



# Observation of $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$ and $B_s^0 \rightarrow \psi(2S)K_S^0$ decays

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**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  $103 \text{ fb}^{-1}$ , the  $B_s^0 \rightarrow \psi(2S)K_S^0$  and  $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$  decays are observed with significances exceeding 5 standard deviations. The resulting branching fraction ratios, measured for the first time, correspond to  $\mathcal{B}(B_s^0 \rightarrow \psi(2S)K_S^0)/\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0) = (3.33 \pm 0.69(\text{stat}) \pm 0.11(\text{syst}) \pm 0.34(f_s/f_d)) \times 10^{-2}$  and  $\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-)/\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0) = 0.480 \pm 0.013(\text{stat}) \pm 0.032(\text{syst})$ , where the last uncertainty in the first ratio is related to the uncertainty in the ratio of production cross sections of  $B_s^0$  and  $B^0$  mesons,  $f_s/f_d$ .

## 1 Introduction

Decays of neutral B mesons into charmonium resonances ( $J/\psi$ ,  $\psi(2S)$ , 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  $B \rightarrow \psi(2S)K\pi^+$  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  $\bar{B}$  can be used to measure time-dependent CP asymmetry [14–27] as well.

This paper presents the first measurement of the  $B_s^0 \rightarrow \psi(2S)K_S^0$  and  $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$  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  $103 \text{ fb}^{-1}$  [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  $K_S^0$  mesons are reconstructed using their decays into  $\mu^+\mu^-$  and  $\pi^+\pi^-$ , respectively. The  $B^0 \rightarrow \psi(2S)K_S^0$  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  $B_s^0 \rightarrow \psi(2S)K_S^0$  or  $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$  decays. Therefore, using this normalization reduces the systematic uncertainties related to muon and track reconstruction. The relative branching fractions are measured using the relations

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

where  $\mathcal{B}$  is the branching fraction,  $N$  is the number of reconstructed events in data,  $\epsilon$  is the total reconstruction efficiency, and  $f_d/f_s$  is the ratio of production cross sections of  $B^0$  and  $B_s^0$  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].

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## 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  $\mu$ s [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  $B_s^0$  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  $B_s^0$  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  $P_{\text{vtx}}(\mu^+\mu^-) > 1\%$  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  $m_{\psi(2S)}^{\text{PDG}} = 3686.10$  MeV [13]).

The  $K_S^0 \rightarrow \pi^+\pi^-$  candidates are formed from displaced two-prong vertices, as described in Ref. [41]. The  $\pi^+\pi^-$

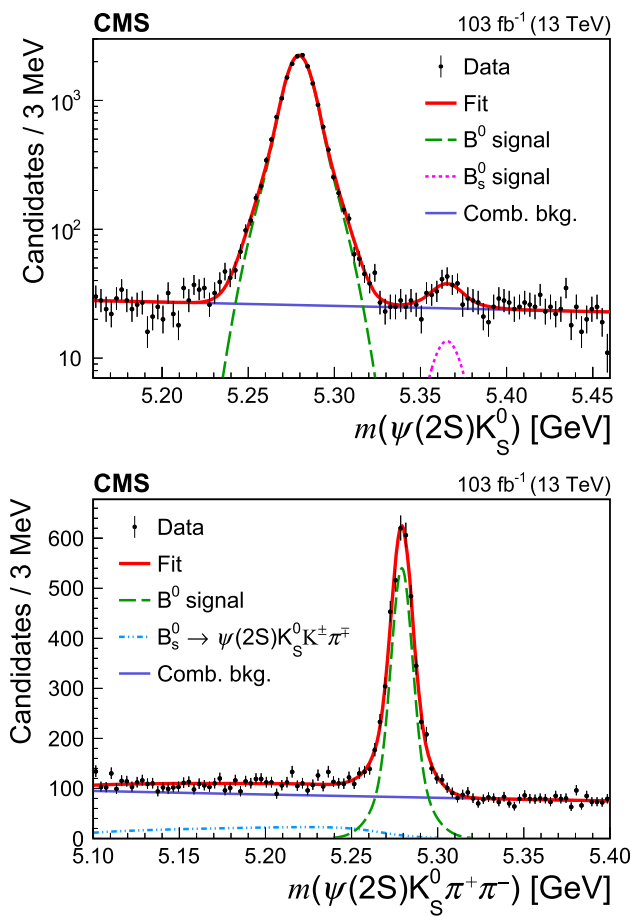
invariant mass is required to be within  $\pm 20$  MeV of the world average value  $m_{K_S^0}^{\text{PDG}} = 497.611$  MeV [13], which corresponds to approximately three times the mass resolution. Selected  $\pi^+$  and  $\pi^-$  tracks are then refitted with their invariant mass constrained to  $m_{K_S^0}^{\text{PDG}}$ , and the obtained  $K_S^0$  candidate is required to have  $P_{\text{vtx}}(\pi^+\pi^-) > 1\%$ .

