

# Study of excited $\Lambda^0_b$ states decaying to $\Lambda^0_b\pi^+\pi^-$ in proton-proton collisions at $\sqrt{s}=13\text{TeV}$

## Journal Article

### Author(s):

CMS Collaboration; Sirunyan, Albert M.; Tumasyan, Armen R.; Adam, Wolfgang; Ambrogio, Federico; Bergauer, Thomas; Dragicevic, Marko; Erö, János; Escalante Del Valle, Alberto; Flechl, Martin; Frühwirth, Rudolf K.; Jeitler, Manfred A.; Krammer, N.; Krätschmer, Ilse; Liko, Dietrich; Madlener, Thomas; Mikulec, Ivan; Rad, Navid K.; Schieck, Jochen R.; Schöffbeck, Robert; Spanring, Markus; et al.

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# Study of excited $\Lambda_b^0$ states decaying to $\Lambda_b^0\pi^+\pi^-$ in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration\*

CERN, Switzerland



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## ABSTRACT

A study of excited  $\Lambda_b^0$  baryons is reported, based on a data sample collected in 2016–2018 with the CMS detector at the LHC in proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of up to  $140\text{ fb}^{-1}$ . The existence of four excited  $\Lambda_b^0$  states:  $\Lambda_b^0(5912)^0$ ,  $\Lambda_b^0(5920)^0$ ,  $\Lambda_b^0(6146)^0$ , and  $\Lambda_b^0(6152)^0$  in the  $\Lambda_b^0\pi^+\pi^-$  mass spectrum is confirmed, and their masses are measured. The  $\Lambda_b^0\pi^+\pi^-$  mass distribution exhibits a broad excess of events in the region of 6040–6100 MeV, whose origin cannot be discerned with the present data.

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## 1. Introduction

Studies of excited baryonic states are an important aspect of hadron spectroscopy and help to shed light on the mechanisms responsible for dynamics of quarks and baryon formation. In particular, spectroscopy of baryons that contain a heavy-flavor quark, such as the  $\Lambda_b^0$  baryon, can test predictions of heavy-quark effective theory [1]. A number of theoretical calculations exist for various orbital and radial excitations of the ground state baryons containing a b quark [2–16], including those of the  $\Lambda_b^0$  baryon. In general, there are a number of excited  $\Lambda_b^0$  baryon states predicted in the 5.9–6.4 GeV mass range. However, predictions are very diverse in terms of the specific mass spectrum and do not point to any common narrow mass region in which to search for these excited states. As an additional complication, the widths and the production cross sections of various excited states are generally unknown. This situation makes experimental searches for excited heavy-quark baryons both challenging and important for testing various theoretical models.

The existence of two narrow excited  $\Lambda_b^0$  states,  $\Lambda_b^0(5912)^0$  and  $\Lambda_b^0(5920)^0$ , in the  $\Lambda_b^0\pi^+\pi^-$  invariant mass spectrum near the kinematic threshold was reported by the LHCb Collaboration in 2012 [17] (charge-conjugate states are implied throughout

this Letter). The measured masses are  $M(\Lambda_b^0(5912)^0) = 5911.97 \pm 0.67$  MeV and  $M(\Lambda_b^0(5920)^0) = 5919.77 \pm 0.67$  MeV, and the respective natural widths were found to be below 0.83 and 0.75 MeV at 95% confidence level. The latter state was confirmed by the CDF Collaboration [18] soon thereafter with the mass measured to be  $M(\Lambda_b^0(5920)^0) = 5919.22 \pm 0.76$  MeV. The precision of these measurements was limited by the large uncertainty in the  $\Lambda_b^0$  mass at the time; the current world-average values  $M(\Lambda_b^0(5912)^0) = 5912.20 \pm 0.21$  MeV and  $M(\Lambda_b^0(5920)^0) = 5919.92 \pm 0.19$  MeV [19] are based on the updated  $\Lambda_b^0$  mass measurement [20,21]. Recently, the LHCb experiment has also presented an observation of two narrow higher-mass states in the  $\Lambda_b^0\pi^+\pi^-$  spectrum, with the following masses and widths [22]:  $M(\Lambda_b^0(6146)^0) = 6146.17 \pm 0.43$  MeV,  $\Gamma(\Lambda_b^0(6146)^0) = 2.9 \pm 1.3$  MeV, and  $M(\Lambda_b^0(6152)^0) = 6152.51 \pm 0.38$  MeV,  $\Gamma(\Lambda_b^0(6152)^0) = 2.1 \pm 0.9$  MeV.

In this Letter, a study of the  $\Lambda_b^0\pi^+\pi^-$  invariant mass distribution in the 5900–6400 GeV range by the CMS Collaboration is reported. Both the  $\Lambda_b^0(5912)^0$  and  $\Lambda_b^0(5920)^0$  states near the kinematic threshold are confirmed and their masses are measured. In addition, the  $\Lambda_b^0\pi^+\pi^-$  distribution is investigated in the higher-mass region and signals consistent with the  $\Lambda_b^0(6146)^0$  and  $\Lambda_b^0(6152)^0$  states are observed. The ground state baryon  $\Lambda_b^0$  is reconstructed via its decays into the  $J/\psi\Lambda$  and  $\psi(2S)\Lambda$  channels. The analysis uses the proton-proton (pp) collision data recorded

\* E-mail address: [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch).

with the CMS detector in 2016–2018, during the CERN LHC Run 2 at  $\sqrt{s} = 13$  TeV, corresponding to an integrated luminosity of up to  $140 \text{ fb}^{-1}$ .

## 2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [23].

Events of interest are selected using a two-tiered trigger system [24]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than  $4 \mu\text{s}$ . The L1 trigger used in the analysis required at least two muons. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage. The set of HLT algorithms used in the analysis requires two opposite-sign (OS) muons with various pseudorapidity  $\eta$  and transverse momentum  $p_T$  thresholds, compatible with being produced in the dimuon decays of  $J/\psi$  or  $\psi(2S)$  mesons. Given that no single trigger algorithm is dedicated to the decay signature of interest, the analysis uses a combination of several triggers, with integrated luminosities up to  $140 \text{ fb}^{-1}$ .

## 3. Event selection

The event selection begins by requiring two OS muons passing the CMS soft-muon identification criteria [25] with  $p_T > 3 \text{ GeV}$  and  $|\eta| < 2.2$ . The muons must form a common vertex with a  $\chi^2$  fit probability ( $P_{\text{vtx}}$ ) greater than 1%. The dimuon invariant mass is required to satisfy  $2.90 < M(\mu^+\mu^-) < 3.95 \text{ GeV}$ . If  $M(\mu^+\mu^-)$  is below  $3.4 \text{ GeV}$ , the dimuon system is considered to be a  $J/\psi$  candidate, or a  $\psi(2S)$  candidate otherwise.

Another  $\psi(2S)$  decay channel is also used to increase the signal yield:  $\psi(2S) \rightarrow J/\psi\pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^-$ . Two additional, high purity [26], OS tracks, assumed to be pions and labeled  $\pi_{\psi(2S)}$ , are required to have  $p_T > 0.35 \text{ GeV}$ . They are fit to a common vertex with a  $J/\psi$  candidate, using a world-average  $J/\psi$  meson mass [19] constraint. The invariant mass of the  $J/\psi$  candidate and the two tracks must satisfy the requirement  $3672 < M(J/\psi\pi^+\pi^-) < 3700 \text{ MeV}$ , corresponding to a window centered on the world-average  $\psi(2S)$  meson mass, with a half-width of approximately three times the corresponding mass resolution.

A  $\Lambda$  candidate is formed from a displaced two-prong vertex, assuming the decay  $\Lambda \rightarrow p\pi^-$ , as described in Ref. [27]. The  $p\pi^-$  invariant mass is required to be within  $\pm 10 \text{ MeV}$  of the world-average  $\Lambda$  baryon mass  $m_{\Lambda}^{\text{PDG}}$  [19], which corresponds to approximately three times the  $\Lambda$  candidate mass resolution. The two tracks are refitted with their invariant mass constrained to  $m_{\Lambda}^{\text{PDG}}$ , and the obtained  $\Lambda$  candidate is required to have  $P_{\text{vtx}} > 1\%$ .

