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Search for the Standard Model Higgs Boson in the Diphoton Decay Channel with 4.9 fb^{-1} of pp Collision Data at $\sqrt{s} = 7$ TeV with ATLAS

G. Aad *et al.**
(ATLAS Collaboration)
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A search for the standard model Higgs boson is performed in the diphoton decay channel. The data used correspond to an integrated luminosity of 4.9 fb^{-1} collected with the ATLAS detector at the Large Hadron Collider in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV. In the diphoton mass range 110–150 GeV, the largest excess with respect to the background-only hypothesis is observed at 126.5 GeV, with a local significance of 2.8 standard deviations. Taking the look-elsewhere effect into account in the range 110–150 GeV, this significance becomes 1.5 standard deviations. The standard model Higgs boson is excluded at 95% confidence level in the mass ranges of 113–115 GeV and 134.5–136 GeV.

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The Higgs mechanism [1] is one of the best-motivated processes to explain electroweak (EW) symmetry breaking. In the standard model (SM), this mechanism explains the generation of the W and Z boson masses and predicts the existence of the only elementary scalar in the SM, the hypothetical Higgs boson. Prior direct searches at LEP, Tevatron and LHC exclude the SM Higgs boson with a mass $m_H < 114.4$ GeV and $145 < m_H < 206$ GeV at 95% confidence level (C.L.) [2–4]. The present search for $H \rightarrow \gamma\gamma$ uses the full 2011 data sample collected by ATLAS at 7 TeV center-of-mass energy and updates prior results with 1.08 fb^{-1} [5].

The ATLAS detector [6] consists of an inner tracking detector surrounded by a superconducting solenoid providing a 2 T magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The main subdetectors relevant to the search presented here are the calorimeters, in particular, the electromagnetic section, and the inner tracking system. The inner detector provides tracking in the pseudorapidity region $|\eta| < 2.5$ and consists of silicon pixel- and microstrip detectors inside a transition radiation tracker. The electromagnetic calorimeter, a lead liquid-argon sampling device, is divided in one barrel ($|\eta| < 1.475$) and two end-cap ($1.375 < |\eta| < 3.2$) sections. The barrel ($|\eta| < 0.8$) and extended barrel ($0.8 < |\eta| < 1.7$) hadron calorimeter sections consist of steel and scintillating tiles, while the end-cap sections ($1.5 < |\eta| < 3.2$) are composed of copper and liquid argon.

The data were recorded using a diphoton trigger [7], each photon having a transverse energy, E_{T}, of at least 20 GeV, seeded by a lower-level trigger that required two clusters in the electromagnetic calorimeter with $E_{\mathrm{T}} > 12$ or 14 GeV, depending on the data-taking period. The trigger efficiency for the signal events passing the final offline selection is 99%. After applying data quality requirements, the total integrated luminosity of the data set used in this analysis is 4.9 ± 0.2 fb^{-1} [8].

Events are required to contain at least one vertex with at least three associated tracks, where the transverse momentum, p_{T}, of each track is required to be larger than 0.4 GeV, as well as two photon candidates each seeded by an energy cluster in the electromagnetic calorimeter with $E_{\mathrm{T}} > 2.5$ GeV. Photons that convert to electron-positron pairs in the inner detector leave one or two tracks that are reconstructed and matched to the clusters in the calorimeter. The photon energy is calibrated separately for converted and unconverted photon candidates using Monte Carlo (MC) simulations of the detector [9]. A correction, depending on pseudorapidity and typically of the order of $\pm 1\%$, is applied to the calibrated photon energy as obtained from studies using $Z \rightarrow ee$ decays in data [10]. Photons are reconstructed in the fiducial region $|\eta| < 2.37$, excluding the calorimeter barrel-to-end-cap transition regions $1.37 < |\eta| < 1.52$. The photon candidates are ordered in E_{T} and the leading (subleading) candidate is required to have $E_{\mathrm{T}} > 40$ GeV (25 GeV). Both candidates are required to pass further identification criteria based on shower shapes measured in the electromagnetic calorimeter and on the energy leakage into the hadron calorimeter [11]. The photon reconstruction and identification efficiency ranges typically from 65% to 95% for E_{T} in the range 25 to 80 GeV. The two photon candidates are required to be isolated by having at most 5 GeV energy deposited in the calorimeters in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ around the candidate, where ϕ is the azimuthal angle, after subtracting the energy assigned to the photon itself. The measured isolation [11] is corrected for lateral shower leakage and ambient energy from

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

TABLE I. Composition of the selected sample as obtained from the data in the mass window of 100–160 GeV. A sum in quadrature of statistical and systematic uncertainties is quoted.

	$\gamma\gamma$	γj	jj	Drell-Yan
Events	$16\,000 \pm 1100$	5230 ± 890	1130 ± 600	165 ± 8
Fraction	$(71 \pm 5)\%$	$(23 \pm 4)\%$	$(5 \pm 3)\%$	$(0.7 \pm 0.1)\%$

multiple proton-proton interactions (pileup), following the method in Ref. [12]. The isolation cut retains $\sim$87% of Higgs boson signal events with $m_H = 120$ GeV while rejecting $\sim$44% of the selected data, which includes jets that can be misidentified as photons.

The opening angle of the two photons, used in the calculation of their invariant mass, is determined using the trajectories of the photons. For a converted photon with a well-measured conversion vertex, the trajectory is determined from the straight line between the barycenter of the associated energy deposits in the calorimeter and the conversion vertex. Otherwise, the trajectory is determined from the barycenters of the showers in the first and second layers of the calorimeter. The extrapolation of the trajectories as well as the average beam spot position are used to determine the origin of the photons along the beam axis, z. The resolution of the z vertex coordinate is $\sim$6 mm on average for two converted photons with reconstructed tracks, and $\sim$15 mm otherwise. The contribution of the resulting angular resolution to the mass resolution is negligible in comparison to that of the energy resolution.