The  $B \rightarrow \psi(2S)K_S^0$  candidates are obtained through a kinematic vertex fit on the  $\mu^+\mu^-K_S^0$  system which constrains the dimuon mass to  $m_{\psi(2S)}^{\text{PDG}}$ . The  $K_S^0$  candidates are required to have  $p_T(K_S^0) > 1$  GeV, a 3D pointing angle between  $\vec{D}(K_S^0)$  and  $\vec{p}(K_S^0)$  to satisfy  $\cos(\vec{D}(K_S^0), \vec{p}(K_S^0)) > 0.99$ , and a transverse displacement significance for  $K_S^0$  of  $D_{xy} > 5\sigma_{D_{xy}}$ . Here  $\vec{D}(K_S^0)$  denotes the vector from the  $K_S^0$  production vertex to the  $K_S^0$  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:  $P_{\text{vtx}}(\mu^+\mu^-K_S^0) > 5\%$ ,  $\cos(\vec{D}_{xy}(B), \vec{p}_T(B)) > 0.99$ , 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  $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$  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 $B_s^0 \rightarrow \psi(2S)K_S^0$ decay

The measured  $\psi(2S)K_S^0$  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  $B_s^0 \rightarrow \psi(2S)K_S^0$  signal (right peak) has the same shape as the  $B^0 \rightarrow \psi(2S)K_S^0$  signal, but it is about 10% wider, because of the larger energy release in the decay. Therefore, the  $B_s^0$  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  $\chi^2$  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  $\psi(2S)K_S^0$  (upper) and  $\psi(2S)K_S^0\pi^+\pi^-$  (lower) candidates. The overlaid results from the fit are described in the text

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

The statistical significance of the  $B_s^0 \rightarrow \psi(2S)K_S^0$  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  $B_s^0$  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.