To form the  $\Lambda_b^0$  candidates, the  $J/\psi$  or  $\psi(2S)$  candidate and the  $\Lambda$  candidate are fit to a common vertex with  $P_{\text{vtx}} > 1\%$ , where the world-average  $J/\psi$  or  $\psi(2S)$  mass [19] constraint is applied to the muon pair. In the case of the  $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$  decay channel, only the  $J/\psi \rightarrow \mu^+\mu^-$  mass constraint is used.

The primary vertex (PV) associated with the  $\Lambda_b^0$  candidate is selected among all the reconstructed vertices by requiring the smallest angle between the reconstructed  $\Lambda_b^0$  candidate momentum and the vector pointing from this vertex to the  $\Lambda_b^0$  decay vertex. The PV is then refitted after removing the tracks associated with the  $\Lambda$  and either the  $J/\psi$  or  $\psi(2S)$  candidates. The decay length of the  $\Lambda_b^0$  candidate in the transverse plane,  $L_{xy}$ , is computed as the two-dimensional distance between the PV and the  $\Lambda_b^0$  decay vertex, and is required to exceed three times its uncertainty. This selection helps to suppress the combinatorial background. In addition, the transverse momentum of the  $\Lambda_b^0$  candidate is required to be well aligned with the transverse displacement vector:  $\cos\alpha > 0.99$ , where  $\alpha$  is the angle between the projections on the plane transverse to the beams of the  $\Lambda_b^0$  candidate momentum and of the vector connecting the PV with the  $\Lambda_b^0$  decay vertex. The numbers of  $\Lambda_b^0$  signal candidates after these requirements are about 39 000, 3400, and 4300 for the  $J/\psi\Lambda$ ,  $\psi(2S)\Lambda$  ( $\psi(2S) \rightarrow \mu^+\mu^-$ ), and  $\psi(2S)\Lambda$  ( $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ ) channels, respectively.

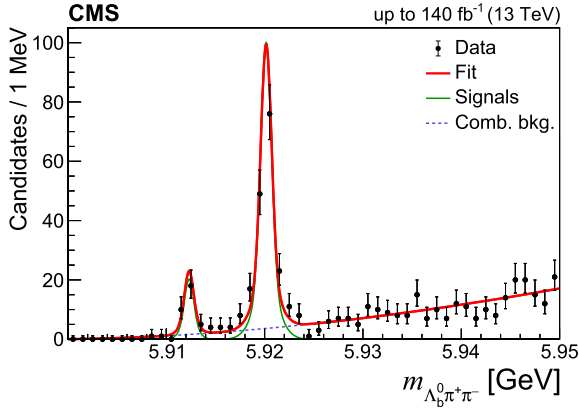
The  $\Lambda_b^0\pi^+\pi^-$  candidates are formed by combining the selected  $\Lambda_b^0$  candidates with two OS tracks originating from the PV, as in Refs. [28–30], since the lifetime of excited  $\Lambda_b^0$  states is expected to be negligible, resulting in prompt decays. Combinations of a  $\Lambda_b^0$  candidate with two prompt same-sign (SS) pions are used as a control channel and form the SS control region, as opposed to the OS signal region. The higher- $p_T$  pion of the pair is labeled  $\pi_1^\pm$  and the lower- $p_T$  pion  $\pi_2^\pm$ . To improve the  $\Lambda_b^0\pi^+\pi^-$  invariant mass resolution, all tracks forming the PV and the selected  $\Lambda_b^0$  candidate, taken as a single “pseudo-track” with the momentum, its uncertainty, and the assigned mass equal to those of the  $\Lambda_b^0$  candidate, are refit to a common vertex. The  $\Lambda_b^0\pi^+\pi^-$  invariant mass  $m_{\Lambda_b^0\pi^+\pi^-}$  is then calculated using the momenta of particles returned by this vertex fit through the relation  $m_{\Lambda_b^0\pi^+\pi^-} = M(\Lambda_b^0\pi^+\pi^-) - M(\Lambda_b^0) + m_{\Lambda_b^0}^{\text{PDG}}$ , where  $m_{\Lambda_b^0}^{\text{PDG}} = 5619.60 \pm 0.17 \text{ MeV}$  is the world-average  $\Lambda_b^0$  baryon mass [19]. The PV refitting procedure improves the  $\Lambda_b^0\pi^+\pi^-$  mass resolution by up to 50%. Unless specified otherwise, multiple  $\Lambda_b^0\pi^+\pi^-$  candidates found in the same event are not discarded.

## 4. Simulated samples and selection optimization

Several simulated signal samples with different masses of excited  $\Lambda_b^0$  states are used in the analysis. The PYTHIA 8.230 package [31] is used to simulate the production of the excited  $\Lambda_b^0$  states. The  $\Sigma_b^0$  baryon, with a modified mass value, is used as a proxy for an excited  $\Lambda_b^0$  baryon. The decays are described with EVTGEN 1.6.0 [32]. Final-state photon radiation is included in EVTGEN using PHOTOS [33,34]. Generated events are then passed to a detailed GEANT4-based simulation [35] of the CMS detector, followed by the same trigger and reconstruction algorithms used for collision data. The simulation includes effects from multiple pp interactions in the same or nearby bunch crossings (pileup) with the multiplicity distribution matching that observed in data.

Simulated samples are used to optimize the selection criteria using the Punzi figure of merit [36], i.e., optimizing the value of  $S/(\frac{S}{2} + \sqrt{B})$ , where  $S$  is the simulated signal yield and  $B$  is the expected background, as estimated using the SS control region. This optimization scheme is independent of the signal normalization.

The selection requirements are optimized separately for the low-mass  $m_{\Lambda_b^0\pi^+\pi^-} < 5950 \text{ MeV}$  and high-mass  $5950 < m_{\Lambda_b^0\pi^+\pi^-} < 6400 \text{ MeV}$  regions, using the  $\Lambda_b^0(5912)^0$  and  $\Lambda_b^0(6150)^0$  simulated signal samples, respectively. For the low-mass region, the optimized criteria are:  $p_T(\pi_1^\pm) > 0.3 \text{ GeV}$ ,  $p_T(\pi_2^\pm) > 0.35 \text{ GeV}$ ,  $\cos\alpha >$



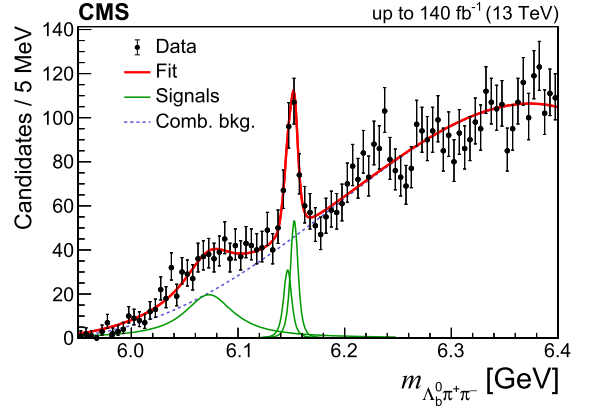
**Fig. 1.** Invariant mass distribution of the selected  $\Lambda_b^0 \pi^+ \pi^-$  candidates near threshold. The vertical bars on the data points display the statistical uncertainties in the data. The overall fit result is shown by the thick solid line, with the thin and dashed lines representing the signal and combinatorial background components, respectively.

$0.995$ ,  $\cos \alpha^{3D} > 0.995$ , and  $p_T(\pi_{\psi(2S)}) > 0.4 \text{ GeV}$ , where  $\alpha^{3D}$  is a three-dimensional analog of the angle  $\alpha$ . For the high-mass region, the optimized requirements are found to be  $p_T(\pi_2^\pm) > 0.7 \text{ GeV}$ ,  $p_T(\pi_1^\pm) > 1.4 \text{ GeV}$ ,  $p_T(\Lambda_b^0) > 16 \text{ GeV}$ ,  $P_{\text{vtx}}(\Lambda_b^0) > 2\%$ , and  $P_{\text{vtx}}(\Lambda_b^0 \pi^+ \pi^-) > 8\%$ . In the high-mass region, due to higher backgrounds, if multiple excited  $\Lambda_b^0$  candidates in an event pass the above requirements, only the highest  $p_T$  candidate is kept. In the low-mass region the average number of candidates per event is very close to one, while in the high-mass region it is around two.