In total, 22 489 events pass the selection in the diphoton mass range 100–160 GeV. To confirm the dominance of the diphoton processes ($\gamma\gamma$) over backgrounds with one or two misidentified jets (γj, jj), the composition of the selected sample is estimated using the data. A sideband technique [5] is used to estimate the numbers of $\gamma\gamma$, γj, or jj events. The fraction of true diphoton events is estimated to be $(71 \pm 5)\%$. The amount of Drell-Yan background is estimated by selecting $Z \rightarrow ee$ decays in data where either one or both electrons pass the photon selection. The measured composition is summarized in Table I and is compatible with MC expectations. This decomposition is not directly used in the signal search; however, it is used to validate the parametrization of the background fit (see below).

The events are separated into nine mutually exclusive categories with different mass resolutions and signal-to-background ratios, to increase the sensitivity to a possible Higgs boson signal. Categories are defined by the conversion status, η of the selected photons, and p_{Tt} [13], the component of the diphoton pT that is orthogonal to the thrust axis, as proposed in Ref. [14]. Events with two unconverted photons are separated into *unconverted central* ($|\eta| < 0.75$ for both candidates) and *unconverted rest* (all other events). Events with at least one converted photon are separated into *converted central* ($|\eta| < 0.75$ for both candidates), *converted transition* (at least one photon with $1.3 < |\eta| < 1.75$), and *converted rest* (all other events). Excepting the *converted transition* category, each category is further divided by a cut at $p_{\mathrm{Tt}} = 40$ GeV into two categories, *low* p_{Tt} and *high* p_{Tt}. MC studies show that signal events, particularly those produced in vector-boson fusion (VBF) or in associated production (W/ZH and $t\bar{t}H$), have on average larger p_{Tt} than background events. The number of data events in each category is given in Table II.

The distribution of the invariant mass of the diphoton events, $m_{\gamma\gamma}$, summed over all categories, is shown in Fig. 1. The sum of the background-only fits (described below) to the invariant mass in each of the categories is superimposed. The signal expectation for a SM Higgs boson with $m_H = 120$ GeV is also shown. The presence of the Higgs boson will appear as a narrow resonance in the

TABLE II. Mass resolution σ_{CB} (see text) and FWHM (both in GeV), expected number of signal events (N_{S}) for $m_H = 120$ GeV, and number of events in the data (N_{D}) in each category for 4.9 fb^{-1}, N_{S} and N_{D} are for the mass range 100–160 GeV. The signal-to-background ratios (S/B) are given in a mass window containing 90% of the signal for $m_H = 120$ GeV.

Category	σ_{CB}	FWHM	N_{S}	N_{D}	S/B
Unconverted central, low p_{Tt}	1.4	3.4	9.1	1763	0.05
Unconverted central, high p_{Tt}	1.4	3.3	2.6	235	0.11
Unconverted rest, low p_{Tt}	1.7	4.0	17.7	6234	0.02
Unconverted rest, high p_{Tt}	1.6	3.9	4.7	1006	0.04
Converted central, low p_{Tt}	1.6	3.9	6.0	1318	0.03
Converted central, high p_{Tt}	1.5	3.6	1.7	184	0.08
Converted rest, low p_{Tt}	2.0	4.7	17.0	7311	0.01
Converted rest, high p_{Tt}	1.9	4.5	4.8	1072	0.03
Converted transition	2.3	5.9	8.5	3366	0.01
All categories	1.7	4.1	72.1	22 489	0.02

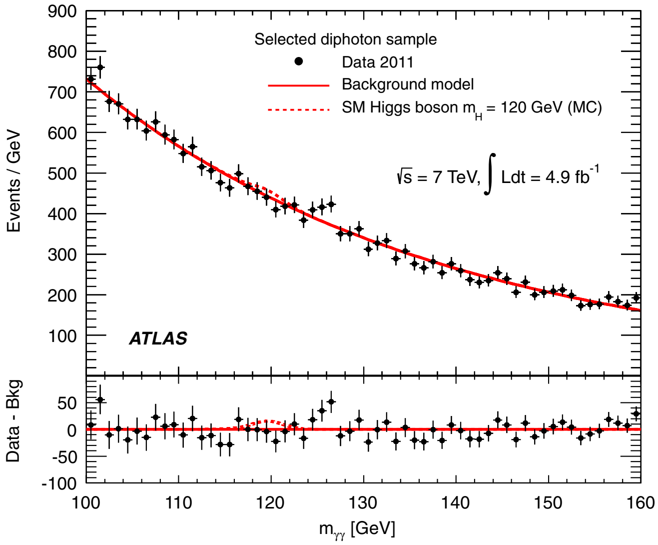

FIG. 1 (color online). Invariant mass distribution for the selected data sample, overlaid with the total background (see text). The bottom inset displays the residual of the data with respect to the total background. The Higgs boson expectation for a mass hypothesis of 120 GeV corresponding to the SM cross section is also shown.

invariant mass of the selected photon pairs superimposed on a smoothly falling background. The residual of the data with respect to the total background as a function of $m_{\gamma\gamma}$ is also shown in Fig. 1.

Higgs boson production and decay are simulated with several MC samples that are passed through a full detector simulation [15] using GEANT4 [16]. Pileup effects are simulated by overlaying each MC event with a variable number of MC inelastic proton-proton collisions [17]. POWHEG [18], interfaced to PYTHIA [19] for showering and hadronization, is used for generation of gluon-fusion and VBF production. PYTHIA is used to generate the Higgs boson production in association with W/Z and $t\bar{t}$.