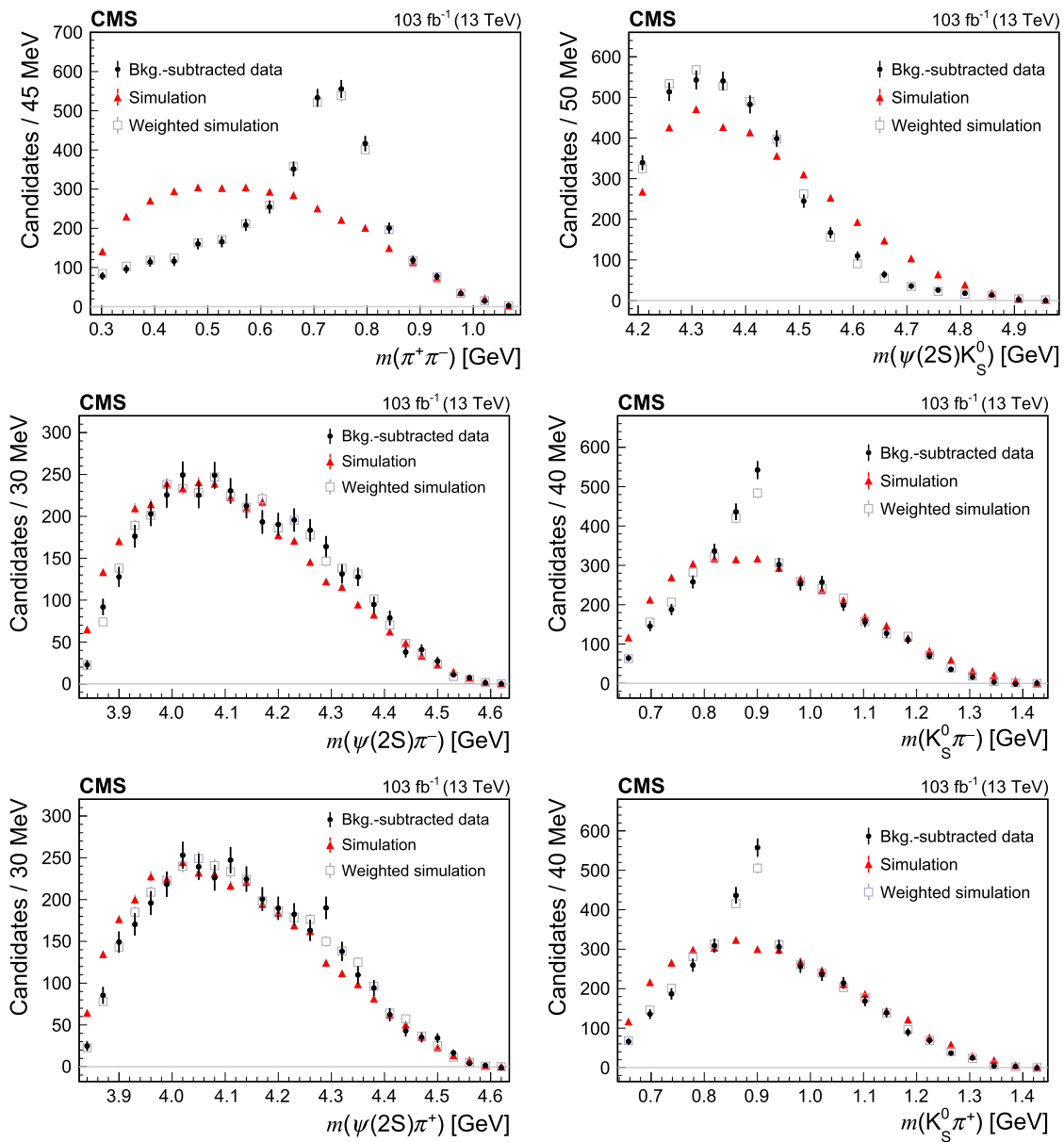
### 5 Observation of the $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$ decay

As shown in Fig. 1 (lower), the measured  $\psi(2S)K_S^0\pi^+\pi^-$  mass distribution presents a clear  $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$  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  $B_s^0 \rightarrow \psi(2S)K_S^0K^\mp\pi^\pm$  decay contributes to the reconstructed  $\psi(2S)K_S^0\pi^+\pi^-$  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  $N(B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-)$  is found to be  $3498 \pm 87$ , where the uncertainty is statistical only. The  $\chi^2$  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  $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$  signal, evaluated as described in Sect. 4, exceeds 30 standard deviations.

The intermediate invariant mass distributions, corresponding to the four-body  $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$  decay, are produced using the  $\mathcal{P}$ lot [48] technique to subtract the non- $B^0$  background, using the  $m(\psi(2S)K_S^0\pi^+\pi^-)$  distribution fit described above. The correlations between the intermediate invariant masses and  $m(\psi(2S)K_S^0\pi^+\pi^-)$  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 ( $\psi(2S)K_S^0$ ,  $\psi(2S)\pi^\pm$ ,  $\psi(2S)K_S^0\pi^\pm$ ,  $\psi(2S)\pi^+\pi^-$ ) 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  $K_S^0\pi^\pm$ ,  $\pi^+\pi^-$ , and  $K_S^0\pi^+\pi^-$ , respectively.



**Fig. 2** Distributions of 2-body intermediate invariant masses from the  $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$  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

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

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

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  $\epsilon(B_s^0 \rightarrow \psi(2S)K_S^0)$ . It was verified that the corresponding variations of  $B_s^0$  lifetime result in negligible changes in the efficiency.