## 5. Observed $\Lambda_b^0 \pi^+ \pi^-$ invariant mass spectra

The observed invariant mass distribution  $m_{\Lambda_b^0 \pi^+ \pi^-}$  of the selected signal candidates near the threshold is shown in Fig. 1. The two narrow peaks corresponding to the  $\Lambda_b^0(5912)^0$  and  $\Lambda_b^0(5920)^0$  baryons are modeled with double-Gaussian functions with the resolution parameters fixed to those obtained in simulation (effective resolutions are about 0.6 and 0.8 MeV). The background is modeled with a threshold function  $(x - x_0)^\beta$ , where  $x_0$  is the mass threshold value. The value of  $\beta$ , as well as the masses and normalizations of the two signal functions, are free parameters of an unbinned maximum-likelihood fit to data. The best-fit signal yields are  $28.4 \pm 5.8$  and  $159 \pm 14$  events, and the measured masses are  $5912.32 \pm 0.12 \text{ MeV}$  and  $5920.16 \pm 0.07 \text{ MeV}$ , respectively, where the uncertainties are statistical only. The presence of each of the peaks is established with a statistical significance of 5.7 and well over 6 standard deviations ( $\sigma$ ), for the  $\Lambda_b^0(5912)^0$  and  $\Lambda_b^0(5920)^0$  states, respectively, thereby confirming the existence of these two baryon states. The significances have been evaluated with the likelihood-ratio technique by applying the one- and two-peak signal hypotheses. The likelihood ratios are evaluated using an asymptotic formula [37,38]. The means and resolution parameters of the two peaks are allowed to vary in the fit within the Gaussian constraints from Ref. [19] and the simulation. The significance of the  $\Lambda_b^0(5912)^0$  state varies between 5.4 and 5.7 $\sigma$  with the variations in the fit model used to estimate the systematic uncertainties, as detailed in Section 6; the significance of the  $\Lambda_b^0(5920)^0$  state remains well above 6 $\sigma$ .

Higher masses in the  $m_{\Lambda_b^0 \pi^+ \pi^-}$  distribution are studied as well, as shown in Fig. 2. A narrow peak at approximately 6150 MeV is evident, consistent with an overlap of the  $\Lambda_b^0(6146)^0$  and  $\Lambda_b^0(6152)^0$  signals, as well as a broad enhancement in the region below 6100 MeV. None of these features are present in the SS con-



**Fig. 2.** Invariant mass distribution of the selected  $\Lambda_b^0 \pi^+ \pi^-$  candidates in the high-mass region. The vertical bars on the data points represent the statistical uncertainties in the data. The overall fit result is shown by the thick solid line. The thin lines present the contributions from the two signal peaks and the broad enhancement. The dashed line displays the combinatorial background.

trol region, as shown in the supplemental material [URL will be inserted by publisher].

A number of cross-checks have been performed to understand if the broad enhancement can be the result of a kinematic reflection or produced by a background process. It was found that the enhancement is not compatible with the partially reconstructed decays of  $\Lambda_b^0(6146)^0$  or  $\Lambda_b^0(6152)^0$  states into  $\Lambda_b^0 \pi^+ \pi^- \pi^0$  (where the  $\pi^0$  is lost). To check if it can be due to some other state decaying into the  $\Lambda_b^0 K^\pm \pi^\mp$  channels, the  $\Lambda_b^0 K \pi$  invariant mass distributions are obtained by substituting the pion mass with the kaon mass. No significant enhancements over the smooth background are found. The  $m_{\Lambda_b^0 \pi^+ \pi^-}$  background distribution is found to be in agreement between the SS and OS regions in the simulation and does not show any enhancement in the 6000–6100 MeV mass region. The two-dimensional distributions of the  $\Lambda_b^0 \pi^+ \pi^-$  mass versus the  $\Lambda_b^0 \pi^+$  and  $\Lambda_b^0 \pi^-$  masses from data are shown in the supplemental material [URL will be inserted by publisher]. If the  $\Lambda_b^0 \pi^\pm$  invariant mass ranges corresponding to the  $\Sigma_b^-, \Sigma_b^+, \Sigma_b^{*-},$  and  $\Sigma_b^{*+}$  baryons are vetoed, the SS and OS mass distributions in data are found to be in agreement in the region below 6100 MeV and do not exhibit a broad enhancement, as shown in the supplemental material [URL will be inserted by publisher]. This suggests that the broad excess might be related to the intermediate  $\Sigma_b^\pm$  and  $\Sigma_b^{*\pm}$  baryon states, although the current size of the data set does not allow this hypothesis to be tested.

The observed  $m_{\Lambda_b^0 \pi^+ \pi^-}$  distribution in the high-mass region is fit with a sum of three signal functions and a smooth background function obtained by multiplying the threshold function  $(x - x_0)^\beta$  by a first-order polynomial. The signal function describing the broad structure below 6100 MeV is a single Breit-Wigner function convolved with a double-Gaussian resolution function obtained from simulation. The narrow peak around 6150 MeV is modeled with the sum of two Breit-Wigner functions, each convolved with a double-Gaussian resolution function obtained from simulation, having an effective mass resolution of about 3.8 MeV. The natural widths of the two signals are fixed to those measured by the LHCb Collaboration [22]. The fit results for the yields and masses, respectively, are  $301 \pm 72$  and  $6073 \pm 5 \text{ MeV}$  for the broad enhancement,  $70 \pm 35$  and  $6146.5 \pm 1.9 \text{ MeV}$  for the  $\Lambda_b^0(6146)^0$ , and  $113 \pm 35$  and  $6152.7 \pm 1.1 \text{ MeV}$  for the  $\Lambda_b^0(6152)^0$ . The measured natural width of the broad excess is  $55 \pm 11$  (stat) MeV. While this work was under the journal review, a similar structure, consistent with the one reported here and possibly a new baryon state, has been observed by the LHCb Collaboration [39].

Using the likelihood-ratio technique and the one- versus two-peak hypotheses, the presence of two peaks has a statistical significance of  $0.4\sigma$ , indicating that the data are also consistent with a single peak at 6150 MeV. For the double-peak hypothesis, the natural widths of the two states are allowed to vary in the fit within the Gaussian constraints from the LHCb measurement [22]. In the single-peak hypothesis, the mass and the natural width of the signal peak are free parameters of the fit. In both cases, the mass resolution is allowed to float in the fit within its Gaussian uncertainty estimated from simulation. The local statistical significance of the single-peak hypothesis with respect to the background-only hypothesis is found to be over  $6\sigma$  in the baseline fit, and varies between  $5.4$  and  $6.5\sigma$  with the changes in the fit range and the model used to estimate the systematic uncertainties, as detailed in Section 6. The broad enhancement has a local statistical significance of about  $4\sigma$ . Resonances with masses between 6200 and 6400 MeV have been also considered in the fit model and no significant excess was found. The present amount of data does not allow us to perform conclusive studies of  $\Sigma_b^{*\pm} \rightarrow \Lambda_b^0 \pi^\pm$  decay contributions to the resonances decaying into  $\Lambda_b^0 \pi^+ \pi^-$ .

## 6. Systematic uncertainties

Several sources of systematic uncertainties in the measured masses are considered. To evaluate the systematic uncertainties related to the choice of the fit model, several alternative signal and background functions are tested. Uncertainties related to the choice of the signal and background models are evaluated separately. The systematic uncertainty in each measurement is calculated as the maximum deviation of the observed mass value from the baseline fit result. The alternative signal model corresponds to a single-Gaussian resolution function; the alternative background models for the low- and high-mass regions are first- and second-order polynomials, respectively, multiplied by the same threshold function as in the baseline fit.

For the high-mass region, the nature of the broad excess below 6100 MeV is unclear, therefore an additional fit is performed in the region  $m_{\Lambda_b^0 \pi^+ \pi^-} > 6100$  MeV, and the observed deviations from the baseline fit result in the measured masses are taken as the systematic uncertainties related to the possible presence of the broad resonance.

The systematic uncertainty from the choice of the fit range is evaluated by extending the range up to 6650 MeV. The observed deviations in the measured masses are taken as the systematic uncertainties. The systematic uncertainties due to fit range variations are negligible for the  $\Lambda_b^0(5912)^0$  and  $\Lambda_b^0(5920)^0$  states.