The Higgs boson production cross sections are computed up to next-to-next-to-leading order (NNLO) [20] in QCD for the gluon-fusion process. In addition, QCD soft-gluon resummations up to next-to-next-to-leading log improve the NNLO calculation [21]. The next-to-leading order (NLO) EW corrections are applied [22]. These results are compiled in Refs. [23] assuming factorization between QCD and EW corrections. The cross sections for the VBF process are calculated with full NLO QCD and EW corrections [24], and approximate NNLO QCD corrections are available [25]. The W/ZH processes are calculated at NLO [26] and at NNLO [27], and NLO EW radiative corrections [28] are applied. The full NLO QCD corrections for $t\bar{t}H$ are calculated [29]. The Higgs boson cross sections, branching ratios [30], and their uncertainties are compiled in Ref. [31].

The cross sections multiplied by the branching ratio into two photons are listed in Table III. The number of signal events produced by gluon fusion is rescaled to take into account the expected destructive interference between the $gg \to \gamma\gamma$ continuum background and the $gg \to H \to \gamma\gamma$ process [32], leading to a reduction of the production rate by 2–5% depending on m_H and analysis category. The fractions of gluon fusion, VBF, WH, ZH, and $t\bar{t}H$ production are approximately 87%, 7%, 3%, 2% and 1%, respectively, for $m_H = 120$ GeV.

The shower shape variables of the simulated samples are shifted to agree with the corresponding distributions in the data [11] and the photon energy resolution is broadened to account for differences observed between $Z \to ee$ data and MC events. Events generated with POWHEG at NLO have been reweighted to match the Higgs boson p_T distribution predicted by HQT [33]. The signal yields expected for 4.9 fb^{-1} and selection efficiencies are given in Table III.

The invariant mass shape of the signal in each category is modeled by the sum of a Crystal Ball function [34] describing the core of the distribution with a width σ_{CB}, and a wide Gaussian with a small amplitude describing the tails of the mass distribution. In Fig. 2, the sum of all signal processes in all categories is shown for a Higgs boson with $m_H = 120$ GeV. The expected full-width-at-half-maximum (FWHM) is 4.1 GeV and σ_{CB} is 1.7 GeV. The resolution varies with category (see Table II). The signal-to-background ratio (S/B), calculated in a mass window symmetric about the signal maximum and containing 90% of the signal, varies from 0.11 to 0.01 depending on the category and is also shown in Table II.

The background in each category is estimated from the data by fitting the diphoton mass spectrum in the range 100–160 GeV with an exponential function with free slope and normalization parameters. The background curve in Fig. 1 is the sum of these nine contributions. For each category, a single exponential fit satisfactorily describes the mass spectrum. This has been checked using large samples of diphoton events produced by the RESBOS [35] and DIPHOX [36] MC generators.

TABLE III. Higgs boson production cross section multiplied by the branching ratio into two photons, expected number of signal events summed over all categories for 4.9 fb^{-1}, and selection efficiencies for various Higgs boson masses.

m_H [GeV]	110	115	120	125	130	135	140	145	150
$\sigma \times BR$ [fb]	45	44	43	40	36	32	27	22	16
Signal events	69	72	72	69	65	58	50	41	31
Efficiency [%]	31	33	34	35	37	37	38	38	39

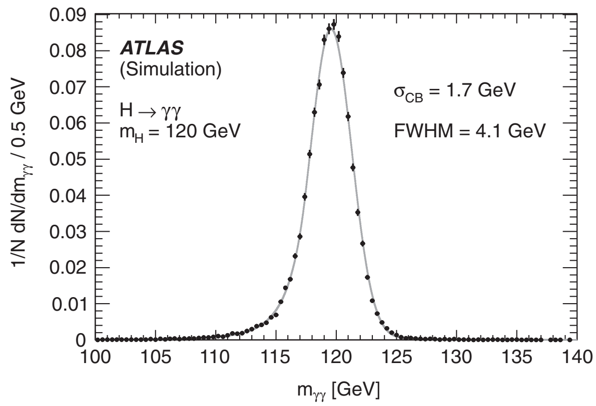

FIG. 2. Reconstructed invariant mass distribution for a simulated signal of $m_H = 120$ GeV summed over all categories, superimposed with the fit to the signal model.

The difference between the exponential function and the true background will contribute to an excess or a deficit of events over background expectations. In order to take this into account in a conservative way, a term is included in the likelihood function that allows for a signal-like component that is consistent with the background uncertainty. For each category this uncertainty is estimated from MC simulations by the difference between the mass distribution of diphoton events generated with RESBOS and the result of the exponential fit to this distribution. Photon reconstruction and identification efficiencies are taken into account. The MC events are scaled to correspond to 4.9 fb^{-1} of data. The uncertainty is then the maximal difference between the MC shape and the model integrated in a sliding mass window of 4 GeV, the approximate FWHM of the expected signal. The uncertainties obtained are $\pm(0.1 - 7.9)$ events depending on the category. Pseudoexperiments are used to check that the sum of $\gamma\gamma$, γj, and jj events can also be described well by the exponential model. The background uncertainties are further validated by fitting the data with functions that have more degrees of freedom than the single exponential, and comparing the residuals to those obtained with the exponential fit.

