Eur. Phys. J. C (2022) 82:499
https://doi.org/10.1140/epjc/s10052-022-10315-y

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Observation of $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ and $B^0_s \to \psi(2S)K^0_S$ decays

CMS Collaboration*
CERN, 1211 Geneva 23, Switzerland

Received: 22 January 2022 / Accepted: 8 April 2022

Abstract Using a data sample of $\sqrt{s} = 13$ TeV proton-proton collisions collected by the CMS experiment at the LHC in 2017 and 2018 with an integrated luminosity of 103 fb^{-1}, the $B^0_s \to \psi(2S)K^0_S$ and $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ decays are observed with significances exceeding 5 standard deviations. The resulting branching fraction ratios, measured for the first time, correspond to $\mathcal{B}(B^0_s \to \psi(2S)K^0_S)/\mathcal{B}(B^0 \to \psi(2S)K^0_S) = (3.33 \pm 0.69(\text{stat}) \pm 0.11\,(\text{syst}) \pm 0.34\,(f_s/f_d)) \times 10^{-2}$ and $\mathcal{B}(B^0 \to \psi(2S)K^0_S\pi^+\pi^-)/\mathcal{B}(B^0 \to \psi(2S)K^0_S) = 0.480 \pm 0.013\,(\text{stat}) \pm 0.032\,(\text{syst})$, where the last uncertainty in the first ratio is related to the uncertainty in the ratio of production cross sections of B^0_s and B^0 mesons, f_s/f_d.

1 Introduction

Decays of neutral B mesons into charmonium resonances (J/ψ, $\psi(2S)$, etc.) are well suited to study the flavour sector of the standard model (SM) and to search for indications of new physics beyond the SM. In the last decade, interest in b hadron decays to final states containing a charmonium resonance has increased after several exotic hadrons have been observed as intermediate resonances in multibody decays. Starting from the observation of $X(3872)$ [1], many new charmonium-like states have been observed, such as $X(4140)$ [2–5], $Y(4260)$ [6,7], and others, with properties (mass, width and decay pattern) not fitting into the landscape of traditional charmonium states. The first charged tetraquark candidate, $Z(4430)^+$ was discovered in the $B \to \psi(2S)K\pi^+$ decay as a peak in the $\psi(2S)\pi^+$ mass spectrum [8–11]. Many other exotic hadrons have been observed in the last 15 years [12,13], and the nature of most of them is still unclear. Moreover, channels whose final state is accessible both from B and $\overline{B}$ can be used to measure time-dependent *CP* asymmetry [14–27] as well.

This paper presents the first measurement of the $B^0_s \to \psi(2S)K^0_S$ and $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ decays, using a data sample of proton-proton collisions at $\sqrt{s} = 13$ TeV collected by the CMS experiment at the CERN LHC in 2017 and 2018 with an integrated luminosity of 103 fb^{-1} [28,29]. Both decays can potentially be used for *CP* asymmetry measurements, and, in addition, the second one can also be used to search for intermediate exotic resonances. The $\psi(2S)$ and K^0_S mesons are reconstructed using their decays into $\mu^+\mu^-$ and $\pi^+\pi^-$, respectively. The $B^0 \to \psi(2S)K^0_S$ decay is chosen as the normalization channel for the measurement of the branching fractions, since its probability is precisely known [13], and its topology and kinematic properties are similar to those of the $B^0_s \to \psi(2S)K^0_S$ or $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ decays. Therefore, using this normalization reduces the systematic uncertainties related to muon and track reconstruction. The relative branching fractions are measured using the relations

$$\begin{aligned} R_s &\equiv \frac{\mathcal{B}(B^0_s \to \psi(2S)K^0_S)}{\mathcal{B}(B^0 \to \psi(2S)K^0_S)} \\ &= \frac{f_d}{f_s}\,\frac{\epsilon(B^0 \to \psi(2S)K^0_S)}{\epsilon(B^0_s \to \psi(2S)K^0_S)}\,\frac{N(B^0_s \to \psi(2S)K^0_S)}{N(B^0 \to \psi(2S)K^0_S)}, \\ R_{\pi^+\pi^-} &\equiv \frac{\mathcal{B}(B^0 \to \psi(2S)K^0_S\pi^+\pi^-)}{\mathcal{B}(B^0 \to \psi(2S)K^0_S)} \\ &= \frac{\epsilon(B^0 \to \psi(2S)K^0_S)}{\epsilon(B^0 \to \psi(2S)K^0_S\pi^+\pi^-)} \\ &\quad \times \frac{N(B^0 \to \psi(2S)K^0_S\pi^+\pi^-)}{N(B^0 \to \psi(2S)K^0_S)}, \end{aligned} \tag{1}$$

where $\mathcal{B}$ is the branching fraction, N is the number of reconstructed events in data, ϵ is the total reconstruction efficiency, and f_d/f_s is the ratio of production cross sections of B^0 and B^0_s mesons (also called fragmentation fraction ratio). Charge-conjugate states are implied to be included throughout the paper.

Tabulated results are provided in the HEPData record for this analysis [30].

* e-mail: cms-publication-committee-chair@cern.ch

Published online: 31 May 2022

2 The CMS detector and simulated event samples

The central feature of the CMS apparatus [31] 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. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system [32]. The first level, 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 μs [33]. The first-level trigger used in this analysis requires at least two muons. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing that reduces the event rate to around 1 kHz before data storage. The high-level trigger algorithm used in the analysis requires two opposite-sign muons compatible with the dimuon decay of a $\psi(2S)$ meson with transverse momentum (p_T) larger than 18 GeV.

Simulated Monte Carlo samples for the decays of interest are generated for the analysis. The PYTHIA 8.230 package [34] with the CP5 tune [35] is used to simulate the production of the B^0 and B^0_s mesons, whose subsequent decays are performed by EVTGEN 1.6.0 [36], where final-state photon radiation is included using PHOTOS 3.61 [37,38]. The lifetimes of B^0 and B^0_s mesons used in the generation are 1.52 and 1.47 ps, respectively. The generated events are passed to a detailed GEANT4-based simulation [39] of the CMS detector, and are then processed using the same trigger and reconstruction as used for the collision data. The simulation includes effects from multiple proton-proton interactions in the same or nearby bunch crossings (pileup) with the multiplicity distribution tuned to match those of the data.

3 Event reconstruction and selection

The reconstruction procedure starts with finding two muons of opposite charges, that must match those that triggered the event readout. The muon candidates are required to have $p_T(\mu^\pm) > 3$ GeV, a pseudorapidity $|\eta(\mu^\pm)| < 2.4$, and to satisfy general identification (soft-muon) criteria [40]. The two muons with a two-prong vertex fit probability $P_{vtx}(\mu^+\mu^-) > 1\%$ are paired to form the $\psi(2S)$ candidate, which must have $p_T(\psi(2S)) > 18$ GeV and an invariant mass $3500 < m(\mu^+\mu^-) < 3950$ MeV (the world average $\psi(2S)$ meson mass is $m^{PDG}_{\psi(2S)} = 3686.10$ MeV [13]).

The $K^0_S \to \pi^+\pi^-$ candidates are formed from displaced two-prong vertices, as described in Ref. [41]. The $\pi^+\pi^-$ invariant mass is required to be within ±20 MeV of the world average value $m^{PDG}_{K^0} = 497.611$ MeV [13], which corresponds to approximately three times the mass resolution. Selected π^+ and π^- tracks are then refitted with their invariant mass constrained to $m^{PDG}_{K^0}$, and the obtained K^0_S candidate is required to have $P_{vtx}(\pi^+\pi^-) > 1\%$.

The $B \to \psi(2S)K^0_S$ candidates are obtained through a kinematic vertex fit on the $\mu^+\mu^-K^0_S$ system which constrains the dimuon mass to $m^{PDG}_{\psi(2S)}$. The K^0_S candidates are required to have $p_T(K^0_S) > 1$ GeV, a 3D pointing angle between $\vec{D}(K^0_S)$ and $\vec{p}(K^0_S)$ to satisfy $\cos(\vec{D}(K^0_S), \vec{p}(K^0_S)) > 0.99$, and a transverse displacement significance for K^0_S of $D_{xy} > 5\sigma_{D_{xy}}$. Here $\vec{D}(K^0_S)$ denotes the vector from the K^0_S production vertex to the K^0_S decay vertex, while D_{xy} and $\sigma_{D_{xy}}$ correspond to the length of $\vec{D}_{xy}$, the transverse component of $\vec{D}$, and its uncertainty. To suppress the combinatorial background, additional requirements are applied: $P_{vtx}(\mu^+\mu^-K^0_S) > 5\%$, $\cos(\vec{D}_{xy}(B), \vec{p}_T(B)) > 0.99$, and $D_{xy}(B) > 5\sigma_{D_{xy}(B)}$, where the B meson transverse displacement $D_{xy}(B)$ is calculated with respect to the primary vertex (PV). From all reconstructed proton-proton collision points, the PV is chosen as the one with the smallest B pointing angle, as in Refs. [42–44]. The pointing angle is the angle formed by the B candidate momentum and the vector from the PV to the reconstructed B candidate vertex. Furthermore, if in this procedure any of the tracks used in the B candidate reconstruction is included in the fit of the chosen PV, the track is removed, and the PV is refitted.

For the $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ candidates, two additional, oppositely charged, high-purity [45] tracks, assumed to be pions and having $p_T > 0.9$ GeV, are included in the B meson vertex fit, while the rest of the selection criteria are the same.

4 Observation of the $B^0_s \to \psi(2S)K^0_S$ decay

The measured $\psi(2S)K^0_S$ invariant mass distribution is presented in Fig. 1 (upper). The B^0 signal (left peak) is described with a double Gaussian function with common mean, whose parameters are free to vary in an unbinned maximum-likelihood fit. It is found in simulation that the $B^0_s \to \psi(2S)K^0_S$ signal (right peak) has the same shape as the $B^0 \to \psi(2S)K^0_S$ signal, but it is about 10% wider, because of the larger energy release in the decay. Therefore, the B^0_s signal is modelled with a double Gaussian function of the same shape as the B^0 signal, with the resolution parameters scaled by the ratio of the widths found in the simulation. The background is modelled with an exponential function. The good quality of the fit is verified by calculating the χ^2 between the binned distribution and the fit function, resulting in $\chi^2 = 83$ for 91 degrees of freedom.