In the baseline fits of the  $m_{\Lambda_b^0 \pi^+ \pi^-}$  distributions, the mass resolutions are fixed to those estimated from simulated event samples. The systematic uncertainty associated with a possible difference between data and simulation is calculated using the following procedure. The mass resolutions are compared between data and simulation for the copious  $\Lambda_b^0 \rightarrow J/\psi \Lambda$  signal: they are, respectively, 15.25 and 15.78 MeV, corresponding to a difference of 3.5%. This difference is considered to be the uncertainty in the resolution due to the data-simulation difference. To estimate the effect of this uncertainty on the measured masses, the baseline fits are redone with the resolutions increased or decreased by 3.5%, and the largest deviation in the measured masses from the baseline fit results is considered as the systematic uncertainty due to the mass resolution.

The measured masses of the  $\Lambda_b^0(6146)^0$  and  $\Lambda_b^0(6152)^0$  states have an additional systematic uncertainty due to the fact that their natural widths were fixed in the nominal fit to the values reported by LHCb. To estimate the respective uncertainty, the nominal fit is repeated with the natural widths fixed to the central values ob-

tained by LHCb plus or minus the corresponding uncertainties (in total 8 additional fits are performed).

A potential bias in the mass measurement due to a possible misalignment of the tracker detectors has been evaluated by comparing distributions obtained in 2016, 2017, and 2018 running periods, which is a reasonable comparison, given that an important fraction of the CMS tracking detector was replaced between the 2016 and 2017 data taking. As expected, the alignment of the detector leads to a negligible systematic uncertainty in the results reported in this Letter.

The various systematic uncertainties are summarized in Table 1, together with the total uncertainties calculated as the quadratic sum of the individual sources.

## 7. Summary

In summary, using the pp collision data recorded with the CMS detector at  $\sqrt{s} = 13$  TeV, corresponding to an integrated luminosity of up to  $140 \text{ fb}^{-1}$ , the existence of the  $\Lambda_b^0(5912)^0$  and  $\Lambda_b^0(5920)^0$  baryons is confirmed. Their masses, with respect to the  $\Lambda_b^0$  mass, are measured to be  $292.72 \pm 0.12 \pm 0.01$  MeV and  $300.56 \pm 0.07 \pm 0.01$  MeV, respectively, where the first uncertainty is statistical and the second is systematic. By adding the known  $\Lambda_b^0$  mass of  $5619.60 \pm 0.17$  MeV [19], we report the mass measurements

$$M(\Lambda_b^0(5912)^0) = 5912.32 \pm 0.12 \pm 0.01 \pm 0.17 \text{ MeV},$$

$$M(\Lambda_b^0(5920)^0) = 5920.16 \pm 0.07 \pm 0.01 \pm 0.17 \text{ MeV},$$

where the third uncertainty is the uncertainty in the world-average  $\Lambda_b^0$  mass. The obtained values are consistent with the world-average values and have similar precision.

In addition, the  $\Lambda_b^0 \pi^+ \pi^-$  invariant mass spectrum is investigated in the mass range up to 6400 MeV. A narrow peak is observed with a mass close to 6150 MeV, with a significance over 5 standard deviations, consistent with the superposition of the  $\Lambda_b^0(6146)^0$  and  $\Lambda_b^0(6152)^0$  baryons recently observed by the LHCb Collaboration [22]. The masses of these states are measured to be

$$M(\Lambda_b^0(6146)^0) = 6146.5 \pm 1.9 \pm 0.8 \pm 0.2 \text{ MeV},$$

$$M(\Lambda_b^0(6152)^0) = 6152.7 \pm 1.1 \pm 0.4 \pm 0.2 \text{ MeV},$$

where the first uncertainty is statistical, the second is systematic, and the third is the uncertainty in the world-average  $\Lambda_b^0$  mass value. The corresponding mass differences with respect to the  $\Lambda_b^0$  mass are

$$M(\Lambda_b^0(6146)^0) - M(\Lambda_b^0) = 526.9 \pm 1.9 \pm 0.8 \text{ MeV},$$

$$M(\Lambda_b^0(6152)^0) - M(\Lambda_b^0) = 533.1 \pm 1.1 \pm 0.4 \text{ MeV}.$$

These measurements are not as precise as, but are in good agreement with the LHCb results [22].

In addition, a broad excess of events is observed in the region 6040–6100 MeV, not present in the same-sign  $\Lambda_b^0 \pi^\pm \pi^\pm$  distribution. If it is fit with a single Breit-Wigner function, the returned mass and width are  $6073 \pm 5$  (stat) MeV and  $55 \pm 11$  (stat) MeV. However, it is not excluded that this enhancement is an overlap of more than one state with close masses or is created by the partially reconstructed decays of higher-mass states. More data are needed to elucidate the nature of this excess.

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We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the

**Table 1**

Systematic uncertainties (in MeV) in the measured masses. A dash means that the corresponding uncertainty is negligible, and “N/A” means that it does not apply.

Source	$M(\Lambda_b^0(5912)^0)$	$M(\Lambda_b^0(5920)^0)$	$M(\Lambda_b^0(6146)^0)$	$M(\Lambda_b^0(6152)^0)$
Signal model	0.005	0.011	0.21	0.23
Background model	0.004	–	0.16	0.14
Inclusion of the broad excess region	N/A	N/A	0.35	0.14
Fit range	–	–	0.40	0.02
Mass resolution	0.007	0.001	0.01	0.09
Knowledge of $\Gamma$	N/A	N/A	0.43	0.26
Total	0.009	0.011	0.77	0.41

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## Appendix A. Supplementary material

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## The CMS Collaboration

A.M. Sirunyan<sup>†</sup>, A. Tumasyan

*Yerevan Physics Institute, Yerevan, Armenia*

W. Adam, F. Ambroggi, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth<sup>1</sup>, M. Jeitler<sup>1</sup>, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck<sup>1</sup>, R. Schöfbeck, M. Spanring, W. Waltenberger, C.-E. Wulz<sup>1</sup>, M. Zarucki

*Institut für Hochenergiephysik, Wien, Austria*

V. Drugakov, V. Mossolov, J. Suarez Gonzalez

*Institute for Nuclear Problems, Minsk, Belarus*

M.R. Darwish, E.A. De Wolf, D. Di Croce, X. Janssen, T. Kello<sup>2</sup>, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haeve, P. Van Mechelen, S. Van Putte, N. Van Remortel

*Universiteit Antwerpen, Antwerpen, Belgium*

F. Blekman, E.S. Bols, S.S. Chhibra, J. D’Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

*Vrije Universiteit Brussel, Brussel, Belgium*

D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, L. Moureaux, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom

*Université Libre de Bruxelles, Bruxelles, Belgium*

T. Cornelis, D. Dobur, I. Khvastunov<sup>3</sup>, M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Ghent University, Ghent, Belgium

G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, V. Lemaitre, J. Prisciandaro, A. Saggio, P. Vischia, J. Zobec

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>4</sup>, E. Coelho, E.M. Da Costa, G.G. Da Silveira<sup>5</sup>, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, J. Martins<sup>6</sup>, D. Matos Figueiredo, M. Medina Jaime<sup>7</sup>, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote<sup>4</sup>, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

C.A. Bernardes<sup>a</sup>, L. Calligaris<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>b</sup>, D.S. Lemos, P.G. Mercadante<sup>b</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>

<sup>a</sup> Universidade Estadual Paulista, São Paulo, Brazil

<sup>b</sup> Universidade Federal do ABC, São Paulo, Brazil

A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

University of Sofia, Sofia, Bulgaria

W. Fang<sup>2</sup>, X. Gao<sup>2</sup>, L. Yuan

Beihang University, Beijing, China

M. Ahmad, Z. Hu, Y. Wang

Department of Physics, Tsinghua University, Beijing, China

G.M. Chen<sup>8</sup>, H.S. Chen<sup>8</sup>, M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang<sup>8</sup>, J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Q. Wang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