The dominant experimental uncertainty on the signal yield is the photon reconstruction and identification efficiency ($\pm$ 11%), which is estimated with data by using electrons from Z and W decays and photons selected from $Z \to \ell\ell\gamma$ ($\ell = e, \mu$) events. Pileup also affects the identification efficiency and contributes to the uncertainty ($\pm$ 4%). Further uncertainties on the signal yield are related to the trigger ($\pm$1%), Higgs boson p_T modeling ($\pm$1%), isolation ($\pm$5%), and luminosity ($\pm$3.9%). Uncertainties on the predicted cross sections are due to uncertainties on the QCD renormalization and factorization scales ($^{+12}_{-8}$%) and on the parton density functions ([37] and references therein) and α_s ($\pm$8%). The total uncertainty on the signal yield is $^{+20}_{-17}$%. The total uncertainty on the mass resolution is $\pm$14%, dominated by the uncertainty on the energy resolution of the calorimeter, determined from $Z \to ee$ events ($\pm$12%). Further uncertainties on the mass resolution result from an imperfect knowledge of material in front of the calorimeter affecting the extrapolation from electron to photon calibration ($\pm$6%), the impact of pileup ($\pm$3%) estimated from events taken with random triggers, and the photon angle measurement ($\pm$1%) estimated using $Z \to ee$ events. The uncertainty on the knowledge of the material in front of the calorimeter is used to derive the amount of event migration between the converted and unconverted categories ($\pm$ 4.5%). Different parton density functions and scale variations in HQT calculations are used to derive possible event migration between high and low p_{Tt} categories ($\pm$ 8%).

A modified frequentist approach (CL_S) [38] for setting limits and a frequentist approach to calculate the p_0 value are used [39]. The p_0 is the probability that the background fluctuates to the observed number of events or higher. The combined likelihood, which is a function of the ratio of the measured cross section relative to that of the SM prediction, is constructed from the unbinned likelihood functions of the nine categories. Systematic uncertainties are incorporated by introducing nuisance parameters with constraints. Asymptotic formulae [40] are used to derive the limits and p_0 values, which are refined with pseudoexperiments [41], as functions of the hypothetical Higgs boson mass.

The observed and expected local p_0 values and the 95% C.L. limits on the Higgs boson production in units of the SM cross section are displayed in Figs. 3 and 4. Before considering the uncertainty on the signal mass position, the largest excess with respect to the

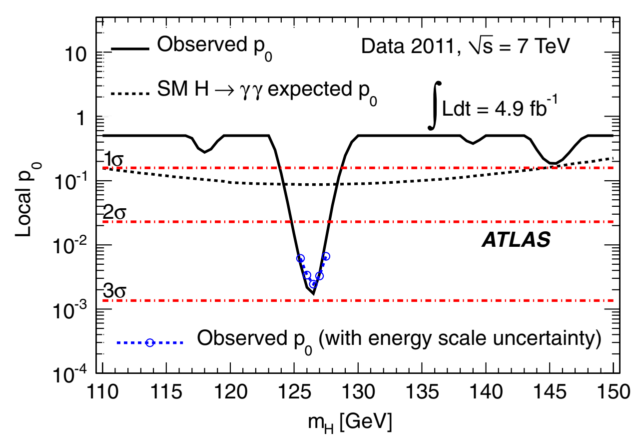

FIG. 3 (color online). The observed local p_0, the probability that the background fluctuates to the observed number of events or higher (solid line). The open points indicate the observed local p_0 value when energy scale uncertainties are taken into account. The dotted line shows the expected median local p_0 for the signal hypothesis when tested at m_H.

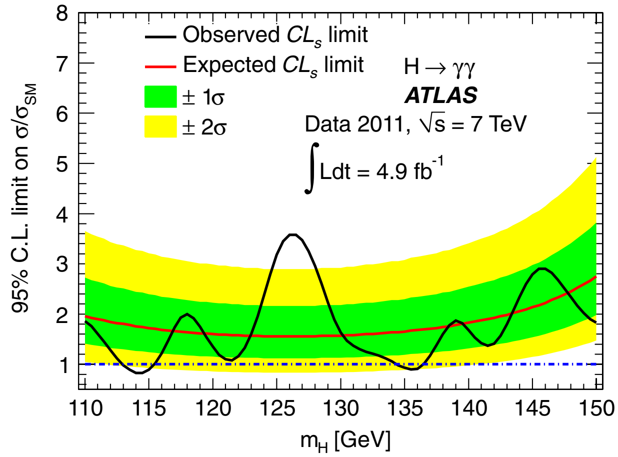

FIG. 4 (color online). Observed and expected 95% C.L. limits on the SM Higgs boson production normalized to the predicted cross section as a function of m_H.

background-only hypothesis in the mass range 110–150 GeV is observed at 126.5 GeV with a local significance of 2.9 standard deviations. The uncertainty on the mass position ($\pm$ 0.7 GeV) due to the imperfect knowledge of the photon energy scale has a small effect on the significance. When this uncertainty is taken into account, the significance is 2.8 standard deviations; this becomes 1.5 standard deviations when the look-elsewhere effect [42] for the mass range 110–150 GeV is included. The median expected upper limits of the cross section in the absence of a true signal, at the 95% C.L., vary between 1.6 and 1.7 times the SM cross section in the mass range 115–130 GeV, and between 1.6 and 2.7 in the mass range 110–150 GeV. The observed 95% C.L. upper limit of the cross section relative to the SM cross section is between 0.83 and 3.6 over the full mass range. A SM Higgs boson is excluded at 95% C.L. in the mass ranges of 113–115 GeV and 134.5–136 GeV. These results are combined with SM Higgs searches in other decay channels in Ref. [41].