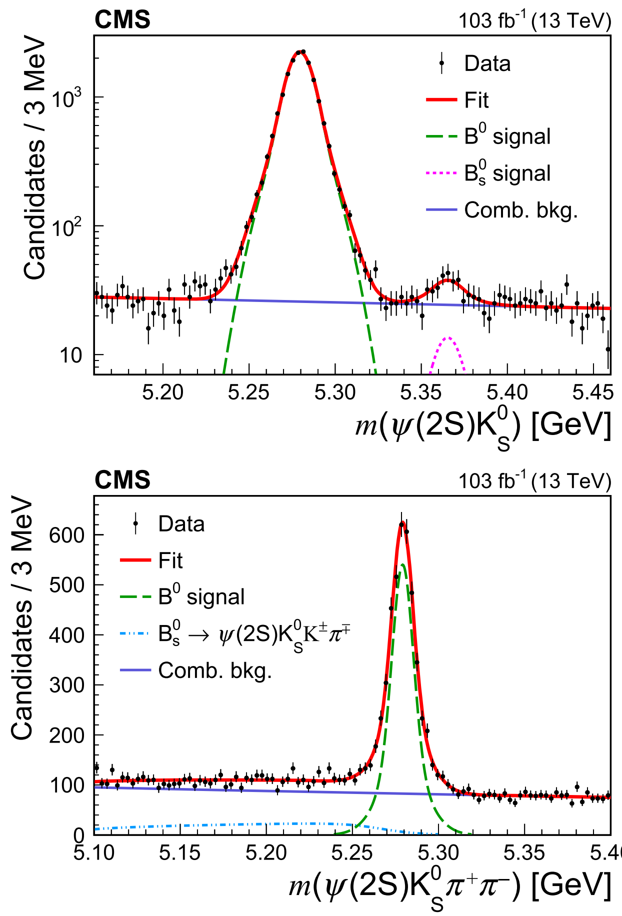

Fig. 1 Measured invariant mass distributions of $\psi(2S)K^0_S$ (upper) and $\psi(2S)K^0_S\pi^+\pi^-$ (lower) candidates. The overlaid results from the fit are described in the text

The ratio of signal yields $N(B^0_s \to \psi(2S)K^0_S)/N(B^0 \to \psi(2S)K^0_S) = (6.8 \pm 1.4) \times 10^{-3}$ is extracted from the fit. Its uncertainty is calculated by taking into account the correlation between the uncertainties in B^0_s and B^0 yields, which are found to be 113 ± 23 and 16660 ± 140, respectively, where the uncertainties are statistical only.

The statistical significance of the $B^0_s \to \psi(2S)K^0_S$ signal is evaluated with the likelihood ratio technique, comparing the background-only and signal-plus-background hypotheses, with the standard asymptotic formula [46], assuming that the conditions to apply Wilks' theorem [47] are satisfied. For a significance estimation, the mass difference between the B^0_s and B^0 signals is fixed to the known value of 83.78 MeV [13]. The obtained significance is 5.2 standard deviations and varies in the range 5.1–5.4 standard deviations when accounting for the systematic uncertainties due to the choice of the fit model, discussed in Sect. 7.

5 Observation of the $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ decay

As shown in Fig. 1 (lower), the measured $\psi(2S)K^0_S\pi^+\pi^-$ mass distribution presents a clear $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ signal peak on top of a relatively small background. The B^0 signal is modelled with a double Gaussian function with common mean with all parameters free to vary, and the combinatorial background is described by an exponential function.

Studies of simulated events show that the $B^0_s \to \psi(2S)K^0_S K^\mp\pi^\pm$ decay contributes to the reconstructed $\psi(2S)K^0_S\pi^+\pi^-$ mass distribution when the charged kaon is reconstructed as a pion. This relevant background contribution is accounted for in the fit to data by including a dedicated component with a freely varying normalization and a fixed shape that is obtained from simulation (Fig. 1, lower).

The signal yield $N(B^0 \to \psi(2S)K^0_S\pi^+\pi^-)$ is found to be 3498 ± 87, where the uncertainty is statistical only. The χ^2 between the binned distribution and the fit function is 75 for 92 degrees of freedom, demonstrating the good quality of the fit. The significance of the $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ signal, evaluated as described in Sect. 4, exceeds 30 standard deviations.

The intermediate invariant mass distributions, corresponding to the four-body $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ decay, are produced using the $_s\mathcal{P}$lot [48] technique to subtract the non-B^0 background, using the $m(\psi(2S)K^0_S\pi^+\pi^-)$ distribution fit described above. The correlations between the intermediate invariant masses and $m(\psi(2S)K^0_S\pi^+\pi^-)$ have been checked to be below 10%. Figures 2 and 3 show the 2- and 3-body invariant mass distributions. Overlaid are the predictions of the 4-body phase space simulations, which provide poor description of the data since the simulations do not account for the intermediate resonance structure. The simulation after application of the reweighting procedure described in Sect. 7 is also shown. The mass distributions of $\psi(2S)$ and one or two light mesons ($\psi(2S)K^0_S$, $\psi(2S)\pi^\pm$, $\psi(2S)K^0_S\pi^\pm$, $\psi(2S)\pi^+\pi^-$) do not present any significant narrow peak that could indicate a contribution from an exotic charmonium state. The small excess at about 4.3 GeV in the $m(\psi(2S)\pi^+)$ distribution (Fig. 2, bottom left) is not significant, and there is no similar excess in the $m(\psi(2S)\pi^-)$ distribution (Fig. 2, middle left). Moreover, exotic states previously found in this mass range are known to have large natural widths [12,13]. Signs of the $K^*(892)^\pm$ (Fig. 2, middle and bottom right), $\rho(770)^0$ (Fig. 2, top left), and $K_1(1270)^0$ (Fig. 3, top right) resonances are seen in the mass distributions of $K^0_S\pi^\pm$, $\pi^+\pi^-$, and $K^0_S\pi^+\pi^-$, respectively.

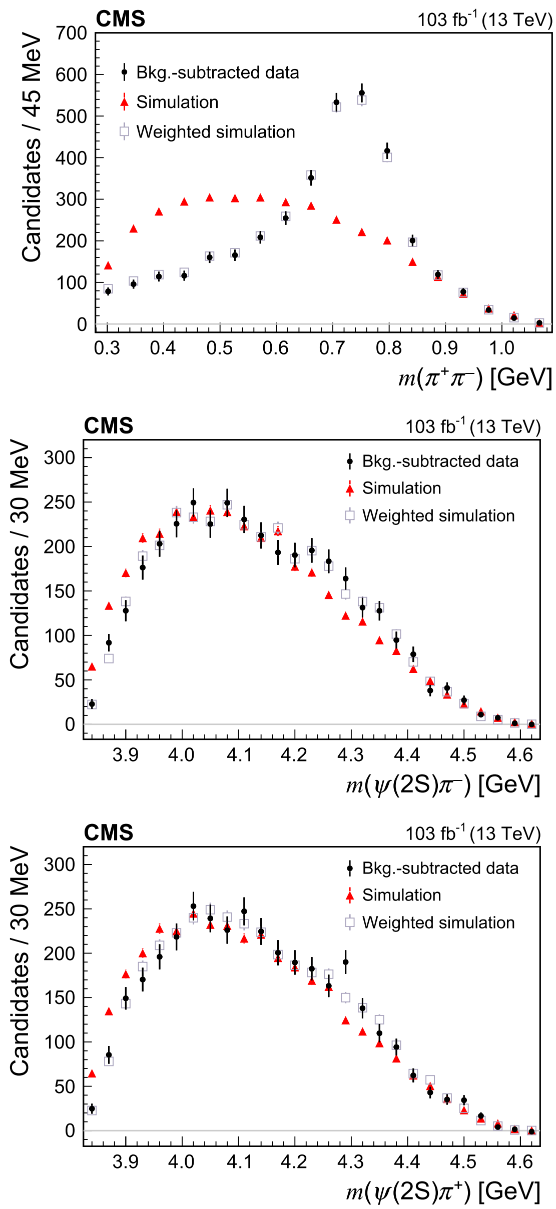

Fig. 2 Distributions of 2-body intermediate invariant masses from the $B^0 \rightarrow \psi(2S)K^0_S\pi^+\pi^-$ decay. The data distributions (black dots) are background subtracted. Overlaid are the predictions of phase space simulations (red triangles), as well as the predictions after applying the reweighting procedure described in Sect. 7 (grey squares)

6 Efficiencies

The total reconstruction efficiency for each decay channel is evaluated using samples of simulated events. It is calculated as the number of reconstructed events divided by the number of generated events, and includes the detector acceptance, trigger, and candidate reconstruction efficiencies. Only the ratios of such efficiencies are needed to measure the ratios R_s and $R_{\pi^+\pi^-}$, thus reducing the systematic uncertainties associated with muon and track reconstruction.

The obtained efficiency ratios are found to be

$$\frac{\epsilon(B^0 \rightarrow \psi(2S)K^0_S)}{\epsilon(B^0_s \rightarrow \psi(2S)K^0_S)} = 1.019 \pm 0.013 \quad \text{and}$$

$$\frac{\epsilon(B^0 \rightarrow \psi(2S)K^0_S)}{\epsilon(B^0 \rightarrow \psi(2S)K^0_S\pi^+\pi^-)} = 2.288 \pm 0.026,$$

where the uncertainties are statistical only and are related to the size of the simulated event samples. The first ratio is close to unity, as expected, while the second ratio is significantly greater than unity because of the presence of two additional tracks in the denominator. The lifetimes of heavy and light B_s^0 meson eigenstates differ by about 0.2 ps [13], which can have an impact on the efficiency $\epsilon(B_s^0 \to \psi(2S)K_S^0)$. It was verified that the corresponding variations of B_s^0 lifetime result in negligible changes in the efficiency.

The validation of Monte Carlo samples is performed by comparing distributions of variables used in the event selection between simulation and background-subtracted data. No significant deviation is found, and thus no systematic uncertainties in the efficiency ratio are assigned related to data-simulation discrepancies in those variables.