M. Xiao

Zhejiang University, Hangzhou, China

C. Avila, A. Cabrera, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

Universidad de Antioquia, Medellin, Colombia

D. Giljanović, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia



Z. Antunovic, M. Kovac

*University of Split, Faculty of Science, Split, Croatia*

V. Brigljevic, D. Ferencek, K. Kadija, D. Majumder, B. Mesic, M. Roguljic, A. Starodumov<sup>9</sup>, T. Susa

*Institute Rudjer Boskovic, Zagreb, Croatia*

M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

*University of Cyprus, Nicosia, Cyprus*

M. Finger<sup>10</sup>, M. Finger Jr.<sup>10</sup>, A. Kveton, J. Tomsa

*Charles University, Prague, Czech Republic*

E. Ayala

*Escuela Politecnica Nacional, Quito, Ecuador*

E. Carrera Jarrin

*Universidad San Francisco de Quito, Quito, Ecuador*

Y. Assran<sup>11,12</sup>, S. Elgammal<sup>12</sup>

*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

*Department of Physics, University of Helsinki, Helsinki, Finland*

E. Brücken, F. Garcia, J. Havukainen, J.K. Heikkilä, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominiemi

*Helsinki Institute of Physics, Helsinki, Finland*

P. Luukka, T. Tuuva

*Lappeenranta University of Technology, Lappeenranta, Finland*

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro<sup>13</sup>, M. Titov, G.B. Yu

*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*

S. Ahuja, C. Amendola, F. Beaudette, M. Bonanomi, P. Busson, C. Charlot, B. Diab, G. Falmagne, R. Granier de Cassagnac, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, France*

J.-L. Agram<sup>14</sup>, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte<sup>14</sup>, J.-C. Fontaine<sup>14</sup>, D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, N. Tonon, P. Van Hove

*Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France*

S. Gadrat

*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*

S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*

T. Toriashvili<sup>15</sup>

*Georgian Technical University, Tbilisi, Georgia*

Z. Tsamalaidze<sup>10</sup>

*Tbilisi State University, Tbilisi, Georgia*

C. Autermann, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde

*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*

M. Erdmann, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*

G. Flügge, W. Haj Ahmad<sup>16</sup>, O. Hlushchenko, T. Kress, T. Müller, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl<sup>17</sup>

*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*

M. Aldaya Martin, P. Asmuss, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borrás<sup>18</sup>, V. Botta, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranichis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, L.I. Estevez Banos, E. Gallo<sup>19</sup>, A. Geiser, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari, N.Z. Jomhari, H. Jung, A. Kasem<sup>18</sup>, M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann<sup>20</sup>, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, R.E. Sosa Ricardo, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev, R. Zlebick

*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

R. Aggleton, S. Bein, L. Benato, A. Benecke, T. Dreyer, A. Ebrahimi, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, T. Lange, A. Malara, J. Multhaupt, C.E.N. Niemeyer, A. Reimers, O. Rieger, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, B. Vormwald, I. Zoi

*University of Hamburg, Hamburg, Germany*

M. Akbiyik, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann<sup>17</sup>, C. Heidecker, U. Husemann, M.A. Iqbal, S. Kudella, S. Maier, S. Mitra, M.U. Mozer, D. Müller, Th. Müller, M. Musich, A. Nürnberg, G. Quast, K. Rabbertz, D. Savoiu, D. Schäfer, M. Schnepf, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, C. Wöhrmann, R. Wolf, S. Wozniewski

*Karlsruher Institut fuer Technologie, Karlsruhe, Germany*

G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, A. Stakia

*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*

M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, K. Vellidis, E. Vourliotis

*National and Kapodistrian University of Athens, Athens, Greece*

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

*National Technical University of Athens, Athens, Greece*

I. Evangelou, C. Foudas, P. Giannelios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitaras, N. Manthos, I. Papadopoulos, J. Strologas, F.A. Triantis, D. Tsitsonis

*University of Ioánnina, Ioánnina, Greece*

M. Bartók<sup>21</sup>, R. Chudasama, M. Csanad, P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*

G. Bencze, C. Hajdu, D. Horvath<sup>22</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>†</sup>

*Wigner Research Centre for Physics, Budapest, Hungary*

N. Beni, S. Czellar, J. Karacsi<sup>21</sup>, J. Molnar, Z. Szillasi

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

P. Raics, D. Teyssier, Z.L. Trocsanyi, G. Zilizi

*Institute of Physics, University of Debrecen, Debrecen, Hungary*

T. Csorgo, S. Lökös, W.J. Metzger, F. Nemes, T. Novak

*Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary*

S. Choudhury, J.R. Komaragiri, L. Panwar, P.C. Tiwari

*Indian Institute of Science (IISc), Bangalore, India*

S. Bahinipati<sup>23</sup>, C. Kar, G. Kole, P. Mal, V.K. Muraleedharan Nair Bindhu, A. Nayak<sup>24</sup>, D.K. Sahoo<sup>23</sup>, S.K. Swain

*National Institute of Science Education and Research, HBNI, Bhubaneswar, India*

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhir<sup>25</sup>, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Viridi

*Panjab University, Chandigarh, India*

A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah, R. Sharma

*University of Delhi, Delhi, India*

R. Bhardwaj<sup>26</sup>, M. Bharti<sup>26</sup>, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep<sup>26</sup>, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber<sup>27</sup>, M. Maity<sup>28</sup>, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh<sup>26</sup>, S. Thakur<sup>26</sup>

*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

*Indian Institute of Technology Madras, Madras, India*

D. Dutta, V. Jha, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla

*Bhabha Atomic Research Centre, Mumbai, India*

T. Aziz, M.A. Bhat, S. Dugad, R. Kumar Verma, G.B. Mohanty, N. Sur

*Tata Institute of Fundamental Research-A, Mumbai, India*

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

*Tata Institute of Fundamental Research-B, Mumbai, India*

S. Dube, B. Kansal, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

*Indian Institute of Science Education and Research (IISER), Pune, India*

S. Chenarani, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi

*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*

M. Felcini, M. Grunewald

*University College Dublin, Dublin, Ireland*

M. Abbrescia<sup>a,b</sup>, R. Aly<sup>a,b,29</sup>, C. Aruta, C. Calabria<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, A. Di Florio<sup>a,b</sup>, W. Elmetenawee<sup>a,b</sup>, L. Fiore<sup>a</sup>, A. Gelmi<sup>a,b</sup>, G. Iaselli<sup>a,c</sup>, M. Ince<sup>a,b</sup>, S. Lezki<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, J.A. Merlin<sup>a</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a</sup>, F.M. Simone<sup>a,b</sup>, R. Venditti<sup>a</sup>, P. Verwilligen<sup>a</sup>

<sup>a</sup> INFN Sezione di Bari, Bari, Italy

<sup>b</sup> Università di Bari, Bari, Italy

<sup>c</sup> Politecnico di Bari, Bari, Italy

G. Abbiendi<sup>a</sup>, C. Battilana<sup>a,b</sup>, D. Bonacorsi<sup>a,b</sup>, L. Borgonovi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, C. Ciocca<sup>a</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, E. Fontanesi<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, F. Iemmi<sup>a,b</sup>, S. Lo Meo<sup>a,30</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, F. Primavera<sup>a,b</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a</sup>

<sup>a</sup> INFN Sezione di Bologna, Bologna, Italy

<sup>b</sup> Università di Bologna, Bologna, Italy

S. Albergo<sup>a,b,31</sup>, S. Costa<sup>a,b</sup>, A. Di Mattia<sup>a</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,31</sup>, C. Tuve<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Catania, Catania, Italy

<sup>b</sup> Università di Catania, Catania, Italy

G. Barbagli<sup>a</sup>, A. Cassese, R. Ceccarelli, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, F. Fiori<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, G. Latino<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Lizzo, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, R. Seidita, G. Sguazzoni<sup>a</sup>, L. Viliani<sup>a</sup>

<sup>a</sup> INFN Sezione di Firenze, Firenze, Italy

<sup>b</sup> Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, D. Piccolo

*INFN Laboratori Nazionali di Frascati, Frascati, Italy*

M. Bozzo<sup>a,b</sup>, F. Ferro<sup>a</sup>, R. Mulargia<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Genova, Genova, Italy