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Solodkov,[126] O. V. Solovyanov,[126] N. Soni,[2] V. Sopko,[125] B. Sopko,[125] M. Sosebee,[7] R. Soualah,[162a,162c] A. Soukharev,[105] S. Spagnolo,[70a,70b] F. Spanò,[74] R. Spighi,[19a] G. Spigo,[29] F. Spila,[130a,130b] R. Spiwoks,[29] M. Spousta,[124] T. Spreitzer,[156] B. Spurlock,[7] R. D. St. Denis,[52] J. Stahlman,[118] R. Stamen,[57a] E. Stanecka,[38] R. W. Stanek,[5] C. Stanescu,[132a] M. Stanescu-Bellu,[41] S. Stapnes,[115] E. A. Starchenko,[126] J. Stark,[54] P. Staroba,[123] P. Starovoitov,[89] A. Staude,[96] P. Stavina,[142a] G. Steele,[52] P. Steinbach,[43] P. Steinberg,[24] I. Stekl,[125] B. Stelzer,[140] H. J. Stelzer,[86] O. Stelzer-Chilton,[157a] H. Stenzel,[51] S. Stern,[97] K. Stevenson,[73] G. A. Stewart,[29] J. A. Stillings,[20] M. C. Stockton,[83] K. Stoerig,[47] G. Stoicea,[25a] S. Stonjek,[97] P. Strachota,[124] A. R. Stradling,[7] A. Straessner,[43] J. Strandberg,[145] S. Strandberg,[144a,144b] A. Strandlie,[115] M. Strang,[107] E. Strauss,[141] M. Strauss,[109] P. Strizenec,[142b] R. Ströhmer,[171] D. M. Strom,[112] J. A. Strong,[74,a] R. Stroynowski,[39] J. Strube,[127] B. Stugu,[13] I. Stumer,[24,a] J. Stupak,[146] P. Sturm,[172] N. A. Styles,[41] D. A. Soh,[149,u] D. Su,[141] HS. Subramania,[2] A. Succurro,[11] Y. Sugaya,[114] T. Sugimoto,[99] C. Suhr,[104] K. Suita,[65] M. Suk,[124] V. V. Sulin,[92] S. Sultansoy,[3d] T. Sumida,[66] X. Sun,[54] J. E. Sundermann,[47] K. Suruliz,[137] S. Sushkov,[11] G. Susinno,[36a,36b] M. R. Sutton,[147] Y. Suzuki,[64] Y. Suzuki,[65] M. Svatos,[123] Yu. M. Sviridov,[126] S. Swedish,[166] I. Sykora,[142a] T. Sykora,[124] B. Szeless,[29] J. Sánchez,[165] D. Ta,[103] K. Tackmann,[41] A. Taffard,[161] R. Tafirout,[157a] N. Taiblum,[151] Y. Takahashi,[99] H. Takai,[24] R. Takashima,[67] H. Takeda,[65] T. Takeshita,[138] Y. Takubo,[64] M. Talby,[81] A. Talyshev,[105,g] M. C. Tamsett,[24] J. Tanaka,[153] R. Tanaka,[113] S. Tanaka,[129] S. Tanaka,[64] Y. Tanaka,[98] A. J. Tanasijczuk,[140] K. Tani,[65] N. Tannoury,[81] G. P. Tappern,[29] S. Tapprogge,[79] D. Tardif,[156] S. Tarem,[150] F. Tarrade,[28] G. F. Tartarelli,[87a] P. Tas,[124] M. Tasevsky,[123] E. Tassi,[36a,36b] M. Tatarkhanov,[14] Y. Tayalati,[133d] C. Taylor,[75] F. E. Taylor,[90] G. N. Taylor,[84] W. Taylor,[157b] M. Teinturier,[113] M. Teixeira Dias Castanheira,[73] P. Teixeira-Dias,[74] K. K. Temming,[47] H. Ten Kate,[29] P. K. Teng,[149] S. Terada,[64] K. Terashi,[153] J. Terron,[78] M. Testa,[46]