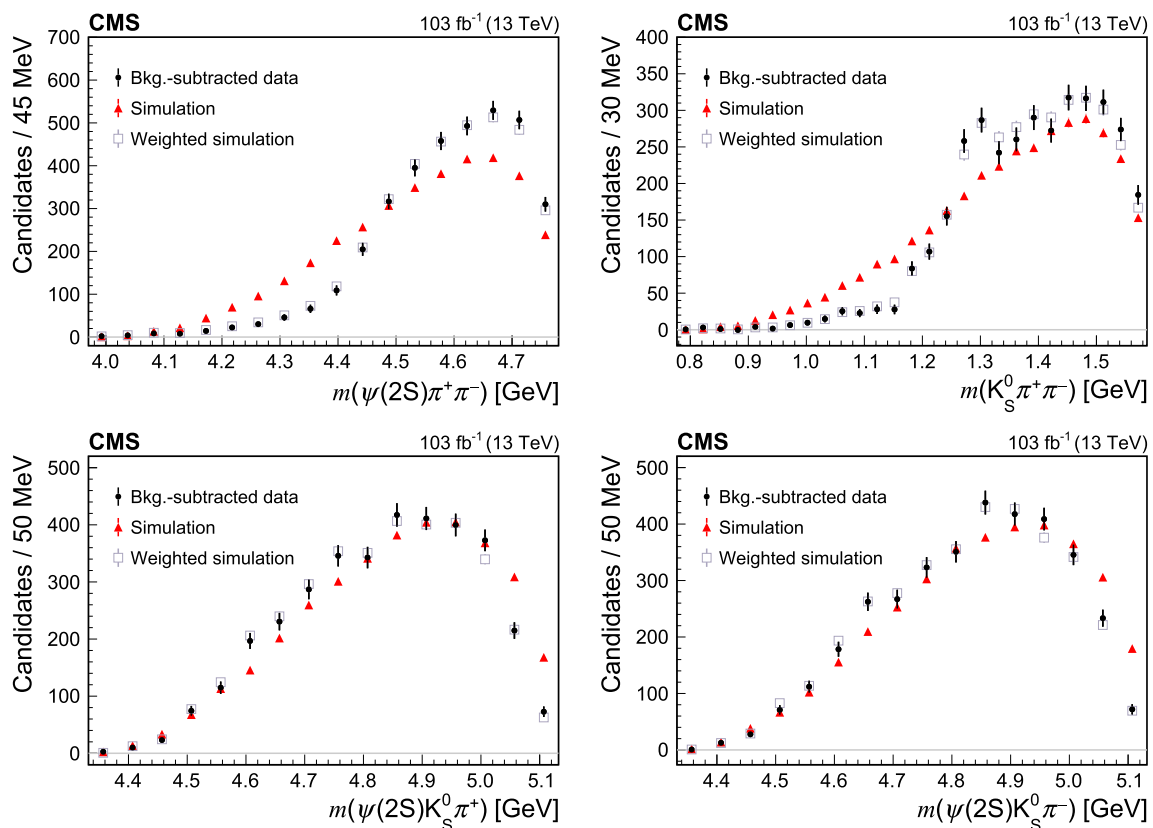
The validation of Monte Carlo samples is performed by comparing distributions of variables used in the event selection between simulation and background-subtracted data. No significant deviation is found, and thus no systematic uncertainties in the efficiency ratio are assigned related to data-simulation 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  $B_s^0 \rightarrow \psi(2S)K_S^0$  and  $B^0 \rightarrow \psi(2S)K_S^0$  decays have the same number of tracks in the final state, uncertain-