<sup>b</sup> Università di Genova, Genova, Italy

A. Benaglia<sup>a</sup>, A. Beschi<sup>a,b</sup>, F. Brivio<sup>a,b</sup>, V. Ciriolo<sup>a,b,17</sup>, M.E. Dinardo<sup>a,b</sup>, P. Dini<sup>a</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, L. Guzzi<sup>a,b</sup>, M. Malberti<sup>a</sup>, S. Malvezzi<sup>a</sup>, D. Menasce<sup>a</sup>, F. Monti<sup>a,b</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, T. Tabarelli de Fatis<sup>a,b</sup>, D. Valsecchi<sup>a,b,17</sup>, D. Zuolo<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Milano-Bicocca, Milano, Italy

<sup>b</sup> Università di Milano-Bicocca, Milano, Italy

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, A. De Iorio<sup>a,b</sup>, A. Di Crescenzo<sup>a,b</sup>, F. Fabozzi<sup>a,c</sup>, F. Fienga<sup>a</sup>, G. Galati<sup>a</sup>, A.O.M. Iorio<sup>a,b</sup>, L. Layer<sup>a,b</sup>, L. Lista<sup>a,b</sup>, S. Meola<sup>a,d,17</sup>, P. Paolucci<sup>a,17</sup>, B. Rossi<sup>a</sup>, C. Sciacca<sup>a,b</sup>, E. Voevodina<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Napoli, Napoli, Italy

<sup>b</sup> Università di Napoli 'Federico II', Napoli, Italy

<sup>c</sup> Università della Basilicata, Potenza, Italy

<sup>d</sup> Università G. Marconi, Roma, Italy

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a</sup>, D. Bisello<sup>a,b</sup>, A. Boletti<sup>a,b</sup>, A. Bragagnolo<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, U. Dosselli<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino<sup>a</sup>, S.Y. Hoh<sup>a,b</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, J. Pazzini<sup>a,b</sup>, M. Presilla<sup>b</sup>, P. Ronchese<sup>a,b</sup>, R. Rossin<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, A. Tiko<sup>a</sup>, M. Tosi<sup>a,b</sup>, M. Zanetti<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, A. Zucchetta<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Padova, Padova, Italy

<sup>b</sup> Università di Padova, Padova, Italy

<sup>c</sup> Università di Trento, Trento, Italy

A. Braghieri<sup>a</sup>, D. Fiorina<sup>a,b</sup>, P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, M. Ressegotti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a</sup>, P. Vitulo<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Pavia, Pavia, Italy

<sup>b</sup> Università di Pavia, Pavia, Italy

M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, D. Ciangottini<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, R. Leonardi<sup>a,b</sup>, E. Manoni<sup>a</sup>, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Rossi<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, D. Spiga<sup>a</sup>

<sup>a</sup> INFN Sezione di Perugia, Perugia, Italy

<sup>b</sup> Università di Perugia, Perugia, Italy

K. Androsov<sup>a</sup>, P. Azzurri<sup>a</sup>, G. Bagliesi<sup>a</sup>, V. Bertacchi<sup>a,c</sup>, L. Bianchini<sup>a</sup>, T. Boccali<sup>a</sup>, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,b</sup>, R. Dell'Orso<sup>a</sup>, S. Donato<sup>a</sup>, L. Giannini<sup>a,c</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a</sup>, F. Ligabue<sup>a,c</sup>, E. Manca<sup>a,c</sup>, G. Mandorli<sup>a,c</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, A. Rizzi<sup>a,b</sup>, G. Rolandi<sup>a,c</sup>, S. Roy Chowdhury<sup>a,c</sup>, A. Scribano<sup>a</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, N. Turini, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

<sup>a</sup> INFN Sezione di Pisa, Pisa, Italy

<sup>b</sup> Università di Pisa, Pisa, Italy

<sup>c</sup> Scuola Normale Superiore di Pisa, Pisa, Italy

F. Cavallari<sup>a</sup>, M. Cipriani<sup>a,b</sup>, D. Del Re<sup>a,b</sup>, E. Di Marco<sup>a</sup>, M. Diemoz<sup>a</sup>, E. Longo<sup>a,b</sup>, P. Meridiani<sup>a</sup>, G. Organtini<sup>a,b</sup>, F. Pandolfi<sup>a</sup>, R. Paramatti<sup>a,b</sup>, C. Quaranta<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>, L. Soffi<sup>a,b</sup>, R. Tramontano<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Roma, Rome, Italy

<sup>b</sup> Sapienza Università di Roma, Rome, Italy

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, N. Bartosik<sup>a</sup>, R. Bellan<sup>a,b</sup>, A. Bellora<sup>a,b</sup>, C. Biino<sup>a</sup>, A. Cappati<sup>a,b</sup>, N. Cartiglia<sup>a</sup>, S. Cometti<sup>a</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, N. Demaria<sup>a</sup>, J.R. González Fernández<sup>a</sup>, B. Kiani<sup>a,b</sup>, F. Legger<sup>a</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, E. Monteil<sup>a,b</sup>, M. Monteno<sup>a</sup>, M.M. Obertino<sup>a,b</sup>, G. Ortona<sup>a</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G.L. Pinna Angioni<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Salvatico<sup>a,b</sup>, V. Sola<sup>a</sup>, A. Solano<sup>a,b</sup>, D. Soldi<sup>a,b</sup>, A. Staiano<sup>a</sup>, D. Trocino<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Torino, Torino, Italy

<sup>b</sup> Università di Torino, Torino, Italy

<sup>c</sup> Università del Piemonte Orientale, Novara, Italy

S. Belforte <sup>a</sup>, V. Candelise <sup>a,b</sup>, M. Casarsa <sup>a</sup>, F. Cossutti <sup>a</sup>, A. Da Rold <sup>a,b</sup>, G. Della Ricca <sup>a,b</sup>, F. Vazzoler <sup>a,b</sup>, A. Zanetti <sup>a</sup>

<sup>a</sup> INFN Sezione di Trieste, Trieste, Italy

<sup>b</sup> Università di Trieste, Trieste, Italy

B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

*Kyungpook National University, Daegu, Republic of Korea*

H. Kim, D.H. Moon

*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea*

B. Francois, T.J. Kim, J. Park

*Hanyang University, Seoul, Republic of Korea*

S. Cho, S. Choi, Y. Go, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, Y. Roh, J. Yoo

*Korea University, Seoul, Republic of Korea*

J. Goh

*Kyung Hee University, Department of Physics, Republic of Korea*

H.S. Kim

*Sejong University, Seoul, Republic of Korea*

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, M. Oh, S.B. Oh, B.C. Radburn-Smith, U.K. Yang, H.D. Yoo, I. Yoon

*Seoul National University, Seoul, Republic of Korea*

D. Jeon, J.H. Kim, J.S.H. Lee, I.C. Park, I.J. Watson

*University of Seoul, Seoul, Republic of Korea*

Y. Choi, C. Hwang, Y. Jeong, J. Lee, Y. Lee, I. Yu

*Sungkyunkwan University, Suwon, Republic of Korea*

V. Veckalns <sup>32</sup>

*Riga Technical University, Riga, Latvia*

V. Dudenas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis, J. Vaitkus

*Vilnius University, Vilnius, Lithuania*

F. Mohamad Idris <sup>33</sup>, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

*Universidad de Sonora (UNISON), Hermosillo, Mexico*

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz <sup>34</sup>, R. Lopez-Fernandez, A. Sanchez-Hernandez

*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

*Universidad Iberoamericana, Mexico City, Mexico*

J. Eysermans, I. Pedraza, H.A. Salazar Ibarquen, C. Uribe Estrada

*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*

A. Morelos Pineda

*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*

J. Mijuskovic<sup>3</sup>, N. Raicevic

*University of Montenegro, Podgorica, Montenegro*

D. Krofcheck

*University of Auckland, Auckland, New Zealand*

S. Bheesette, P.H. Butler, P. Lujan

*University of Canterbury, Christchurch, New Zealand*

A. Ahmad, M. Ahmad, M.I.M. Awan, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*

V. Avati, L. Grzanka, M. Malawski

*AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland*

H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

*National Centre for Nuclear Research, Swierk, Poland*

K. Bunkowski, A. Byszuk<sup>35</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, M. Walczak

*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*

M. Araujo, P. Bargassa, D. Bastos, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, K. Shchelina, G. Strong, O. Toldaiev, J. Varela