7 Systematic uncertainties

Many systematic uncertainties, related to the efficiency of the trigger as well as the reconstruction and identification of the muons, cancel out in the measured ratios R_s and $R_{\pi^+\pi^-}$. Since the $B_s^0 \to \psi(2S)K_S^0$ and $B^0 \to \psi(2S)K_S^0$ decays have the same number of tracks in the final state, uncertainties related to the track reconstruction are of the same size and correlated, and therefore cancel out when propagated to the measured ratio R_s. For the ratio $R_{\pi^+\pi^-}$, we consider an additional uncertainty of 4.2% from the uncertainty in the tracking efficiency of two additional pions [49].

The systematic uncertainty related to the choice of the fit model is evaluated by testing different models. The largest deviation in the measured ratio from its baseline value is taken as a systematic uncertainty, separately for the variations of the signal and background models. Several alternative signal models were considered. One is a double Gaussian function for B^0 and B_s^0 signals with the resolution shape fixed to the expectations taken from simulation with only the resolution scaling parameter being free in the fit. Another signal model is a Student's *t*-distribution [50] with the value of the *n* parameter fixed to the one measured in simulation. Alternative background models include polynomials of the second and third degrees, an exponential multiplied by a polynomial, and a power function multiplied by an exponential, where in

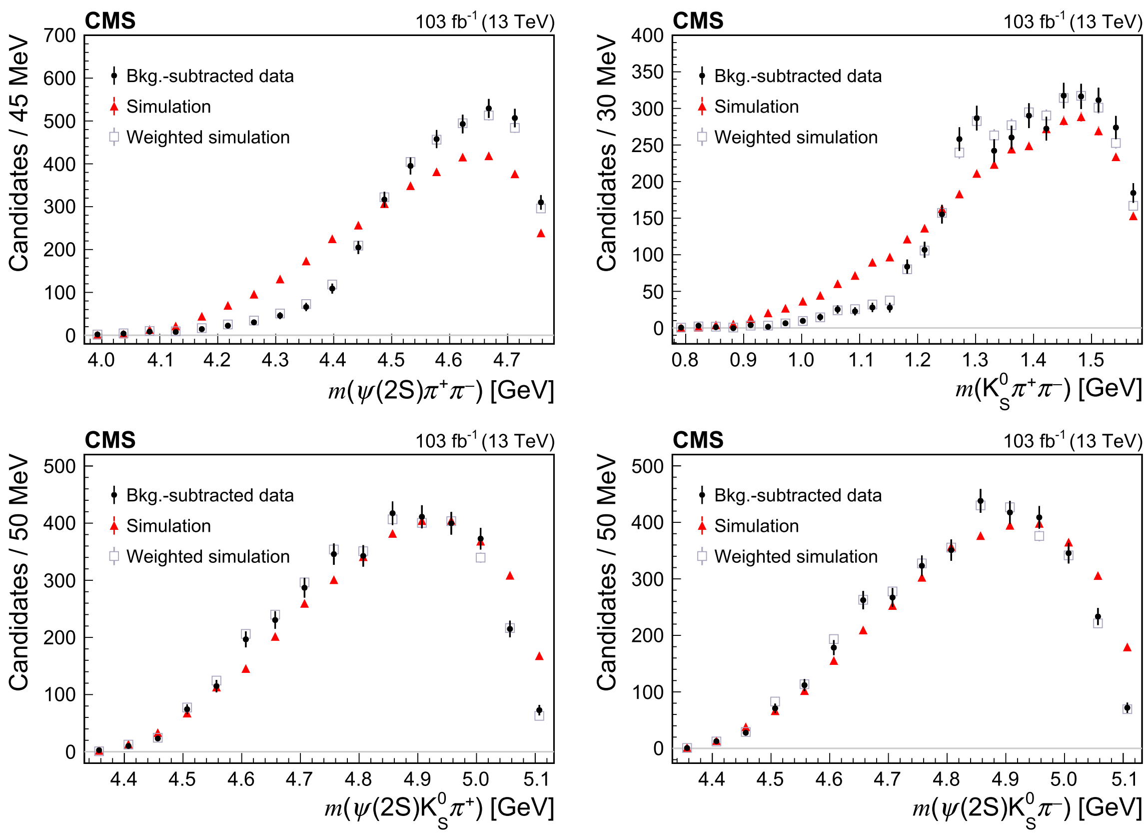

Fig. 3 Distributions of 3-body intermediate invariant masses from the $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decay. Data distributions (black dots) are background subtracted. Overlaid are the predictions of phase space simulations (red triangles), as well as the predictions after applying the reweighting procedure described in Sect. 7 (grey squares)

Table 1 Systematic uncertainties (in %) of the measured branching fraction ratios

Source	R_s	$R_{\pi^+\pi^-}$
Background model	2.5	0.8
Signal model	1.5	0.8
Shape of $B_s^0 \to \psi(2S)K_S^0K^\mp\pi^\pm$ contribution	–	0.5
Finite size of simulation samples	1.3	1.1
Intermediate resonances	–	5.0
Tracking efficiency	–	4.2
Total	3.2	6.7

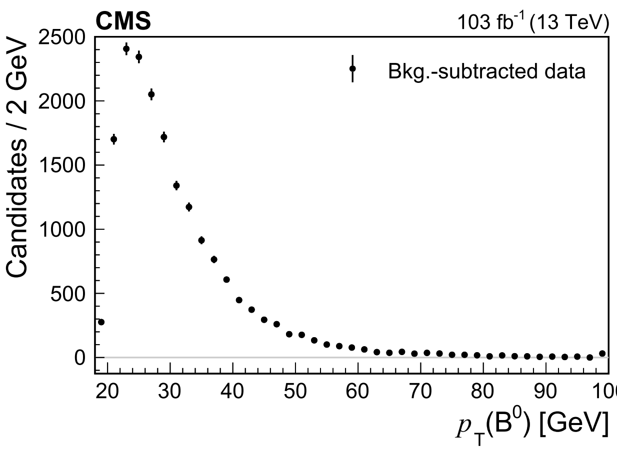

Fig. 4 Background-subtracted $p_T(B^0)$ distribution in data for the $B^0 \to \psi(2S)K_S^0$ signal. The last bin includes the overflow

all cases the background shape parameters are free to vary in the fits.

The uncertainty related to the finite size of the simulation samples (used to measure the efficiencies in Sect. 6) is also considered as a systematic uncertainty.

The uncertainty associated with the shape of the $B_s^0 \to \psi(2S)K_S^0K^\mp\pi^\pm$ contribution to the $\psi(2S)K_S^0\pi^+\pi^-$ invariant mass distribution is estimated by varying the shape parameters within their uncertainties. The largest deviation of $N(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)$ from the baseline value is 0.5% which is taken as a systematic uncertainty.

As discussed in Sect. 5, the simulation for the $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decay does not take into account the intermediate resonance structure, leading to a significant disagreement between data and simulation in the 2- and 3-body mass distributions. This results in a potential bias in the efficiency reported in Sect. 6. To estimate the corresponding systematic uncertainty, the simulated sample is reweighted to be consistent with the data, and the difference between the baseline efficiency and the efficiency obtained on the weighted sample is taken as a systematic uncertainty. Due to the limited number of events, it is impossible to assign weights taking the ratio of data to simulation in bins of multi-dimensional phase space of the considered 4-body decay. An iterative procedure has been developed that operates with one-dimensional weights corresponding to each 2- and 3-body invariant mass, gradually making the mass distributions on weighted simulation sample closer and closer to data, until a satisfactory agreement in all intermediate invariant mass distributions is achieved. The distributions of invariant masses obtained with the weighted simulation sample are presented in Figs. 2 and 3. The efficiency obtained on the weighted simulation sample deviates from the baseline value by 5%, which is taken as a systematic uncertainty due to the intermediate resonance structure. This efficiency correction procedure with iterative reweighting is verified using a dedicated simulation sample instead of data, in which the contributions from $K^*(892)^\pm$ and $\rho(770)^0$ resonances are included with arbitrary magnitudes.

All uncertainties described above, excluding the one related to f_s/f_d for the ratio R_s, are summarized in Table 1 together with a total systematic uncertainty, calculated as a sum in quadrature of the individual sources.

A measurement of the ratio of the B_s^0 and B^0 fragmentation fractions, f_s/f_d, in proton-proton collisions at the LHC has been recently reported by the LHCb Collaboration [51]: $f_s/f_d = (0.263 \pm 0.008) - (17.6 \pm 2.1) \times 10^{-4}\, p_T(B)$, where $p_T(B)$ in GeV is the transverse momentum of a B meson produced in 13 TeV proton-proton collisions. The ratio was found to be independent of the rapidity of the B meson, but with a significant dependence on the transverse momentum of the B candidate. The $p_T(B)$ distribution used in this analysis is shown in Fig. 4, where the background is subtracted using $_s\mathcal{P}$lot. Using the LHCb result and the average $p_T(B)$ in our events of 31.2 GeV, the f_s/f_d value for the kinematic range of this analysis is obtained to be $f_s/f_d = 0.208 \pm 0.007$. The LHCb f_s/f_d measurement is mostly dependent on the events with $p_T < 20$ GeV, while the majority of the events in this analysis have $p_T(B) > 20$ GeV. Therefore, we assign an additional systematic uncertainty on f_s/f_d as the difference between 0.208 and the value obtained under the assumption that f_s/f_d becomes constant (0.2278) in the region $p_T > 20$ GeV. This additional uncertainty is estimated to be 0.020, and the total uncertainty on f_s/f_d is obtained by summing it in quadrature with the uncertainty of 0.007 obtained above. The resulting fragmentation fraction ratio used in the R_s measurement is $f_s/f_d = 0.208 \pm 0.021$, with a relative uncertainty of 10%.