R. J. Teuscher,[156,k] J. Thadome,[172] J. Therhaag,[20] T. Theveneaux-Pelzer,[76] M. Thioye,[173] S. Thoma,[47] J. P. Thomas,[17] E. N. Thompson,[34] P. D. Thompson,[17] P. D. Thompson,[156] A. S. Thompson,[52] L. A. Thomsen,[35] E. Thomson,[118] M. Thomson,[27] R. P. Thun,[85] F. Tian,[34] M. J. Tibbetts,[14] T. Tic,[123] V. O. Tikhomirov,[92] Y. A. Tikhonov,[105,g] S. Timoshenko,[94] P. Tipton,[173] F. J. Tique Aires Viegas,[29] S. Tisserant,[81] J. Tobias,[47] B. Toczek,[37] T. Todorov,[4] S. Todorova-Nova,[159] B. Toggerson,[161] J. Tojo,[64] S. Tokár,[142a] K. Tokunaga,[65] K. Tokushuku,[64] K. Tollefson,[86] M. Tomoto,[99] L. Tompkins,[30] K. Toms,[101] G. Tong,[32a] A. Tonoyan,[13] C. Topfel,[16] N. D. Topilin,[63] I. Torchiani,[29] E. Torrence,[112] H. Torres,[76] E. Torró Pastor,[165] J. Toth,[81,z] F. Touchard,[81] D. R. Tovey,[137] T. Trefzger,[171] L. Tremblet,[29] A. Tricoli,[29] I. M. Trigger,[157a] S. Trincaz-Duvoid,[76] T. N. Trinh,[76] M. F. Tripiana,[68] W. Trischuk,[156] A. Trivedi,[24,y] B. Trocmé,[54] C. Troncon,[87a] M. Trottier-McDonald,[140] M. Trzebinski,[38] A. Trzupek,[38] C. Tsarouchas,[29] J. C-L. Tseng,[116] M. Tsiakiris,[103] P. V. Tsiareshka,[88] D. Tsionou,[4,cc] G. Tsipolitis,[9] V. Tsiskaridze,[47] E. G. Tskhadadze,[50a] I. I. Tsukerman,[93] V. Tsulaia,[14] J.-W. Tsung,[20] S. Tsuno,[64] D. Tsybychev,[146] A. Tua,[137] A. Tudorache,[25a] V. Tudorache,[25a] J. M. Tuggle,[30] M. Turala,[38] D. Turecek,[125] I. Turk Cakir,[3e] E. Turlay,[103] R. Turra,[87a,87b] P. M. Tuts,[34] A. Tykhonov,[72] M. Tylmad,[144a,144b] M. Tyndel,[127] G. Tzanakos,[8] K. Uchida,[20] I. Ueda,[153] R. Ueno,[28] M. Ugland,[13] M. Uhlenbrock,[20] M. Uhrmacher,[53] F. Ukegawa,[158] G. Unal,[29] D. G. Underwood,[5] A. Undrus,[24] G. Unel,[161] Y. Unno,[64] D. Urbaniec,[34] G. Usai,[7] M. Uslenghi,[117a,117b] L. Vacavant,[81] V. Vacek,[125] B. Vachon,[83] S. Vahsen,[14] J. Valenta,[123] P. Valente,[130a] S. Valentinetti,[19a,19b] S. Valkar,[124] E. Valladolid Gallego,[165] S. Vallecorsa,[150] J. A. Valls Ferrer,[165] H. van der Graaf,[103] E. van der Kraaij,[103] R. Van Der Leeuw,[103] E. van der Poel,[103] D. van der Ster,[29] N. van Eldik,[82] P. van Gemmeren,[5] Z. van Kesteren,[103] I. van Vulpen,[103] M. Vanadia,[97] W. Vandelli,[29] G. Vandoni,[29] A. Vaniachine,[5] P. Vankov,[41] F. Vannucci,[76] F. Varela Rodriguez,[29] R. Vari,[130a] E. W. Varnes,[6] T. Varol,[82] D. Varouchas,[14] A. Vartapetian,[7] K. E. Varvell,[148] V. I. Vassilakopoulos,[55] F. Vazeille,[33] T. Vazquez Schroeder,[53] G. Vegni,[87a,87b] J. J. Veillet,[113] C. Vellidis,[8] F. Veloso,[122a] R. Veness,[29] S. Veneziano,[130a] A. Ventura,[70a,70b] D. Ventura,[136] M. Venturi,[47] N. Venturi,[156] V. Vercesi,[117a] M. Verducci,[136] W. Verkerke,[103] J. C. Vermeulen,[103] A. Vest,[43] M. C. Vetterli,[140,e] I. Vichou,[163] T. Vickey,[143b,dd] O. E. Vickey Boeriu,[143b] G. H. A. Viehhauser,[116] S. Viel,[166] M. Villa,[19a,19b] M. Villaplana Perez,[165] E. Vilucchi,[46] M. G. Vincter,[28] E. Vinek,[29] V. B. Vinogradov,[63] M. Virchaux,[134,a] J. Virzi,[14] O. Vitells,[169] M. Viti,[41] I. Vivarelli,[47] F. Vives Vaque,[2] S. Vlachos,[9] D. Vladoiu,[96] M. Vlasak,[125] N. Vlasov,[20] A. Vogel,[20] P. Vokac,[125] G. Volpi,[46] M. Volpi,[84] G. Volpini,[87a] H. von der Schmitt,[97] J. von Loeben,[97] H. von Radziewski,[47] E. von Toerne,[20] V. Vorobel,[124] A. P. Vorobiev,[126] V. Vorwerk,[11] M. Vos,[165] R. Voss,[29] T. T. Voss,[172] J. H. Vossebeld,[71] N. Vranjes,[134] M. Vranjes Milosavljevic,[103] V. Vrba,[123] M. Vreeswijk,[103] T. Vu Anh,[47] R. Vuillermet,[29] I. Vukotic,[113] W. Wagner,[172] P. Wagner,[118] H. Wahlen,[172] J. Wakabayashi,[99] S. Walch,[85] J. Walder,[69] R. Walker,[96] W. Walkowiak,[139] R. Wall,[173] P. Waller,[71] C. Wang,[44] H. Wang,[170] H. Wang,[32b,ee] J. Wang,[149] J. Wang,[54] J. C. Wang,[136] R. Wang,[101] S. M. Wang,[149] A. Warburton,[83] C. P. Ward,[27] M. Warsinsky,[47] C. Wasicki,[41] P. M. Watkins,[17] A. T. Watson,[17] I. J. Watson,[148] M. F. Watson,[17] G. Watts,[136] S. Watts,[80] A. T. Waugh,[148] B. M. Waugh,[75] M. Weber,[127] M. S. Weber,[16] P. Weber,[53] A. R. Weidberg,[116] P. Weigell,[97] J. Weingarten,[53] C. Weiser,[47] H. Wellenstein,[22] P. S. Wells,[29] T. Wenaus,[24] D. Wendland,[15] S. Wendler,[121] Z. Weng,[149,u] T. Wengler,[29] S. Wenig,[29] N. Wermes,[20] M. Werner,[47] P. Werner,[29] M. Werth,[161] M. Wessels,[57a] J. Wetter,[159] C. Weydert,[54] K. Whalen,[28] S. J. Wheeler-Ellis,[161] S. P. Whitaker,[21] A. White,[7] M. J. White,[84] S. R. Whitehead,[116] D. Whiteson,[161] D. Whittington,[59] F. Wicek,[113] D. Wicke,[172] F. J. Wickens,[127] W. Wiedenmann,[170] M. Wielers,[127] P. Wienemann,[20] C. Wiglesworth,[73] L. A. M. Wiik,[47] P. A. Wijeratne,[75] A. Wildauer,[165] M. A. Wildt,[41,q] I. Wilhelm,[124] H. G. Wilkens,[29] J. Z. Will,[96] E. Williams,[34] H. H. Williams,[118] W. Willis,[34] S. Willocq,[82] J. A. Wilson,[17] M. G. Wilson,[141] A. Wilson,[85] I. Wingerter-Seez,[4] S. Winkelmann,[47] F. Winklmeier,[29] M. Wittgen,[141] M. W. Wolter,[38] H. Wolters,[122a,i] W. C. Wong,[40] G. Wooden,[85] B. K. Wosiek,[38] J. Wotschack,[29] M. J. Woudstra,[82] K. W. Wozniak,[38] K. Wraight,[52] C. Wright,[52] M. Wright,[52] B. Wrona,[71] S. L. Wu,[170] X. Wu,[48] Y. Wu,[32b,ff] E. Wulf,[34] R. Wunstorf,[42] B. M. Wynne,[45] S. Xella,[35] M. Xiao,[134] S. Xie,[47] Y. Xie,[32a] C. Xu,[32b,gg] D. Xu,[137] G. Xu,[32a] B. Yabsley,[148] S. Yacoob,[143b] M. Yamada,[64] H. Yamaguchi,[153] A. Yamamoto,[64] K. Yamamoto,[62] S. Yamamoto,[153] T. Yamamura,[153] T. Yamanaka,[153] J. Yamaoka,[44] T. Yamazaki,[153] Y. Yamazaki,[65] Z. Yan,[21] H. Yang,[85] U. K. Yang,[80] Y. Yang,[59] Y. Yang,[32a] Z. Yang,[144a,144b] S. Yanush,[89] Y. Yao,[14] Y. Yasu,[64] G. V. Ybeles Smit,[128] J. Ye,[39] S. Ye,[24] M. Yilmaz,[3c] R. Yoosoofmiya,[121] K. Yorita,[168] R. Yoshida,[5] C. Young,[141] S. 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(ATLAS Collaboration)