*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev<sup>36,37</sup>, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

*Joint Institute for Nuclear Research, Dubna, Russia*

L. Chtchipounov, V. Golovtcov, Y. Ivanov, V. Kim<sup>38</sup>, E. Kuznetsova<sup>39</sup>, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev

*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

*Institute for Nuclear Research, Moscow, Russia*

V. Epshteyn, V. Gavrillov, N. Lychkovskaya, A. Nikitenko<sup>40</sup>, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

*Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia*

T. Aushev

*Moscow Institute of Physics and Technology, Moscow, Russia*

O. Bychkova, R. Chistov<sup>41</sup>, M. Danilov<sup>41</sup>, S. Polikarpov<sup>41</sup>, E. Tarkovskii

*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

*P.N. Lebedev Physical Institute, Moscow, Russia*

A. Belyaev, E. Boos, M. Dubinin<sup>42</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*

A. Barnyakov<sup>43</sup>, V. Blinov<sup>43</sup>, T. Dimova<sup>43</sup>, L. Kardapoltsev<sup>43</sup>, I. Ovtin<sup>43</sup>, Y. Skovpen<sup>43</sup>

*Novosibirsk State University (NSU), Novosibirsk, Russia*

I. Azhgirey, I. Bayshev, S. Bitiukov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

*Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia*

A. Babaev, A. Iuzhakov, V. Okhotnikov

*National Research Tomsk Polytechnic University, Tomsk, Russia*

V. Borchsh, V. Ivanchenko, E. Tcherniaev

*Tomsk State University, Tomsk, Russia*

P. Adzic<sup>44</sup>, P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

*University of Belgrade, Faculty of Physics and VINCA Institute of Nuclear Sciences, Serbia*

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, C. Willmott

*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*

C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

*Universidad Autónoma de Madrid, Madrid, Spain*

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, S. Sanchez Cruz

*Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain*

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Russo<sup>45</sup>, L. Scodellaro, I. Vila, J.M. Vizan Garcia

*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*

K. Malagalage

*University of Colombo, Colombo, Sri Lanka*

W.G.D. Dharmaratna, N. Wickramage

*University of Ruhuna, Department of Physics, Matara, Sri Lanka*



T.K. Aarrestad, D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, E. Brondolin, T. Camporesi, A. Caratelli, G. Cerminara, E. Chapon, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, O. Davignon, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita<sup>46</sup>, D. Fasanella, S. Fiorendi, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, T. James, P. Janot, O. Karacheban<sup>20</sup>, J. Kaspar, J. Kieseler, M. Krammer<sup>1</sup>, N. Kratochwil, C. Lange, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo<sup>17</sup>, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas<sup>47</sup>, J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsiros, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

*CERN, European Organization for Nuclear Research, Geneva, Switzerland*

L. Caminada<sup>48</sup>, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

*Paul Scherrer Institut, Villigen, Switzerland*

M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, R.A. Manzoni, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

*ETH Zurich – Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*

C. Amsler<sup>49</sup>, C. Botta, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, B. Kilminster, S. Leontsinis, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, K. Schweiger, Y. Takahashi, S. Wertz

*Universität Zürich, Zurich, Switzerland*

C.M. Kuo, W. Lin, A. Roy, T. Sarkar<sup>28</sup>, S.S. Yu

*National Central University, Chung-Li, Taiwan*

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

*National Taiwan University (NTU), Taipei, Taiwan*

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas, N. Suwonjandee

*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*

A. Bat, F. Boran, A. Celik<sup>50</sup>, S. Damarseckin<sup>51</sup>, Z.S. Demiroglu, F. Dolek, C. Dozen<sup>52</sup>, I. Dumanoglu<sup>53</sup>, G. Gokbulut, Y. Guler, E. Gurpinar Guler<sup>54</sup>, I. Hos<sup>55</sup>, C. Isik, E.E. Kangal<sup>56</sup>, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir<sup>57</sup>, A.E. Simsek, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*

B. Isildak<sup>58</sup>, G. Karapinar<sup>59</sup>, M. Yalvac<sup>60</sup>

*Middle East Technical University, Physics Department, Ankara, Turkey*

I.O. Atakisi, E. Gülmez, M. Kaya<sup>61</sup>, O. Kaya<sup>62</sup>, Ö. Özçelik, S. Tekten<sup>63</sup>, E.A. Yetkin<sup>64</sup>

*Bogazici University, Istanbul, Turkey*

A. Cakir, K. Cankocak<sup>53</sup>, Y. Komurcu, S. Sen<sup>65</sup>

*Istanbul Technical University, Istanbul, Turkey*

S. Cerci<sup>66</sup>, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci<sup>66</sup>

*Istanbul University, Istanbul, Turkey*

B. Grynyov

*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*

L. Levchuk

*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*

E. Bhal, S. Bologna, J.J. Brooke, D. Burns<sup>67</sup>, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, J. Taylor, A. Titterton

*University of Bristol, Bristol, United Kingdom*

K.W. Bell, A. Belyaev<sup>68</sup>, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

*Rutherford Appleton Laboratory, Didcot, United Kingdom*

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, G.S. Chahal<sup>69</sup>, D. Colling, P. Dauncey, G. Davies, M. Della Negra, P. Everaerts, G. Hall, G. Iles, M. Komm, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, A. Morton, J. Nash<sup>70</sup>, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, T. Strebler, A. Tapper, K. Uchida, T. Virdee<sup>17</sup>, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli, S.C. Zenz

*Imperial College, London, United Kingdom*

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, I.D. Reid, L. Teodorescu, S. Zahid

*Brunel University, Uxbridge, United Kingdom*

A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

*Baylor University, Waco, USA*

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

*Catholic University of America, Washington, DC, USA*

A. Buccilli, S.I. Cooper, S.V. Gleyzer, C. Henderson, P. Rumerio, C. West

*The University of Alabama, Tuscaloosa, USA*

A. Albert, D. Arcaro, Z. Demiragli, D. Gastler, C. Richardson, J. Rohlf, D. Sperka, D. Spitzbart, I. Suarez, L. Sulak, D. Zou

*Boston University, Boston, USA*

G. Benelli, B. Burkle, X. Coubez<sup>18</sup>, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan<sup>71</sup>, K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir<sup>72</sup>, R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

*Brown University, Providence, USA*

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko<sup>†</sup>, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

*University of California, Davis, Davis, USA*

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

*University of California, Los Angeles, USA*

K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, B.R. Yates, Y. Zhang

*University of California, Riverside, Riverside, USA*

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, M. Derdzinski, J. Duarte, R. Gerosa, D. Gilbert, B. Hashemi, D. Klein, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil, G. Zevi Della Porta

*University of California, San Diego, La Jolla, USA*

N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, J. Richman, U. Sarica, D. Stuart, S. Wang

*University of California, Santa Barbara – Department of Physics, Santa Barbara, USA*

D. Anderson, A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

*California Institute of Technology, Pasadena, USA*

J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

*Carnegie Mellon University, Pittsburgh, USA*

J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

*University of Colorado Boulder, Boulder, USA*

J. Alexander, Y. Cheng, J. Chu, A. Datta, A. Frankenthal, K. Mcdermott, J.R. Patterson, D. Quach, A. Ryd, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

*Cornell University, Ithaca, USA*

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, R. Heller, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena<sup>42</sup>, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, M. Wang, H.A. Weber, A. Woodard

*Fermi National Accelerator Laboratory, Batavia, USA*

D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

*University of Florida, Gainesville, USA*

Y.R. Joshi

*Florida International University, Miami, USA*

T. Adams, A. Askew, R. Habibullah, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, T. Perry, H. Prosper, C. Schiber, R. Yohay, J. Zhang

*Florida State University, Tallahassee, USA*

M.M. Baarmand, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

*Florida Institute of Technology, Melbourne, USA*

M.R. Adams, L. Apanasevich, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, V. Kumar, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, H. Wang, X. Wang, Z. Wu

*University of Illinois at Chicago (UIC), Chicago, USA*

M. Alhuseini, B. Bilki<sup>54</sup>, K. Dilsiz<sup>73</sup>, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili<sup>74</sup>, A. Moeller, J. Nachtman, H. Ogul<sup>75</sup>, Y. Onel, F. Ozok<sup>76</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi<sup>77</sup>