8 Measured branching fractions

The branching fraction ratio of the $B_s^0 \to \psi(2S)K_S^0$ decay relative to the $B^0 \to \psi(2S)K_S^0$ one is measured using Eq. (1) to be

$$R_s = \frac{\mathcal{B}(B_s^0 \to \psi(2S)K_S^0)}{\mathcal{B}(B^0 \to \psi(2S)K_S^0)} = (3.33 \pm 0.69\,(\text{stat}) \pm 0.11\,(\text{syst}) \pm 0.34\,(f_s/f_d)) \times 10^{-2},$$

where the last uncertainty is related to the used value $f_s/f_d = 0.208 \pm 0.021$. Since the knowledge of f_s/f_d at large p_T can be updated with future measurements, allowing to improve the R_s evaluation, we also provide the measurement of the product

$$R_s \frac{f_s}{f_d} = \frac{f_s}{f_d} \frac{\mathcal{B}(B_s^0 \to \psi(2S)K_S^0)}{\mathcal{B}(B^0 \to \psi(2S)K_S^0)} = (0.69 \pm 0.14\,(\text{stat}) \pm 0.02\,(\text{syst})) \times 10^{-2}.$$

In addition, the transverse momentum distribution of the measured B candidates is presented in Fig. 4 and in the HEPData record for this analysis [30].

The branching fraction ratio of the $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decay with respect to the $B^0 \to \psi(2S)K_S^0$ one is measured to be

$$R_{\pi^+\pi^-} = \frac{\mathcal{B}(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)}{\mathcal{B}(B^0 \to \psi(2S)K_S^0)} = 0.480 \pm 0.013\,(\text{stat}) \pm 0.032\,(\text{syst}).$$

This ratio is very close to the similar ratio measured with J/ψ instead of $\psi(2S)$ [52].

Using the world average value $\mathcal{B}(B^0 \to \psi(2S)K_S^0) = (2.90 \pm 0.25) \times 10^{-4}$ [13], the branching fractions of the two newly observed decays are evaluated:

$$\mathcal{B}(B_s^0 \to \psi(2S)K_S^0) = (0.97 \pm 0.20\,(\text{stat}) \pm 0.03\,(\text{syst}) \pm 0.22\,(f_s/f_d) \pm 0.08\,(\mathcal{B})) \times 10^{-5},$$

$$\mathcal{B}(B^0 \to \psi(2S)K_S^0\pi^+\pi^-) = (13.9 \pm 0.4\,(\text{stat}) \pm 0.9\,(\text{syst}) \pm 1.2\,(\mathcal{B})) \times 10^{-5},$$

where the last uncertainties are from the uncertainty in $\mathcal{B}(B^0 \to \psi(2S)K_S^0)$.

9 Summary

The $B_s^0 \to \psi(2S)K_S^0$ and $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decays are observed using proton-proton collision data collected by the CMS experiment at 13 TeV with an integrated luminosity of 103 fb^{-1}. Their branching fractions are measured with respect to the $B^0 \to \psi(2S)K_S^0$ decay to be $\mathcal{B}(B_s^0 \to \psi(2S)K_S^0)/\mathcal{B}(B^0 \to \psi(2S)K_S^0) = (3.33 \pm 0.69\,(\text{stat}) \pm 0.11\,(\text{syst}) \pm 0.34\,(f_s/f_d)) \times 10^{-2}$, and $\mathcal{B}(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)/\mathcal{B}(B^0 \to \psi(2S)K_S^0) = 0.480 \pm 0.013\,(\text{stat}) \pm 0.032\,(\text{syst})$, where the last uncertainty in the first ratio corresponds to the uncertainty in the ratio of production cross sections of B_s^0 and B^0 mesons. The 2- and 3-body invariant mass distributions of the $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decay products do not show significant exotic narrow structures in addition to the known light meson resonances. Further studies with more data will be needed to investigate more precisely the internal dynamics of the $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decay, and to perform *CP* asymmetry measurements in the two observed decays in the future.

Acknowledgements We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid and other centres for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Rachada-pisek Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256-GRK2497; the Lendület ("Momentum") Programme and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Science and Higher Education and the National Science Center, contracts Opus 2014/15/B/ST2/03998 and 2015/19/B/ST2/02861 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018

(Portugal); the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Higher Education, projects no. 0723-2020-0041 and no. FSWW-2020-0008, and the Russian Foundation for Basic Research, project No.19-42-703014 (Russia); MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Stavros Niarchos Foundation (Greece); the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS policy as stated in "CMS data preservation, re-use and open access policy" (https://cms-docdb.cern.ch/cgibin/PublicDocDB/RetrieveFile?docid=6032\&filename=CMSDataPolicyV1.2.pdf\&version=2)."]

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Funded by SCOAP[3].

References

1. Belle Collaboration, Observation of a narrow charmoniumlike state in exclusive $B^\pm \to K^\pm\pi^+\pi^- J/\psi$ decays. Phys. Rev. Lett. **91**, 262001 (2003). https://doi.org/10.1103/PhysRevLett.91.262001. arXiv:hep-ex/0309032
2. CDF Collaboration, Evidence for a narrow near-threshold structure in the $J/\psi\phi$ mass spectrum in $B^+ \to J/\psi\phi K^+$ decays. Phys. Rev. Lett. **102**, 242002 (2009). https://doi.org/10.1103/PhysRevLett.102.242002. arXiv:0903.2229
3. CDF Collaboration, Observation of the $Y(4140)$ structure in the $J/\psi\phi$ mass spectrum in $B^\pm \to J/\psi\phi K^\pm$ decays. Mod. Phys. Lett. A **32**, 1750139 (2017). https://doi.org/10.1142/S0217732317501395. arXiv:1101.6058
4. CMS Collaboration, Observation of a peaking structure in the $J/\psi\phi$ mass spectrum from $B^\pm \to J/\psi\phi K^\pm$ decays. Phys. Lett. B **734**, 261 (2014). https://doi.org/10.1016/j.physletb.2014.05.055. arXiv:1309.6920
5. LHCb Collaboration, Amplitude analysis of $B^+ \to J/\psi\phi K^+$ decays. Phys. Rev. D **95**, 012002 (2017). https://doi.org/10.1103/PhysRevD.95.012002. arXiv:1606.07898
6. BaBar Collaboration, Observation of a broad structure in the $\pi^+\pi^- J/\psi$ mass spectrum around 4.26 GeV/c^2. Phys. Rev. Lett **95**, 142001 (2005). https://doi.org/10.1103/PhysRevLett.95.142001. arXiv:hep-ex/0506081
7. BESIII Collaboration, Precise measurement of the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section at center-of-mass energies from 3.77 to 4.60 GeV. Phys. Rev. Lett **118**, 092001 (2017). https://doi.org/10.1103/PhysRevLett.118.092001. arXiv:1611.01317
8. Belle Collaboration, Observation of a resonancelike structure in the $\pi^\pm\psi'$ mass distribution in exclusive $B \to K\pi^\pm\psi'$ decays. Phys. Rev. Lett. **100**, 142001 (2008). https://doi.org/10.1103/PhysRevLett.100.142001. arXiv:0708.1790
9. Belle Collaboration, Dalitz analysis of $B \to K\pi^+\psi'$ decays and the $Z(4430)^+$. Phys. Rev. D **80**, 031104 (2009). https://doi.org/10.1103/PhysRevD.80.031104. arXiv:0905.2869
10. Belle Collaboration, Experimental constraints on the spin and parity of the $Z(4430)^+$. Phys. Rev. D **88**, 074026 (2013). https://doi.org/10.1103/PhysRevD.88.074026. arXiv:1306.4894
11. LHCb Collaboration, Observation of the resonant character of the $Z(4430)^-$ state. Phys. Rev. Lett **112**, 222002 (2014). https://doi.org/10.1103/PhysRevLett.112.222002. arXiv:1404.1903
12. A. Hosaka et al., Exotic hadrons with heavy flavors: X, Y, Z, and related states. Prog. Theor. Exp. Phys **2016**, 062C01 (2016). https://doi.org/10.1093/ptep/ptw045. arXiv:1603.09229
13. Particle Data Group, P.A. Zyla et al., Review of particle physics. Prog. Theor. Exp. Phys. **2020**, 083C01 (2020). https://doi.org/10.1093/ptep/ptaa104
14. N. Cabibbo, Unitary symmetry and leptonic decays. Phys. Rev. Lett. **10**, 531 (1963). https://doi.org/10.1103/PhysRevLett.10.531
15. Belle Collaboration, Observation of large CP violation in the neutral B meson system. Phys. Rev. Lett. **87**, 091802 (2001). https://doi.org/10.1103/PhysRevLett.87.091802. arXiv:hep-ex/0107061
16. BaBar Collaboration, Observation of CP violation in the B^0 meson system. Phys. Rev. Lett. **87**, 091801 (2001). https://doi.org/10.1103/PhysRevLett.87.091801. arXiv:hep-ex/0107013
17. BaBar Collaboration, Evidence for CP violation in $B^0 \to J/\psi\pi^0$ decays. Phys. Rev. Lett. **101**, 021801 (2008). https://doi.org/10.1103/PhysRevLett.101.021801. arXiv:0804.0896
18. BaBar Collaboration, Measurement of time-dependent CP asymmetry in $B^0 \to c\bar{c}K^{(*)0}$ decays. Phys. Rev. D **79**, 072009 (2009). https://doi.org/10.1103/PhysRevD.79.072009. arXiv:0902.1708
19. Belle Collaboration, Precise measurement of the CP violation parameter $\sin 2\phi_1$ in $B^0 \to (c\bar{c})K^0$ decays. Phys. Rev. Lett. **108**, 171802 (2012). https://doi.org/10.1103/PhysRevLett.108.171802. arXiv:1201.4643
20. LHCb Collaboration, Measurement of the *CP*-violating phase β in $B^0 \to J/\psi\pi^+\pi^-$ decays and limits on penguin effects. Phys. Lett. B **742**, 38 (2015). https://doi.org/10.1016/j.physletb.2015.01.008. arXiv:1411.1634
21. LHCb Collaboration, Measurement of *CP* violation in $B^0 \to J/\psi K^0_S$ decays. Phys. Rev. Lett **115**, 031601 (2015). https://doi.org/10.1103/PhysRevLett.115.031601. arXiv:1503.07089
22. LHCb Collaboration, Measurement of the time-dependent *CP* asymmetries in $B^0_s \to J/\psi K^0_S$. JHEP **06**, 131 (2015). https://doi.org/10.1007/JHEP06(2015)131. arXiv:1503.07055
23. LHCb Collaboration, Measurement of CP violation in $B^0 \to J/\psi K^0_S$ and $B^0 \to \psi(2S)K^0_S$ decays. JHEP **11**, 170 (2017). https://doi.org/10.1007/JHEP11(2017)170. arXiv:1709.03944
24. Belle Collaboration, Measurement of the branching fraction and time-dependent CP asymmetry for $B^0 \to J/\psi\pi^0$ decays. Phys.