[1]*University at Albany, Albany, New York, USA*
[2]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[3a]*Department of Physics, Ankara University, Ankara, Turkey*
[3b]*Department of Physics, Dumlupinar University, Kutahya, Turkey*
[3c]*Department of Physics, Gazi University, Ankara, Turkey*
[3d]*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
[3e]*Turkish Atomic Energy Authority, Ankara, Turkey*
[4]*LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France*
[5]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*
[6]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[7]*Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA*
[8]*Physics Department, University of Athens, Athens, Greece*
[9]*Physics Department, National Technical University of Athens, Zografou, Greece*
[10]*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
[11]*Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain*
[12a]*Institute of Physics, University of Belgrade, Belgrade, Serbia*
[12b]*Vinca Institute of Nuclear Sciences, Belgrade, Serbia*
[13]*Department for Physics and Technology, University of Bergen, Bergen, Norway*
[14]*Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA*
[15]*Department of Physics, Humboldt University, Berlin, Germany*
[16]*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[17]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[18a]*Department of Physics, Bogazici University, Istanbul, Turkey*
[18b]*Division of Physics, Dogus University, Istanbul, Turkey*
[18c]*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
[18d]*Department of Physics, Istanbul Technical University, Istanbul, Turkey*
[19a]*INFN Sezione di Bologna, Bologna, Italy*
[19b]*Dipartimento di Fisica, Università di Bologna, Bologna, Italy*
[20]*Physikalisches Institut, University of Bonn, Bonn, Germany*
[21]*Department of Physics, Boston University, Boston, Massachusetts, USA*
[22]*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
[23a]*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
[23b]*Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil*
[23c]*Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil*
[23d]*Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil*
[24]*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
[25a]*National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[25b]*University Politehnica Bucharest, Bucharest, Romania*
[25c]*West University in Timisoara, Timisoara, Romania*
[26]*Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
[27]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[28]*Department of Physics, Carleton University, Ottawa, Ontario, Canada*
[29]*CERN, Geneva, Switzerland*
[30]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
[31a]*Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago, Chile*
[31b]*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[32a]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
[32b]*Department of Modern Physics, University of Science and Technology of China, Anhui, China*
[32c]*Department of Physics, Nanjing University, Jiangsu, China*
[32d]*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, New York, USA*
[35]*Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark*
[36a]*INFN Gruppo Collegato di Cosenza, Italy*
[36b]*Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy*
[37]*Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Krakow, Poland*
[38]*The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland*
[39]*Physics Department, Southern Methodist University, Dallas Texas, USA*
[40]*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
[41]*DESY, Hamburg and Zeuthen, Germany*
[42]*Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
[43]*Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany*
[44]*Department of Physics, Duke University, Durham, North Carolina, USA*
[45]*SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[46]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[47]*Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany*
[48]*Section de Physique, Université de Genève, Geneva, Switzerland*
[49a]*INFN Sezione di Genova, Italy*
[49b]*Dipartimento di Fisica, Università di Genova, Genova, Italy*
[50a]*E.Andronikashvili Institute of Physics, Georgian Academy of Sciences, Tbilisi, Georgia*
[50b]*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, Virginia, USA*
[56]*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*
[57a]*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[57b]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[57c]*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, Indiana, USA*
[60]*Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
[61]*University of Iowa, Iowa City Iowa, USA*
[62]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
[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]*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
[69]*Physics Department, Lancaster University, Lancaster, United Kingdom*
[70a]*INFN Sezione di Lecce, Italy*
[70b]*Dipartimento di Fisica, Università del Salento, Lecce, Italy*
[71]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[72]*Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia*
[73]*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
[74]*Department of Physics, Royal Holloway University of London, Surrey, United Kingdom*
[75]*Department of Physics and Astronomy, University College London, London, United Kingdom*
[76]*Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*
[77]*Fysiska institutionen, Lunds universitet, Lund, Sweden*
[78]*Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain*
[79]*Institut für Physik, Universität Mainz, Mainz, Germany*
[80]*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[81]*CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France*
[82]*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
[83]*Department of Physics, McGill University, Montreal, Quebec, Canada*
[84]*School of Physics, University of Melbourne, Victoria, Australia*
[85]*Department of Physics, The University of Michigan, Ann Arbor Michigan, USA*