*The University of Iowa, Iowa City, USA*

B. Blumenfeld, A. Cocoros, N. Eminizer, A.V. Gritsan, W.T. Hung, S. Kyriacou, P. Maksimovic, C. Mantilla, J. Roskes, M. Swartz, T.Á. Vámi

*Johns Hopkins University, Baltimore, USA*

C. Baldenegro Barrera, P. Baringer, A. Bean, S. Boren, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, W. Mcbrayer, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

*The University of Kansas, Lawrence, USA*

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

*Kansas State University, Manhattan, USA*

F. Rebassoo, D. Wright

*Lawrence Livermore National Laboratory, Livermore, USA*

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, A.C. Mignerey, S. Nabili, M. Seidel, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

*University of Maryland, College Park, USA*

D. Abercrombie, B. Allen, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. MCGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

*Massachusetts Institute of Technology, Cambridge, USA*

R.M. Chatterjee, A. Evans, S. Guts<sup>†</sup>, P. Hansen, J. Hiltbrand, Sh. Jain, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

*University of Minnesota, Minneapolis, USA*

J.G. Acosta, S. Oliveros

*University of Mississippi, Oxford, USA*

K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Kamalieddin, I. Kravchenko, J.E. Siado, G.R. Snow<sup>†</sup>, B. Stieger, W. Tabb

*University of Nebraska-Lincoln, Lincoln, USA*

G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

*State University of New York at Buffalo, Buffalo, USA*

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

*Northeastern University, Boston, USA*

S. Bhattacharya, J. Bueghly, G. Fedi, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Velasco

*Northwestern University, Evanston, USA*

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, Y. Musienko<sup>36</sup>, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf

*University of Notre Dame, Notre Dame, USA*

J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

*The Ohio State University, Columbus, USA*

G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

*Princeton University, Princeton, USA*

S. Malik, S. Norberg

*University of Puerto Rico, Mayaguez, USA*

A. Barker, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, B. Mahakud, D.H. Miller, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, N. Trevisani, F. Wang, R. Xiao, W. Xie

*Purdue University, West Lafayette, USA*

T. Cheng, J. Dolen, N. Parashar

*Purdue University Northwest, Hammond, USA*

A. Baty, U. Behrens, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton, Z. Tu, A. Zhang

*Rice University, Houston, USA*

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

*University of Rochester, Rochester, USA*

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

*Rutgers, The State University of New Jersey, Piscataway, USA*

H. Acharya, A.G. Delannoy, S. Spanier

*University of Tennessee, Knoxville, USA*

O. Bouhali<sup>78</sup>, M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>79</sup>, H. Kim, S. Luo, S. Malhotra, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, F. De Guio, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Texas Tech University, Lubbock, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

Vanderbilt University, Nashville, USA

L. Ang, M.W. Arenton, P. Barria, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa

Wayne State University, Detroit, USA

K. Black, T. Bose, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, D. Pinna, T. Ruggles, A. Savin, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert

University of Wisconsin – Madison, Madison, WI, USA

† Deceased.

<sup>1</sup> Also at Vienna University of Technology, Vienna, Austria.

<sup>2</sup> Also at Université Libre de Bruxelles, Bruxelles, Belgium.

<sup>3</sup> Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

<sup>4</sup> Also at Universidade Estadual de Campinas, Campinas, Brazil.

<sup>5</sup> Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

<sup>6</sup> Also at UFMS, Nova Andradina, Brazil.

<sup>7</sup> Also at Universidade Federal de Pelotas, Pelotas, Brazil.

<sup>8</sup> Also at University of Chinese Academy of Sciences, Beijing, China.

<sup>9</sup> Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia.

<sup>10</sup> Also at Joint Institute for Nuclear Research, Dubna, Russia.

<sup>11</sup> Also at Suez University, Suez, Egypt.

<sup>12</sup> Now at British University in Egypt, Cairo, Egypt.

<sup>13</sup> Also at Purdue University, West Lafayette, USA.

<sup>14</sup> Also at Université de Haute Alsace, Mulhouse, France.

<sup>15</sup> Also at Tbilisi State University, Tbilisi, Georgia.

<sup>16</sup> Also at Erzincan Binali Yildirim University, Erzincan, Turkey.

<sup>17</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

<sup>18</sup> Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

<sup>19</sup> Also at University of Hamburg, Hamburg, Germany.

<sup>20</sup> Also at Brandenburg University of Technology, Cottbus, Germany.

<sup>21</sup> Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

<sup>22</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

<sup>23</sup> Also at IIT Bhubaneswar, Bhubaneswar, India.

<sup>24</sup> Also at Institute of Physics, Bhubaneswar, India.

<sup>25</sup> Also at G.H.G. Khalsa College, Punjab, India.

<sup>26</sup> Also at Shoolini University, Solan, India.

<sup>27</sup> Also at University of Hyderabad, Hyderabad, India.

<sup>28</sup> Also at University of Visva-Bharati, Santiniketan, India.

<sup>29</sup> Now at INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy.

<sup>30</sup> Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.

<sup>31</sup> Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.

<sup>32</sup> Also at Riga Technical University, Riga, Latvia.

<sup>33</sup> Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.

<sup>34</sup> Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.

<sup>35</sup> Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

<sup>36</sup> Also at Institute for Nuclear Research, Moscow, Russia.

<sup>37</sup> Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia.

<sup>38</sup> Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

<sup>39</sup> Also at University of Florida, Gainesville, USA.

<sup>40</sup> Also at Imperial College, London, United Kingdom.

- <sup>41</sup> Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- <sup>42</sup> Also at California Institute of Technology, Pasadena, USA.
- <sup>43</sup> Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- <sup>44</sup> Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- <sup>45</sup> Also at Università degli Studi di Siena, Siena, Italy.
- <sup>46</sup> Also at INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy.
- <sup>47</sup> Also at National and Kapodistrian University of Athens, Athens, Greece.
- <sup>48</sup> Also at Universität Zürich, Zurich, Switzerland.
- <sup>49</sup> Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
- <sup>50</sup> Also at Burdur Mehmet Akif Ersoy University, BURDUR, Turkey.
- <sup>51</sup> Also at Şırnak University, Şırnak, Turkey.
- <sup>52</sup> Also at Department of Physics, Tsinghua University, Beijing, China.
- <sup>53</sup> Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey.
- <sup>54</sup> Also at Beykent University, Istanbul, Turkey.
- <sup>55</sup> Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey.
- <sup>56</sup> Also at Mersin University, Mersin, Turkey.
- <sup>57</sup> Also at Piri Reis University, Istanbul, Turkey.
- <sup>58</sup> Also at Ozyegin University, Istanbul, Turkey.
- <sup>59</sup> Also at Izmir Institute of Technology, Izmir, Turkey.
- <sup>60</sup> Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey.
- <sup>61</sup> Also at Marmara University, Istanbul, Turkey.
- <sup>62</sup> Also at Milli Savunma University, Istanbul, Turkey.
- <sup>63</sup> Also at Kafkas University, Kars, Turkey.
- <sup>64</sup> Also at Istanbul Bilgi University, Istanbul, Turkey.
- <sup>65</sup> Also at Hacettepe University, Ankara, Turkey.
- <sup>66</sup> Also at Adiyaman University, Adiyaman, Turkey.
- <sup>67</sup> Also at Vrije Universiteit Brussel, Brussel, Belgium.
- <sup>68</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- <sup>69</sup> Also at IPPP Durham University, Durham, United Kingdom.
- <sup>70</sup> Also at Monash University, Faculty of Science, Clayton, Australia.
- <sup>71</sup> Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA.
- <sup>72</sup> Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- <sup>73</sup> Also at Bingol University, Bingol, Turkey.
- <sup>74</sup> Also at Georgian Technical University, Tbilisi, Georgia.
- <sup>75</sup> Also at Sinop University, Sinop, Turkey.
- <sup>76</sup> Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- <sup>77</sup> Also at Nanjing Normal University Department of Physics, Nanjing, China.
- <sup>78</sup> Also at Texas A&M University at Qatar, Doha, Qatar.
- <sup>79</sup> Also at Kyungpook National University, Daegu, Republic of Korea.