Rev. D **98**, 112008 (2018). https://doi.org/10.1103/PhysRevD.98.112008. arXiv:1810.01356
25. LHCb Collaboration, Updated measurement of time-dependent CP-violating observables in $B_s^0 \rightarrow J/\psi K^+K^-$ decays. Eur. Phys. J. C **79**, 706 (2019). https://doi.org/10.1140/epjc/s10052-019-7159-8. arXiv:1906.08356 [Erratum: https://doi.org/10.1140/epjc/s10052-020-7875-0]
26. CMS Collaboration, Measurement of the CP-violating phase ϕ_s in the $B_s^0 \rightarrow J/\psi\phi(1020) \rightarrow \mu^+\mu^-K^+K^-$ channel in proton–proton collisions at $\sqrt{s} = 13$ TeV. Phys. Lett. B **816**, 136188 (2021). https://doi.org/10.1016/j.physletb.2021.136188. arXiv:2007.02434
27. ATLAS Collaboration, Measurement of the CP-violating phase ϕ_s in $B_S^0 \rightarrow J/\psi\phi$ decays in ATLAS at 13 TeV. Eur. Phys. J. C **81**, 342 (2021). https://doi.org/10.1140/epjc/s10052-021-09011-0. arXiv:2001.07115
28. CMS Collaboration, CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary CMS-PAS-LUM-17-004 (2018)
29. CMS Collaboration, CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary CMS-PAS-LUM-18-002 (2019)
30. HEPData record for this analysis (2021). https://doi.org/10.17182/hepdata.114370
31. CMS Collaboration, The CMS experiment at the CERN LHC. JINST **3**, S08004 (2008). https://doi.org/10.1088/1748-0221/3/08/S08004
32. CMS Collaboration, The CMS trigger system. JINST **12**, P01020 (2017). https://doi.org/10.1088/1748-0221/12/01/P01020. arXiv:1609.02366
33. CMS Collaboration, Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV. JINST **15**, P10017 (2020). https://doi.org/10.1088/1748-0221/15/10/P10017. arXiv:2006.10165
34. T. Sjöstrand et al., An introduction to PYTHIA 82. Comput. Phys. Commun. **191**, 159 (2015). https://doi.org/10.1016/j.cpc.2015.01.024. arXiv:1410.3012
35. CMS Collaboration, Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements. Eur. Phys. J. C **80** (2020). https://doi.org/10.1140/epjc/s10052-019-7499-4. arXiv:1903.12179
36. D.J. Lange, The EvtGen particle decay simulation package. Nucl. Instrum. Meth. A **462**, 152 (2001). https://doi.org/10.1016/S0168-9002(01)00089-4
37. E. Barberio, B. van Eijk, Z. Wąs, PHOTOS—a universal Monte Carlo for QED radiative corrections in decays. Comput. Phys. Commun. **66**, 115 (1991). https://doi.org/10.1016/0010-4655(91)90012-A
38. E. Barberio, Z. Wąs, PHOTOS—a universal Monte Carlo for QED radiative corrections: version 2.0. Comput. Phys. Commun **79**, 291 (1994). https://doi.org/10.1016/0010-4655(94)90074-4
39. GEANT4 Collaboration, GEANT4—a simulation toolkit. Nucl. Instrum. Meth. A **506**, 250 (2003). https://doi.org/10.1016/S0168-9002(03)01368-8
40. CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV. JINST **13**, P06015 (2018). https://doi.org/10.1088/1748-0221/13/06/P06015. arXiv:1804.04528
41. CMS Collaboration, CMS tracking performance results from early LHC operation. Eur. Phys. J. C **70**, 1165 (2010). https://doi.org/10.1140/epjc/s10052-010-1491-3. arXiv:1007.1988
42. CMS Collaboration, Search for the X(5568) state decaying into $B_S^0\pi^\pm$ in proton-proton collisions at $\sqrt{s} = 8$ TeV. Phys. Rev. Lett **120**, 202005 (2018). https://doi.org/10.1103/PhysRevLett.120.202005. arXiv:1712.06144
43. CMS Collaboration, Study of the $B^+ \rightarrow J/\psi\bar{\Lambda}p$ decay in proton-proton collisions at $\sqrt{s} = 8$ TeV. JHEP **12**, 100 (2019). https://doi.org/10.1007/JHEP12(2019)100. arXiv:1907.05461
44. CMS Collaboration, Observation of the $\Lambda_b^0 \rightarrow J/\psi\Lambda\phi$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV. Phys. Lett. B **802**, 135203 (2020). https://doi.org/10.1016/j.physletb.2020.135203. arXiv:1911.03789
45. CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker. JINST **9**, P10009 (2014). https://doi.org/10.1088/1748-0221/9/10/P10009. arXiv:1405.6569
46. G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics. Eur. Phys. J. C **71**, 1554 (2011). https://doi.org/10.1140/epjc/s10052-011-1554-0. arXiv:1007.1727 [Erratum: https://doi.org/10.1140/epjc/s10052-013-2501-z]
47. S.S. Wilks, The large-sample distribution of the likelihood ratio for testing composite hypotheses. Ann. Math. Stat. **9**, 60 (1938). https://doi.org/10.1214/aoms/1177732360
48. M. Pivk, F.R. Le Diberder, $_s\mathcal{P}$lot: a statistical tool to unfold data distributions. Nucl. Instrum. Meth. A **555**, 356 (2005). https://doi.org/10.1016/j.nima.2005.08.106. arXiv:physics/0402083
49. CMS Collaboration, Tracking POG results for pion efficiency with the D^* meson using data from 2016 and 2017, CMS Detector Performance Note CMS-DP-2018-050 (2018)
50. S. Jackman, Bayesian analysis for the social sciences. Wiley, New Jersey (2009). https://doi.org/10.1002/9780470686621
51. LHCb Collaboration, Precise measurement of the f_s/f_d ratio of fragmentation fractions and of B_s^0 decay branching fractions. Phys. Rev. D **104**, 032005 (2021). https://doi.org/10.1103/PhysRevD.104.032005. arXiv:2103.06810
52. LHCb Collaboration, Observation of the $B_S^0 \rightarrow J/\psi K_s^0 K^\pm\pi^\mp$ decay. JHEP **07**, 140 (2014). https://doi.org/10.1007/JHEP07(2014)140. arXiv:1405.3219

CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Tumasyan

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J. W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth[1], M. Jeitler[1], N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F. M. Pitters, J. Schieck[1], R. Schöfbeck, D. Schwarz, S. Templ, W. Waltenberger, C. -E. Wulz[1]

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, A. Litomin, V. Makarenko

Universiteit Antwerpen, Antwerpen, Belgium
M. R. Darwish[2], E. A. De Wolf, T. Janssen, T. Kello[3], A. Lelek, H. Rejeb Sfar, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussels, Belgium
E. S. Bols, J. D'Hondt, A. De Moor, M. Delcourt, H. El Faham, S. Lowette, S. Moortgat, A. Morton, D. Müller, A. R. Sahasransu, S. Tavernier, W. Van Doninck, D. Vannerom

Université Libre de Bruxelles, Brussels, Belgium
D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, L. Favart, A. K. Kalsi, K. Lee, M. Mahdavikhorrami, I. Makarenko, L. Moureaux, S. Paredes, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, M. Niedziela, C. Rendón, C. Roskas, A. Samalan, K. Skovpen, M. Tytgat, B. Vermassen, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, A. Bethani, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I. S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliercio, M. Teklishyn, T. T. Tran, P. Vischia, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G. A. Alves, C. Hensel, A. Moraes, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W. L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[4], E. M. Da Costa, G. G. Da Silveira[5], D. De Jesus Damiao, V. Dos Santos Sousa, S. Fonseca De Souza, C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, S. M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo[6], A. Vilela Pereira

Universidade Estadual Paulista (a), Universidade Federal do ABC (b), São Paulo, Brazil
C. A. Bernardes[5], L. Calligaris, T. R. Fernandez Perez Tomei, E. M. Gregores, D. S. Lemos, P. G. Mercadante, S. F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

Beihang University, Beijing, China
T. Cheng, T. Javaid[7], M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, G. Bauer, C. Dozen[8], Z. Hu, J. Martins[9], Y. Wang, K. Yi[10,11]

Institute of High Energy Physics, Beijing, China
E. Chapon, G. M. Chen[7], H. S. Chen[7], M. Chen, F. Iemmi, A. Kapoor, D. Leggat, H. Liao, Z. -A. Liu[7], V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. An, Y. Ban, C. Chen, A. Levin, Q. Li, X. Lyu, Y. Mao, S. J. Qian, D. Wang, J. Xiao, H. Yang

Sun Yat-Sen University, Guangzhou, China
M. Lu, Z. You

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Fudan University, Shanghai, China
X. Gao[3], H. Okawa, Y. Zhang

Zhejiang University, Hangzhou, China, Zhejiang, China
Z. Lin, M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C. Florez, J. Fraga

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, F. Ramirez, J. D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov[12], T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, G. Kole, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P. A. Razis, H. Rykaczewski, H. Saka

Charles University, Prague, Czech Republic
M. Finger[13], M. Finger Jr.[13], A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A. A. Abdelalim[14,15], E. Salama[16,17]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M. A. Mahmoud, Y. Mohammed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, R. K. Dewanjee, K. Ehataht, M. Kadastik, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, M. S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, J. Ott, M. m. Rantanen, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
P. Luukka, H. Petrow, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J. L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, J. Malcles, J. Rander, A. Rosowsky, M. Ö. Sahin, A. Savoy-Navarro[18], M. Titov, G. B. Yu