ties 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

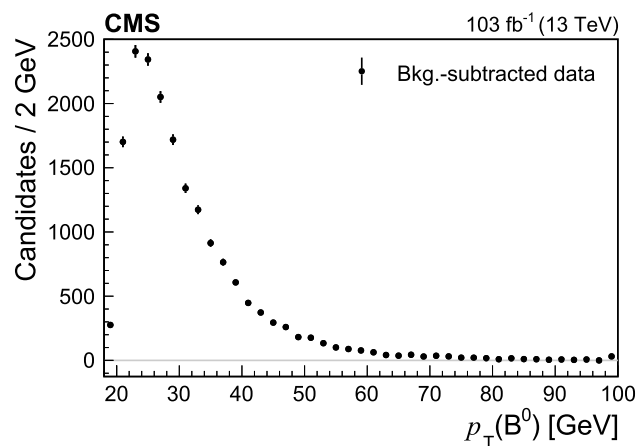


**Fig. 3** Distributions of 3-body intermediate invariant masses from the  $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$  decay. Data distributions (black dots) are background subtracted. Overlaid are the predictions of phase space sim-

ulations (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 $B_s^0 \rightarrow \psi(2S)K_S^0 K^\mp \pi^\pm$ 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  $B^0 \rightarrow \psi(2S)K_S^0$  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  $B_s^0 \rightarrow \psi(2S)K_S^0 K^\mp \pi^\pm$  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  $N(B^0 \rightarrow \psi(2S)K_S^0 \pi^+ \pi^-)$  from the baseline value is 0.5% which is taken as a systematic uncertainty.

As discussed in Sect. 5, the simulation for the  $B^0 \rightarrow \psi(2S)K_S^0 \pi^+ \pi^-$  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  $B_s^0 \rightarrow \psi(2S)K_S^0$  decay relative to the  $B^0 \rightarrow \psi(2S)K_S^0$  one is measured using Eq. (1) to be

$$R_s = \frac{\mathcal{B}(B_s^0 \rightarrow \psi(2S)K_S^0)}{\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0)}$$

$$= (3.33 \pm 0.69 \text{ (stat)} \pm 0.11 \text{ (syst)})$$

$$\pm 0.34 (f_s/f_d) \times 10^{-2},$$

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

$$R_s \frac{f_s}{f_d} = \frac{f_s}{f_d} \frac{\mathcal{B}(B_s^0 \rightarrow \psi(2S)K_S^0)}{\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0)}$$

$$= (0.69 \pm 0.14 \text{ (stat)} \pm 0.02 \text{ (syst)}) \times 10^{-2}.$$

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

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

$$R_{\pi^+\pi^-} = \frac{\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-)}{\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0)}$$

$$= 0.480 \pm 0.013 \text{ (stat)} \pm 0.032 \text{ (syst)}.$$

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

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

$$\mathcal{B}(B_s^0 \rightarrow \psi(2S)K_S^0)$$

$$= (0.97 \pm 0.20 \text{ (stat)} \pm 0.03 \text{ (syst)})$$

$$\pm 0.22 (f_s/f_d) \pm 0.08 (B) \times 10^{-5},$$

$$\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-)$$

$$= (13.9 \pm 0.4 \text{ (stat)} \pm 0.9 \text{ (syst)})$$

$$\pm 1.2 (B) \times 10^{-5},$$

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

### 9 Summary

The  $B_s^0 \rightarrow \psi(2S)K_S^0$  and  $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$  decays are observed using proton-proton collision data collected by the CMS experiment at 13 TeV with an integrated luminosity of  $103 \text{ fb}^{-1}$ . Their branching fractions are measured with respect to the  $B^0 \rightarrow \psi(2S)K_S^0$  decay to be  $\mathcal{B}(B_s^0 \rightarrow \psi(2S)K_S^0)/\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0) = (3.33 \pm 0.69 \text{ (stat)} \pm 0.11 \text{ (syst)} \pm 0.34 (f_s/f_d) \times 10^{-2}$ , and  $\mathcal{B}(B^0 \rightarrow$

$\psi(2S)K_S^0\pi^+\pi^-)/\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0) = 0.480 \pm 0.013 \text{ (stat)} \pm 0.032 \text{ (syst)}$ , 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  $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$  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  $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$  decay, and to perform  $CP$  asymmetry measurements in the two observed decays in the future.

