
[37] [(a)] INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; [(b)] Dipartimento di Fisica, Università della Calabria, Rende, Italy
[38] [(a)] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; [(b)] Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
[39] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
[40] Physics Department, Southern Methodist University, Dallas TX, United States of America
[41] Physics Department, University of Texas at Dallas, Richardson TX, United States of America
[42] DESY, Hamburg and Zeuthen, Germany
[43] Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
[44] Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
[45] Department of Physics, Duke University, Durham NC, United States of America
[46] SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[47] INFN Laboratori Nazionali di Frascati, Frascati, Italy
[48] Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
[49] Section de Physique, Université de Genève, Geneva, Switzerland
[50] [(a)] INFN Sezione di Genova; [(b)] Dipartimento di Fisica, Università di Genova, Genova, Italy
[51] [(a)] E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; [(b)] High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[52] II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[53] SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[54] II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
[55] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
[56] Department of Physics, Hampton University, Hampton VA, United States of America
[57] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
[58] [(a)] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(c)] ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
[59] Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[60] Department of Physics, Indiana University, Bloomington IN, United States of America

[61] Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[62] University of Iowa, Iowa City IA, United States of America
[63] Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
[64] Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
[65] KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[66] Graduate School of Science, Kobe University, Kobe, Japan
[67] Faculty of Science, Kyoto University, Kyoto, Japan
[68] Kyoto University of Education, Kyoto, Japan
[69] Department of Physics, Kyushu University, Fukuoka, Japan
[70] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[71] Physics Department, Lancaster University, Lancaster, United Kingdom
[72] [(a)] INFN Sezione di Lecce; [(b)] Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[73] Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[74] Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
[75] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[76] Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
[77] Department of Physics and Astronomy, University College London, London, United Kingdom
[78] Louisiana Tech University, Ruston LA, United States of America
[79] Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[80] Fysiska institutionen, Lunds universitet, Lund, Sweden
[81] Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
[82] Institut für Physik, Universität Mainz, Mainz, Germany
[83] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[84] CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[85] Department of Physics, University of Massachusetts, Amherst MA, United States of America
[86] Department of Physics, McGill University, Montreal QC, Canada
[87] School of Physics, University of Melbourne, Victoria, Australia
[88] Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
[89] Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
[90] [(a)] INFN Sezione di Milano; [(b)] Dipartimento di Fisica, Università di Milano, Milano, Italy
[91] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
[92] National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
[93] Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
[94] Group of Particle Physics, University of Montreal, Montreal QC, Canada
[95] P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
[96] Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
[97] Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
[98] D.V.Skobeltsyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
[99] Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[100] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[101] Nagasaki Institute of Applied Science, Nagasaki, Japan
[102] Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[103] [(a)] INFN Sezione di Napoli; [(b)] Dipartimento di Fisica, Università di Napoli, Napoli, Italy
[104] Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
[105] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
[106] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[107] Department of Physics, Northern Illinois University, DeKalb IL, United States of America
[108] Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
[109] Department of Physics, New York University, New York NY, United States of America
[110] Ohio State University, Columbus OH, United States of America
[111] Faculty of Science, Okayama University, Okayama, Japan
[112] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
[113] Department of Physics, Oklahoma State University, Stillwater OK, United States of America

[114] Palacký University, RCPTM, Olomouc, Czech Republic
[115] Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
[116] LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[117] Graduate School of Science, Osaka University, Osaka, Japan
[118] Department of Physics, University of Oslo, Oslo, Norway
[119] Department of Physics, Oxford University, Oxford, United Kingdom
[120] [(a)] INFN Sezione di Pavia; [(b)] Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[121] Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
[122] Petersburg Nuclear Physics Institute, Gatchina, Russia
[123] [(a)] INFN Sezione di Pisa; [(b)] Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[124] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
[125] [(a)] Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa; [(b)] Faculdade de Ciências, Universidade de Lisboa, Lisboa; [(c)] Department of Physics, University of Coimbra, Coimbra; [(d)] Centro de Física Nuclear da Universidade de Lisboa, Lisboa; [(e)] Departamento de Fisica, Universidade do Minho, Braga; [(f)] Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); [(g)] Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
[126] Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
[127] Czech Technical University in Prague, Praha, Czech Republic
[128] Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
[129] State Research Center Institute for High Energy Physics, Protvino, Russia
[130] Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[131] Physics Department, University of Regina, Regina SK, Canada
[132] Ritsumeikan University, Kusatsu, Shiga, Japan
[133] [(a)] INFN Sezione di Roma; [(b)] Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
[134] [(a)] INFN Sezione di Roma Tor Vergata; [(b)] Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[135] [(a)] INFN Sezione di Roma Tre; [(b)] Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
[136] [(a)] Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; [(b)] Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; [(c)] Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; [(d)] Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; [(e)] Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
[137] DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
[138] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
[139] Department of Physics, University of Washington, Seattle WA, United States of America
[140] Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[141] Department of Physics, Shinshu University, Nagano, Japan
[142] Fachbereich Physik, Universität Siegen, Siegen, Germany
[143] Department of Physics, Simon Fraser University, Burnaby BC, Canada
[144] SLAC National Accelerator Laboratory, Stanford CA, United States of America
[145] [(a)] Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; [(b)] Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[146] [(a)] Department of Physics, University of Cape Town, Cape Town; [(b)] Department of Physics, University of Johannesburg, Johannesburg; [(c)] School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[147] [(a)] Department of Physics, Stockholm University; [(b)] The Oskar Klein Centre, Stockholm, Sweden
[148] Physics Department, Royal Institute of Technology, Stockholm, Sweden
[149] Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
[150] Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[151] School of Physics, University of Sydney, Sydney, Australia
[152] Institute of Physics, Academia Sinica, Taipei, Taiwan
[153] Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
[154] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[155] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[156] International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

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

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