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, O. Davignon, B. Diab, G. Falmagne, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, I. Kucher, J. Motta, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, U. Sarkar, J. B. Sauvan, Y. Sirois, A. Tarabini, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J. -L. Agram[19], J. Andrea, D. Apparu, D. Bloch, G. Bourgatte, J -M. Brom, E. C. Chabert, C. Collard, D. Darej, J. -C. Fontaine[19], U. Goerlach, C. Grimault, A. -C. Le Bihan, E. Nibigira, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, I. B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, S. Perries, K. Shchablo, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
I. Lomidze, T. Toriashvili[20], Z. Tsamalaidze[13]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, J. Schulz, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Dodonova, D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, A. Pozdnyakov, Y. Rath, H. Reithler, A. Schmidt, S. C. Schuler, A. Sharma, L. Vigilante, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[21], O. Hlushchenko, T. Kress, A. Nowack, O. Pooth, D. Roy, A. Stahl[22], T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, S. Baxter, M. Bayatmakou, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A. A. Bin Anuar, F. Blekman, K. Borras[23], D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, M. De Silva, L. Didukh, G. Eckerlin, D. Eckstein, L. I. Estevez Banos, O. Filatov, E. Gallo[24], A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Jafari[25], N. Z. Jomhari, H. Jung, A. Kasem[23], M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, D. Krücker, W. Lange, K. Lipka, W. Lohmann[26], R. Mankel, I. -A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A. B. Meyer, M. Meyer, J. Mnich, A. Mussgiller, A. Nürnberg, Y. Otarid, D. Pérez Adán, D. Pitzl, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham[27], V. Scheurer, S. Schnake, P. Schütze, C. Schwanenberger[24], M. Shchedrolosiev, R. E. Sosa Ricardo, D. Stafford, N. Tonon, M. Van De Klundert, F. Vazzoler, R. Walsh, D. Walter, Q. Wang, Y. Wen, K. Wichmann, L. Wiens, C. Wissing, S. Wuchterl

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Albrecht, S. Bein, L. Benato, P. Connor, K. De Leo, M. Eich, K. El Morabit, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, M. Hajheidari, J. Haller, A. Hinzmann, G. Kasieczka, R. Klanner, T. Kramer, V. Kutzner, J. Lange, T. Lange, A. Lobanov, A. Malara, C. Matthies, A. Mehta, A. Nigamova, K. J. Pena Rodriguez, M. Rieger, O. Rieger, P. Schleper, M. Schröder, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, A. Tews, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
J. Bechtel, S. Brommer, M. Burkart, E. Butz, R. Caspart, T. Chwalek, W. De Boer[†], A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, J. O. Gosewisch, A. Gottmann, F. Hartmann[22], C. Heidecker, U. Husemann, P. Keicher, R. Koppenhöfer, S. Maier, S. Mitra, Th. Müller, M. Neukum, G. Quast, K. Rabbertz, J. Rauser, D. Savoiu, M. Schnepf, D. Seith, I. Shvetsov, H. J. Simonis, R. Ulrich, J. Van Der Linden, R. F. Von Cube, M. Wassmer, M. Weber, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, A. Kyriakis, D. Loukas, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
M. Diamantopoulou, D. Karasavvas, P. Kontaxakis, C. K. Koraka, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, E. Vourliotis

National Technical University of Athens, Athens, Greece
G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece
K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, N. Manthos, I. Papadopoulos, J. Strologas

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanad, K. Farkas, M. M. A. Gadallah[28], S. Lökös[29], P. Major, K. Mandal, G. Pasztor, A. J. Rádl, O. Surányi, G. I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók[30], G. Bencze, C. Hajdu, D. Horvath[31,32], F. Sikler, V. Veszpremi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
S. Czellar, D. Fasanella, F. Fienga, J. Karancsi[30], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z. L. Trocsanyi[33], B. Ujvari[34]

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[35], F. Nemes[35], T. Novak

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati[36], C. Kar, P. Mal, T. Mishra, V. K. Muraleedharan Nair Bindhu[37], A. Nayak[37], P. Saha, N. Sur, S. K. Swain, D. Vats[37]

Panjab University, Chandigarh, India
S. Bansal, S. B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[38], R. Gupta, A. Kaur, H. Kaur, M. Kaur, P. Kumari, M. Meena, K. Sandeep, J. B. Singh[39], A. K. Virdi

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, B. C. Choudhary, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, S. Saumya, A. Shah

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
M. Bharti[40], R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber[41], M. Maity[42], P. Palit, P. K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan

Indian Institute of Technology Madras, Madras, India
P. K. Behera, S. C. Behera, P. Kalbhor, J. R. Komaragiri[43], D. Kumar[43], A. Muhammad, L. Panwar[43], R. Pradhan, P. R. Pujahari, A. Sharma, A. K. Sikdar, P. C. Tiwari[43]

Bhabha Atomic Research Centre, Mumbai, India
K. Naskar[44]

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, S. Dugad, M. Kumar

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee

Indian Institute of Science Education and Research (IISER), Pune, India
A. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rastogi, S. Sharma

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[45,46], E. Khazaie[46], M. Zeinali[47]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[48], S. M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,b,49], C. Aruta[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], A. Di Pilato[a,b], W. Elmetenawee[a,b], F. Errico[a,b], L. Fiore[a], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], D. Ramos[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F. M. Simone[a,b], Ü. Sözbilir[a], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], L. Brigliadori[a], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F. R. Cavallo[a], C. Ciocca[a], M. Cuffiani[a,b], G. M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,50], L. Lunerti[a,b], S. Marcellini[a], G. Masetti[a], F. L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A. M. Rossi[a,b], T. Rovelli[a,b], G. P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Albergo[a,b,51], S. Costa[a,b,51], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,51], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
G. Barbagli[a], A. Cassese[a], R. Ceccarelli[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a,b], M. Meschini[a], S. Paoletti[a], R. Seidita[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genoa, Italy
M. Bozzo[a,b], F. Ferro[a], R. Mulargia[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milan, Italy
A. Benaglia[a], G. Boldrini, F. Brivio[a,b], F. Cetorelli[a,b], F. De Guio[a,b], M. E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M. T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], B. S. Pinolini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b], D. Valsecchi[a,b,22], D. Zuolo[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy, Università della Basilicata[c], Potenza, Italy, Università G. Marconi[d], Rome, Italy
S. Buontempo[a], F. Carnevali[a,b], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], A. O. M. Iorio[a,b], L. Lista[a,b,52], S. Meola[a,d,22], P. Paolucci[a,22], B. Rossi[a], C. Sciacca[a,b]

INFN Sezione di Padova[a], Università di Padova[b], Padua, Italy, Università di Trento[c], Trento, Italy
P. Azzi[a], N. Bacchetta[a], D. Bisello[a,b], P. Bortignon[a], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], G. Grosso, L. Layer[a,53], E. Lusiani, M. Margoni[a,b], F. Marini, A. T. Meneguzzo[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], G. Strong[a], M. Tosi[a,b], H. Yarar[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
C. Aimè[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], P. Montagna[a,b], S. P. Ratti[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
P. Asenov[a,54], G. M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,54], A. Piccinelli[a,b], M. Presilla[a,b], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy, Università di Siena[d], Siena, Italy
P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], L. Bianchini[a], T. Boccali[a], E. Bossini[a,b], R. Castaldi[a], M. A. Ciocci[a,b], V. D'Amante[a,d], R. Dell'Orso[a], M. R. Di Domenico[a,d], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], E. Manca[a,c], G. Mandorli[a,c], D. Matos Figueiredo, A. Messineo[a,b], M. Musich[a], F. Palla[a], S. Parolia[a,b], G. Ramirez-Sanchez[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,c], A. Scribano[a], N. Shafiei[a,b], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], A. Venturi[a], P. G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Rome, Italy
P. Barria[a], M. Campana[a,b], F. Cavallari[a], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], E. Longo[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], R. Tramontano[a,b]

INFN Sezione di Torino[a], Università di Torino[b], Turin, Italy, Università del Piemonte Orientale[c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], J. Berenguer Antequera[a,b], C. Biino[a], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], M. Grippo[a,b], B. Kiani[a,b], F. Legger[a], C. Mariotti[a], S. Maselli[a], A. Mecca[a,b], E. Migliore[a,b], E. Monteil[a,b], M. Monteno[a], M. M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], M. Ruspa[a,c], K. Shchelina[a], F. Siviero[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a], M. Tornago[a,b], D. Trocino[a], G. Umoret[a,b], A. Vagnerini[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], A. Da Rold[a,b], G. Della Ricca[a,b], G. Sorrentino[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, C. Huh, B. Kim, D. H. Kim, G. N. Kim, J. Kim, J. Lee, S. W. Lee, C. S. Moon, Y. D. Oh, S. I. Pak, S. Sekmen, Y. C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D. H. Moon

Hanyang University, Seoul, Korea
B. Francois, T. J. Kim, J. Park

Korea University, Seoul, Korea
S. Cho, S. Choi, B. Hong, K. Lee, K. S. Lee, J. Lim, J. Park, S. K. Park, J. Yoo

Department of Physics, Kyung Hee University, Seoul, Republic of Korea
J. Goh, A. Gurtu

Sejong University, Seoul, Korea
H. S. Kim, Y. Kim

Seoul National University, Seoul, Korea
J. Almond, J. H. Bhyun, J. Choi, S. Jeon, J. Kim, J. S. Kim, S. Ko, H. Kwon, H. Lee, S. Lee, B. H. Oh, M. Oh, S. B. Oh, H. Seo, U. K. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Jang, D. Y. Kang, Y. Kang, S. Kim, B. Ko, J. S. H. Lee, Y. Lee, J. A. Merlin, I. C. Park, Y. Roh, M. S. Ryu, D. Song, I. J. Watson, S. Yang

Department of Physics, Yonsei University, Seoul, Korea
S. Ha, H. D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, H. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Egaila, Kuwait, Dasman, Kuwait
T. Beyrouthy, Y. Maghrbi

Riga Technical University, Riga, Latvia
K. Dreimanis, V. Veckalns[55]