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## Declarations

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

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




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
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



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











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










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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 

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









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
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V. Botta, L. Feld , K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, J. Schulz, M. Teroerde 



































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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





















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





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

























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

S. Chenarani <sup>48</sup>, S. M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 

























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








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










**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi <sup>a</sup>, S. Bianco <sup>a</sup>, D. Piccolo <sup>a</sup>











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




















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






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






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























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C. Aimè<sup>a,b</sup>, A. Braghieri <sup>a</sup>, S. Calzaferri<sup>a,b</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>, C. Riccardi <sup>a,b</sup>, P. Salvini <sup>a</sup>, I. Vai <sup>a</sup>, P. Vitulo <sup>a,b</sup>














**INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy**

P. Asenov <sup>a,54</sup>, G. M. Bilei <sup>a</sup>, D. Ciangottini <sup>a,b</sup>, L. Fanò <sup>a,b</sup>, M. Magherini<sup>b</sup>, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli <sup>a</sup>, F. Moscatelli <sup>a,54</sup>, A. Piccinelli <sup>a,b</sup>, M. Presilla <sup>a,b</sup>, A. Rossi <sup>a,b</sup>, A. Santocchia <sup>a,b</sup>, D. Spiga <sup>a</sup>, T. Tedeschi <sup>a,b</sup>


































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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,  
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
S. Ha, H. D. Yoo

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
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










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















































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













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




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

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



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











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K. W. Bell, A. Belyaev <sup>90</sup>, C. Brew , R. M. Brown, D. J. A. Cockerill, C. Cooke, K. V. Ellis, K. Harder, S. Harper, M. -L. Holmberg<sup>91</sup>, J. Linacre , K. Manolopoulos, D. M. Newbold , E. Olaiya, D. Petyt, T. Reis , T. Schuh, C. H. Shepherd-Themistocleous, I. R. Tomalin, T. Williams 

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R. Bainbridge , P. Bloch , S. Bonomally, J. Borg , S. Breeze, O. Buchmuller, V. Cepaitis , G. S. Chahal <sup>92</sup>, 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 <sup>93</sup>, 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 <sup>22</sup>, 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 <sup>94</sup>, 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 <sup>23</sup>, D. Cutts , M. Hadley , U. Heintz , J. M. Hogan <sup>95</sup>, T. Kwon, G. Landsberg , K. T. Lau , D. Li, M. Lukasik, J. Luo , M. Narain, N. Pervan, S. Sagir <sup>96</sup>, 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 

















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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













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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. Shephlock, P. Siddireddy, D. Stuart, S. Wang 







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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 




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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. Klijsma , 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 <sup>65</sup>, F. Ravera , A. Reinsvold Hall <sup>97</sup>, 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 

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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










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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 <sup>17</sup>, 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 <sup>98</sup>, L. Emediato, R. P. Gandrajula , O. K. Köseyan , J. -P. Merlo, A. Mestvirishvili <sup>99</sup>, J. Nachtman, H. Ogul <sup>100</sup>, Y. Onel , A. Penzo, C. Snyder, E. Tiras <sup>101</sup>




**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. Rebasoo, 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<sup>†</sup>, 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 











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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<sup>58</sup>, 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 

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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<sup>18</sup>, 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<sup>102</sup>, 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 

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K. Goulianos









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B. Chiarito, J. P. Chou , A. Gandrakota , Y. Gershtein , E. Halkiadakis , A. Hart, M. Heindl , O. Karacheban <sup>26</sup>, 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 

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O. Bouhali <sup>103</sup>, M. Dalchenko , A. Delgado , R. Eusebi, J. Gilmore, T. Huang, T. Kamon <sup>104</sup>, 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 

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- 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
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- 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 Babeş-Bolyai-Facultatea de Fizica, Cluj-Napoca, Romania
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- 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
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- 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
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- 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
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- 71: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
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- 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
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- 79: Also at Adiyaman University, Adiyaman, Turkey
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- 81: Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- 82: Also at Marmara University, Istanbul, Turkey
- 83: Also at Milli Savunma University, Istanbul, Turkey
- 84: Also at Kafkas University, Kars, Turkey
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- 86: Also at Hacettepe University, Ankara, Turkey
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- 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
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- 101: Also at Erciyes University, Kayseri, Turkey
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- 103: Also at Texas A&M University at Qatar, Doha, Qatar
- 104: Also at Kyungpook National University, Daegu, Korea