[86]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
[87a]*INFN Sezione di Milano, Italy*
[87b]*Dipartimento di Fisica, Università di Milano, Milano, Italy*
[88]*B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus*
[89]*National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus*
[90]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[91]*Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada*
[92]*P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia*
[93]*Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
[94]*Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia*
[95]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
[96]*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
[97]*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
[98]*Nagasaki Institute of Applied Science, Nagasaki, Japan*
[99]*Graduate School of Science, Nagoya University, Nagoya, Japan*
[100a]*INFN Sezione di Napoli, Italy*
[100b]*Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy*
[101]*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
[102]*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
[103]*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
[104]*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
[105]*Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia*
[106]*Department of Physics, New York University, New York New York, USA*
[107]*Ohio State University, Columbus, Ohio, USA*
[108]*Faculty of Science, Okayama University, Okayama, Japan*
[109]*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman Oklahoma, USA*
[110]*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
[111]*Palacký University, RCPTM, Olomouc, Czech Republic*
[112]*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
[113]*LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France*
[114]*Graduate School of Science, Osaka University, Osaka, Japan*
[115]*Department of Physics, University of Oslo, Oslo, Norway*
[116]*Department of Physics, Oxford University, Oxford, United Kingdom*
[117a]*INFN Sezione di Pavia, Italy*
[117b]*Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy*
[118]*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
[119]*Petersburg Nuclear Physics Institute, Gatchina, Russia*
[120a]*INFN Sezione di Pisa, Italy*
[120b]*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
[121]*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
[122a]*Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal*
[122b]*Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain*
[123]*Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
[124]*Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic*
[125]*Czech Technical University in Prague, Praha, Czech Republic*
[126]*State Research Center Institute for High Energy Physics, Protvino, Russia*
[127]*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
[128]*Physics Department, University of Regina, Regina, Saskatchewan, Canada*
[129]*Ritsumeikan University, Kusatsu, Shiga, Japan*
[130a]*INFN Sezione di Roma I, Italy*
[130b]*Dipartimento di Fisica, Università La Sapienza, Roma, Italy*
[131a]*INFN Sezione di Roma Tor Vergata, Italy*
[131b]*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
[132a]*INFN Sezione di Roma Tre, Italy*
[132b]*Dipartimento di Fisica, Università Roma Tre, Roma, Italy*
[133a]*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco*
[133b]*Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat, Morocco*
[133c]*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
[133d]*Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco*
[133e]*Faculté des Sciences, Université Mohammed V, Rabat, Morocco*

[134]DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
[135]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
[136]Department of Physics, University of Washington, Seattle, Washington, USA
[137]Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[138]Department of Physics, Shinshu University, Nagano, Japan
[139]Fachbereich Physik, Universität Siegen, Siegen, Germany
[140]Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
[141]SLAC National Accelerator Laboratory, Stanford, California, USA
[142a]Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
[142b]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[143a]Department of Physics, University of Johannesburg, Johannesburg, South Africa
[143b]School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[144a]Department of Physics, Stockholm University, Sweden
[144b]The Oskar Klein Centre, Stockholm, Sweden
[145]Physics Department, Royal Institute of Technology, Stockholm, Sweden
[146]Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA
[147]Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[148]School of Physics, University of Sydney, Sydney, Australia
[149]Institute of Physics, Academia Sinica, Taipei, Taiwan
[150]Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
[151]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[152]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[153]International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
[154]Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[155]Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[156]Department of Physics, University of Toronto, Toronto ON, Canada
[157a]TRIUMF, Vancouver, British Columbia, Canada
[157b]Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
[158]Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan
[159]Science and Technology Center, Tufts University, Medford, Massachusetts, USA
[160]Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[161]Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
[162a]INFN Gruppo Collegato di Udine, Italy
[162b]ICTP, Trieste, Italy
[162c]Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
[163]Department of Physics, University of Illinois, Urbana, Illinois, USA
[164]Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[165]Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingenieriá Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
[166]Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
[167]Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
[168]Waseda University, Tokyo, Japan
[169]Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[170]Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
[171]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
[172]Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[173]Department of Physics, Yale University, New Haven, Connecticut, USA
[174]Yerevan Physics Institute, Yerevan, Armenia
[175]Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

[a]Deceased.
[b]Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal.
[c]Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
[d]Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
[e]Also at TRIUMF, Vancouver, BC, Canada.
[f]Also at Department of Physics, California State University, Fresno, CA, USA.
[g]Also at Novosibirsk State University, Novosibirsk, Russia.
[h]Also at Fermilab, Batavia, IL, USA.
[i]Also at Department of Physics, University of Coimbra, Coimbra, Portugal.

[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, USA.
[n]Also at Department of Physics and Astronomy, University College London, London, United Kingdom.
[o]Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
[p]Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[q]Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[r]Also at Manhattan College, New York, NY, USA.
[s]Also at School of Physics, Shandong University, Shandong, China.
[t]Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
[u]Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
[v]Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
[w]Also at Section de Physique, Université de Genève, Geneva, Switzerland.
[x]Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
[y]Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
[z]Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
[aa]Also at California Institute of Technology, Pasadena, CA, USA.
[bb]Also at LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France.
[cc]Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
[dd]Also at Department of Physics, Oxford University, Oxford, United Kingdom.
[ee]Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
[ff]Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
[gg]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.
[hh]Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
[ii]Also at Institute of Physics, Jagiellonian University, Krakow, Poland