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Carvalho Antunes De Oliveira, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
N. Bin Norjoharuddeen, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J. F. Benitez, A. Castaneda Hernandez, H. A. Encinas Acosta, L. G. Gallegos Maríñez, M. León Coello, J. A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[56], R. Lopez-Fernandez, C. A. Mondragon Herrera, D. A. Perez Navarro, R. Reyes-Almanza, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Pedraza, H. A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
J. Mijuskovic[57], N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
P. H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. I. Asghar, A. Awais, M. I. M. Awan, M. Gul, H. R. Hoorani, W. A. Khan, M. A. Shah, M. Shoaib, M. Waqas

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Laboratório de Instrumentaç ao e Física Experimental de Partículas, Lisbon, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, D. Budkouski, I. Golutvin, I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[58,59], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B. S. Yuldashev[60], A. Zarubin, I. Zhizhin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[61], E. Kuznetsova[62], V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[63], V. Popov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
O. Bychkova, R. Chistov[64], M. Danilov[64], A. Oskin, P. Parygin, S. Polikarpov[64], A. Tulupov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, M. Dubinin[65], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov[66], T. Dimova[66], L. Kardapoltsev[66], A. Kozyrev[66], I. Ovtin[66], O. Radchenko[66], Y. Skovpen[66]

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
I. Azhgirey, I. Bayshev, D. Elumakhov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, V. Okhotnikov

Tomsk State University, Tomsk, Russia
V. Borshch, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[67], M. Dordevic, P. Milenovic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, 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, J. León Holgado, D. Moran, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, L. Urda Gómez, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
J. F. de Trocóniz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J. R. González Fernández, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, N. Trevisani, C. Vico Villalba

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J. A. Brochero Cifuentes, I. J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, P. J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, J. Piedra Gomez, C. Prieels, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J. M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
M. K. Jayananda, B. Kailasapathy[68], D. U. J. Sonnadara, D. D. C. Wickramarathna

Department of Physics, University of Ruhuna, Matara, Sri Lanka
W. G. D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
T. K. Aarrestad, D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon[†], D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Caillol, T. Camporesi, M. Capeans Garrido, G. Cerminara, N. Chernyavskaya, S. S. Chhibra, S. Choudhury, M. Cipriani, L. Cristella, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M. M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, F. Fallavollita[69], A. Florent, L. Forthomme, G. Franzoni, W. Funk, S. Ghosh, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, E. Govorkova, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, A. Lintuluoto, K. Long, C. Lourenço, B. Maier, L. Malgeri, S. Mallios, M. Mannelli, A. C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérrez, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas[70], S. Summers, K. Tatar, V. R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, J. Wanczyk[71], K. A. Wozniak, W. D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[72], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H. C. Kaestli, D. Kotlinski, U. Langenegger, M. Missiroli[72], L. Noehte[72], T. Rohe

ETH Zurich-Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
K. Androsov[71], M. Backhaus, P. Berger, A. Calandri, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, F. Eble, K. Gedia, F. Glessgen, T. A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A. -M. Lyon, R. A. Manzoni, L. Marchese, C. Martin Perez, M. T. Meinhard, F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, S. Pigazzini, M. G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D. A. Sanz Becerra, V. Stampf, J. Steggemann[71], R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[73], P. Bärtschi, C. Botta, D. Brzhechko, M. F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J. K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S. P. Liechti, A. Macchiolo, P. Meiring, V. M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi

National Central University, Chung-Li, Taiwan
C. Adloff[74], C. M. Kuo, W. Lin, A. Roy, T. Sarkar[42], S. S. Yu

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, Y. Chao, K. F. Chen, P. H. Chen, P.s. Chen, H. Cheng, W. -S. Hou, Y.y. Li, R. -S. Lu, E. Paganis, A. Psallidas, A. Steen, H.y. Wu, E. Yazgan, P.r. Yu

Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

Physics Department, Science and Art Faculty, Çukurova University, Adana, Turkey
F. Boran, S. Damarseckin[75], Z. S. Demiroglu, F. Dolek, I. Dumanoglu[76], E. Eskut, Y. Guler[77], E. Gurpinar Guler[77], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[78], A. Polatoz, A. E. Simsek, B. Tali[79], U. G. Tok, S. Turkcapar, I. S. Zorbakir

Physics Department, Middle East Technical University, Ankara, Turkey
G. Karapinar, K. Ocalan[80], M. Yalvac[81]

Bogazici University, Istanbul, Turkey
B. Akgun, I. O. Atakisi, E. Gulmez, M. Kaya[82], O. Kaya[83], Ö. Özçelik, S. Tekten[84], E. A. Yetkin[85]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[76], Y. Komurcu, S. Sen[86]

Istanbul University, Istanbul, Turkey
S. Cerci[79], I. Hos[87], B. Isildak[88], B. Kaynak, S. Ozkorucuklu, H. Sert, C. Simsek, D. Sunar Cerci[79], C. Zorbilmez

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, UK
D. Anthony, E. Bhal, S. Bologna, J. J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, G. P. Heath, H. F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V. J. Smith, N. Stylianou[89], K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, UK
K. W. Bell, A. Belyaev[90], C. Brew, R. M. Brown, D. J. A. Cockerill, C. Cooke, K. V. Ellis, K. Harder, S. Harper, M. -L. Holmberg[91], J. Linacre, K. Manolopoulos, D. M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C. H. Shepherd-Themistocleous, I. R. Tomalin, T. Williams

Imperial College, London, UK
R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, V. Cepaitis, G. S. Chahal[92], D. Colling, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M. H. Hassanshahi, G. Iles, J. Langford, L. Lyons, A. -M. Magnan, S. Malik, A. Martelli, D. G. Monk, J. Nash[93], M. Pesaresi, B. C. Radburn-Smith, D. M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, A. Tapper, K. Uchida, T. Virdee[22], M. Vojinovic, N. Wardle, S. N. Webb, D. Winterbottom

Brunel University, Uxbridge, UK
K. Coldham, J. E. Cole, A. Khan, P. Kyberd, I. D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, TX, USA
S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, A. R. Kanuganti, B. McMaster, M. Saunders, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniyal, A. M. Vargas Hernandez

The University of Alabama, Tuscaloosa, AL, USA
A. Buccilli, S. I. Cooper, D. Di Croce, S. V. Gleyzer, C. Henderson, C. U. Perez, P. Rumerio[94], C. West

Boston University, Boston, MA, USA
A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, E. Fontanesi, D. Gastler, S. May, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan, D. Zou

Brown University, Providence, RI, USA
G. Benelli, B. Burkle, X. Coubez[23], D. Cutts, M. Hadley, U. Heintz, J. M. Hogan[95], T. Kwon, G. Landsberg, K. T. Lau, D. Li, M. Lukasik, J. Luo, M. Narain, N. Pervan, S. Sagir[96], F. Simpson, E. Usai, W. Y. Wong, X. Yan, D. Yu, W. Zhang

University of California, Davis, Davis, CA, USA
J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P. T. Cox, R. Erbacher, G. Haza, F. Jensen, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, B. Regnery, D. Taylor, Y. Yao, F. Zhang

University of California, Los Angeles, CA, USA
M. Bachtis, R. Cousins, A. Datta, D. Hamilton, J. Hauser, M. Ignatenko, M. A. Iqbal, T. Lam, W. A. Nash, S. Regnard, D. Saltzberg, B. Stone, V. Valuev

University of California, Riverside, Riverside, CA, USA
Y. Chen, R. Clare, J. W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O. R. Long, N. Manganelli, W. Si, S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, CA, USA
J. G. Branson, P. Chang, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, R. Gerosa, L. Giannini, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, M. Pieri, B. V. Sathia Narayanan, V. Sharma, M. Tadel, F. Würthwein, Y. Xiang, A. Yagil

Department of Physics, University of California, Santa Barbara, Santa Barbara, CA, USA
N. Amin, C. Campagnari, M. Citron, G. Collura, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, J. Kim, B. Marsh, H. Mei, M. Oshiro, M. Quinnan, J. Richman, U. Sarica, F. Setti, J. Sheplock, P. Siddireddy, D. Stuart, S. Wang

California Institute of Technology, Pasadena, CA, USA
A. Bornheim, O. Cerri, I. Dutta, J. M. Lawhorn, N. Lu, J. Mao, H. B. Newman, T. Q. Nguyen, M. Spiropulu, J. R. Vlimant, C. Wang, S. Xie, Z. Zhang, R. Y. Zhu

Carnegie Mellon University, Pittsburgh, PA, USA
J. Alison, S. An, M. B. Andrews, P. Bryant, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, M. Paulini, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, CO, USA
J. P. Cumalat, W. T. Ford, A. Hassani, G. Karathanasis, E. MacDonald, R. Patel, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K. A. Ulmer, S. R. Wagner, N. Zipper

Cornell University, Ithaca, NY, USA
J. Alexander, S. Bright-Thonney, X. Chen, Y. Cheng, D. J. Cranshaw, S. Hogan, J. Monroy, J. R. Patterson, D. Quach, J. Reichert, M. Reid, A. Ryd, W. Sun, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, IL, USA
M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, L. A. T. Bauerdick, D. Berry, J. Berryhill, P. C. Bhat, K. Burkett, J. N. Butler, A. Canepa, G. B. Cerati, H. W. K. Cheung, F. Chlebana, K. F. Di Petrillo, J. Dickinson, V. D. Elvira, Y. Feng, J. Freeman, Z. Gecse, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R. M. Harris, R. Heller, T. C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K. H. M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[65], F. Ravera, A. Reinsvold Hall[97], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N. V. Tran, L. Uplegger, E. W. Vaandering, H. A. Weber

University of Florida, Gainesville, FL, USA
P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, R. D. Field, D. Guerrero, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, K. H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang, Z. Wu, E. Yigitbasi, X. Zuo

Florida State University, Tallahassee, FL, USA
T. Adams, A. Askew, R. Habibullah, V. Hagopian, K. F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, O. Viazlo, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, FL, USA
M. M. Baarmand, S. Butalla, T. Elkafrawy[17], M. Hohlmann, R. Kumar Verma, D. Noonan, M. Rahmani, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, IL, USA
M. R. Adams, H. Becerril Gonzalez, R. Cavanaugh, S. Dittmer, O. Evdokimov, C. E. Gerber, D. J. Hofman, A. H. Merrit, C. Mills, G. Oh, T. Roy, S. Rudrabhatla, M. B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Ye

The University of Iowa, Iowa City, IA, USA
M. Alhusseini, K. Dilsiz[98], L. Emediato, R. P. Gandrajula, O. K. Köseyan, J. -P. Merlo, A. Mestvirishvili[99], J. Nachtman, H. Ogul[100], Y. Onel, A. Penzo, C. Snyder, E. Tiras[101]

Johns Hopkins University, Baltimore, MD, USA
O. Amram, B. Blumenfeld, L. Corcodilos, J. Davis, A. V. Gritsan, S. Kyriacou, P. Maksimovic, J. Roskes, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, KS, USA
A. Abreu, J. Anguiano, C. Baldenegro Barrera, P. Baringer, A. Bean, Z. Flowers, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, M. Lazarovits, C. Le Mahieu, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, C. Rogan, C. Royon, R. Salvatico, S. Sanders, E. Schmitz, C. Smith, Q. Wang, Z. Warner, J. Williams, G. Wilson

Kansas State University, Manhattan, KS, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam

Lawrence Livermore National Laboratory, Livermore, CA, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, MD, USA
E. Adams, A. Baden, O. Baron, A. Belloni, S. C. Eno, N. J. Hadley, S. Jabeen, R. G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A. C. Mignerey, S. Nabili, C. Palmer, M. Seidel, A. Skuja, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, MA, USA
D. Abercrombie, G. Andreassi, R. Bi, W. Busza, I. A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez Ceballos, M. Goncharov, P. Harris, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y. -J. Lee, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G. S. F. Stephans, J. Wang, Z. Wang, B. Wyslouch

University of Minnesota, Minneapolis, MN, USA
R. M. Chatterjee, A. Evans, J. Hiltbrand, Sh. Jain, B. M. Joshi, M. Krohn, Y. Kubota, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M. A. Wadud

University of Nebraska-Lincoln, Lincoln, NE, USA
K. Bloom, M. Bryson, S. Chauhan, D. R. Claes, C. Fangmeier, L. Finco, F. Golf, C. Joo, I. Kravchenko, I. Reed, J. E. Siado, G. R. Snow[†], W. Tabb, A. Wightman, F. Yan, A. G. Zecchinelli

State University of New York at Buffalo, Buffalo, NY, USA
G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

Northeastern University, Boston, MA, USA
G. Alverson, E. Barberis, Y. Haddad, Y. Han, A. Hortiangtham, A. Krishna, J. Li, J. Lidrych, G. Madigan, B. Marzocchi, D. M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, IL, USA
S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K. A. Hahn, Y. Liu, N. Odell, M. H. Schmitt, M. Velasco

University of Notre Dame, Notre Dame, IN, USA
R. Band, R. Bucci, M. Cremonesi, A. Das, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, D. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, C. Moore, Y. Musienko[58], R. Ruchti, A. Townsend, M. Wayne, M. Zarucki, L. Zygala

The Ohio State University, Columbus, OH, USA
B. Bylsma, L. S. Durkin, B. Francis, C. Hill, M. Nunez Ornelas, K. Wei, B. L. Winer, B. R. Yates

Princeton University, Princeton, NJ, USA
F. M. Addesa, B. Bonham, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, PR, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, IN, USA
A. S. Bakshi, V. E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A. W. Jung, D. Kondratyev, A. M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, A. Purohit, J. F. Schulte, M. Stojanovic[18], J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, IN, USA
J. Dolen, N. Parashar

Rice University, Houston, TX, USA
D. Acosta, A. Baty, T. Carnahan, M. Decaro, S. Dildick, K. M. Ecklund, S. Freed, P. Gardner, F. J. M. Geurts, A. Kumar, W. Li, B. P. Padley, R. Redjimi, J. Rotter, W. Shi, A. G. Stahl Leiton, S. Yang, L. Zhang[102], Y. Zhang

University of Rochester, Rochester, NY, 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, G. P. Van Onsem

The Rockefeller University, New York, NY, USA
K. Goulianos

Rutgers, The State University of New Jersey, Piscataway, NJ, USA
B. Chiarito, J. P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, O. Karacheban[26], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S. A. Thayil, S. Thomas, H. Wang

University of Tennessee, Knoxville, TN, USA
H. Acharya, A. G. Delannoy, S. Fiorendi, S. Spanier

Texas A&M University, College Station, TX, USA
O. Bouhali[103], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[104], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, TX, USA
N. Akchurin, J. Damgov, V. Hegde, K. Lamichhane, S. W. Lee, T. Mengke, S. Muthumuni, T. Peltola, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, TN, USA
E. Appelt, S. Greene, A. Gurrola, W. Johns, A. Melo, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, VA, USA
M. W. Arenton, B. Cardwell, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, C. E. Perez Lara, B. Tannenwald, S. White

Wayne State University, Detroit, MI, USA
N. Poudyal

University of Wisconsin-Madison, Madison, WI, USA
S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, D. Pinna, A. Savin, V. Shang, V. Sharma, W. H. Smith, D. Teague, S. Trembath-Reichert, W. Vetens

† **Deceased**

1: Also at TU Wien, Vienna, Austria
2: Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
3: Also at Université Libre de Bruxelles, Brussels, Belgium
4: Also at Universidade Estadual de Campinas, Campinas, Brazil
5: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
6: Also at The University of the State of Amazonas, Manaus, Brazil
7: Also at University of Chinese Academy of Sciences, Beijing, China
8: Also at Department of Physics, Tsinghua University, Beijing, China
9: Also at UFMS, Nova Andradina, Brazil
10: Also at Department of Physics, Nanjing Normal University, Nanjing, China
11: Now at The University of Iowa, Iowa City, IA, USA
12: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
13: Also at Joint Institute for Nuclear Research, Dubna, Russia
14: Also at Helwan University, Cairo, Egypt
15: Now at Zewail City of Science and Technology, Zewail, Egypt
16: Also at British University in Egypt, Cairo, Egypt
17: Now at Ain Shams University, Cairo, Egypt
18: Also at Purdue University, West Lafayette, IN, USA
19: Also at Université de Haute Alsace, Mulhouse, France
20: Also at Tbilisi State University, Tbilisi, Georgia
21: Also at Erzincan Binali Yildirim University, Erzincan, Turkey

22: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
23: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
24: Also at University of Hamburg, Hamburg, Germany
25: Also at Isfahan University of Technology, Isfahan, Iran
26: Also at Brandenburg University of Technology, Cottbus, Germany
27: Also at Forschungszentrum Jülich, Juelich, Germany
28: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
29: Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
30: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
31: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
32: Now at Universitatea Babes-Bolyai-Facultatea de Fizica, Cluj-Napoca, Romania
33: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
34: Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
35: Also at Wigner Research Centre for Physics, Budapest, Hungary
36: Also at IIT Bhubaneswar, Bhubaneswar, India
37: Also at Institute of Physics, Bhubaneswar, India
38: Also at Punjab Agricultural University, Ludhiana, India
39: Also at UPES-University of Petroleum and Energy Studies, Dehradun, India
40: Also at Shoolini University, Solan, India
41: Also at University of Hyderabad, Hyderabad, India
42: Also at University of Visva-Bharati, Santiniketan, India
43: Also at Indian Institute of Science (IISc), Bangalore, India
44: Also at Indian Institute of Technology (IIT), Mumbai, India
45: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
46: Now at Department of Physics, Isfahan University of Technology, Isfahan, Iran
47: Also at Sharif University of Technology, Tehran, Iran
48: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
49: Now at INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
50: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
51: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
52: Also at Scuola Superiore Meridionale, Università di Napoli Federico II, Naples, Italy
53: Also at Università di Napoli 'Federico II', Naples, Italy
54: Also at Consiglio Nazionale delle Ricerche-Istituto Officina dei Materiali, Perugia, Italy
55: Also at Riga Technical University, Riga, Latvia
56: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
57: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
58: Also at Institute for Nuclear Research, Moscow, Russia
59: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
60: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
61: Also at St. Petersburg Polytechnic University, St. Petersburg, Russia
62: Also at University of Florida, Gainesville, Florida, USA
63: Also at Imperial College, London, UK
64: Also at P.N. Lebedev Physical Institute, Moscow, Russia
65: Also at California Institute of Technology, Pasadena, CA, USA
66: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
67: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
68: Also at Trincomalee Campus, Eastern University, Nilaveli, Sri Lanka
69: Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
70: Also at National and Kapodistrian University of Athens, Athens, Greece
71: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
72: Also at Universität Zürich, Zurich, Switzerland
73: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
74: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France

75: Also at Şırnak University, Sirnak, Turkey
76: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
77: Also at Konya Technical University, Konya, Turkey
78: Also at Piri Reis University, Istanbul, Turkey
79: Also at Adiyaman University, Adiyaman, Turkey
80: Also at Necmettin Erbakan University, Konya, Turkey
81: Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
82: Also at Marmara University, Istanbul, Turkey
83: Also at Milli Savunma University, Istanbul, Turkey
84: Also at Kafkas University, Kars, Turkey
85: Also at Istanbul Bilgi University, Istanbul, Turkey
86: Also at Hacettepe University, Ankara, Turkey
87: Also at Istanbul University-Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
88: Also at Ozyegin University, Istanbul, Turkey
89: Also at Vrije Universiteit Brussel, Brussels, Belgium
90: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
91: Also at Rutherford Appleton Laboratory, Didcot, UK
92: Also at IPPP Durham University, Durham, UK
93: Also at Monash University, Faculty of Science, Clayton, Australia
94: Also at Università di Torino, Turin, Italy
95: Also at Bethel University, St. Paul, MN, USA
96: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
97: Also at United States Naval Academy, Annapolis, MD, USA
98: Also at Bingol University, Bingol, Turkey
99: Also at Georgian Technical University, Tbilisi, Georgia
100: Also at Sinop University, Sinop, Turkey
101: Also at Erciyes University, Kayseri, Turkey
102: Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Fudan University, Shanghai, China
103: Also at Texas A&M University at Qatar, Doha, Qatar
104: Also at Kyungpook National University, Daegu, Korea