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

The CMS Collaboration*

Abstract

Using a data sample of $\sqrt{s} = 13\,\text{TeV}$ 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 $B^0_s \to \psi(2S)K^0_S$ 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.

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*See Appendix A for the list of collaboration members

1 Introduction

Decays of neutral B mesons into charmonium resonances (J/ψ, $\psi(2\mathrm{S})$, 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 $\mathrm{B} \to \psi(2\mathrm{S})\mathrm{K}\pi^+$ decay as a peak in the $\psi(2\mathrm{S})\pi^+$ 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 $\overline{\mathrm{B}}$ can be used to measure time-dependent *CP* asymmetry [14–27] as well.

This paper presents the first measurement of the $\mathrm{B}^0_\mathrm{s} \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S}$ and $\mathrm{B}^0 \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S}\pi^+\pi^-$ decays, using a data sample of proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ collected by the CMS experiment at the CERN LHC in 2017 and 2018 with an integrated luminosity of $103\,\mathrm{fb}^{-1}$ [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 $\psi(2\mathrm{S})$ and K^0_S mesons are reconstructed using their decays into $\mu^+\mu^-$ and $\pi^+\pi^-$, respectively. The $\mathrm{B}^0 \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S}$ 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 $\mathrm{B}^0_\mathrm{s} \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S}$ or $\mathrm{B}^0 \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S}\pi^+\pi^-$ decays. Therefore, using this normalization reduces the systematic uncertainties related to muon and track reconstruction. The relative branching fractions are measured using the relations

$$\begin{aligned} R_\mathrm{s} &\equiv \frac{\mathcal{B}(\mathrm{B}^0_\mathrm{s} \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S})}{\mathcal{B}(\mathrm{B}^0 \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S})} = \frac{f_\mathrm{d}}{f_\mathrm{s}} \frac{\epsilon(\mathrm{B}^0 \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S})}{\epsilon(\mathrm{B}^0_\mathrm{s} \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S})} \frac{N(\mathrm{B}^0_\mathrm{s} \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S})}{N(\mathrm{B}^0 \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S})}, \\ R_{\pi^+\pi^-} &\equiv \frac{\mathcal{B}(\mathrm{B}^0 \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S}\pi^+\pi^-)}{\mathcal{B}(\mathrm{B}^0 \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S})} = \frac{\epsilon(\mathrm{B}^0 \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S})}{\epsilon(\mathrm{B}^0 \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S}\pi^+\pi^-)} \frac{N(\mathrm{B}^0 \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S}\pi^+\pi^-)}{N(\mathrm{B}^0 \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S})}, \end{aligned} \tag{1}$$

where $\mathcal{B}$ is the branching fraction, N is the number of reconstructed events in data, ϵ is the total reconstruction efficiency, and $f_\mathrm{d}/f_\mathrm{s}$ 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].

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 $4\,\mu\mathrm{s}$ [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^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 $p_{\mathrm{T}}(\mu^{\pm}) > 3\,\mathrm{GeV}$, 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 $P_{\mathrm{vtx}}(\mu^+\mu^-) > 1\%$ are paired to form the $\psi(2S)$ candidate, which must have $p_{\mathrm{T}}(\psi(2S)) > 18\,\mathrm{GeV}$ and an invariant mass $3500 < m(\mu^+\mu^-) < 3950\,\mathrm{MeV}$ (the world average $\psi(2S)$ meson mass is $m^{\mathrm{PDG}}_{\psi(2S)} = 3686.10\,\mathrm{MeV}$ [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 $\pm 20\,\mathrm{MeV}$ of the world average value $m^{\mathrm{PDG}}_{K^0} = 497.611\,\mathrm{MeV}$ [13], which corresponds to approximately three times the mass resolution. Selected π^+ and π^- tracks are then refitted with their invariant mass constrained to $m^{\mathrm{PDG}}_{K^0}$, and the obtained K^0_S candidate is required to have $P_{\mathrm{vtx}}(\pi^+\pi^-) > 1\%$.

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 $m^{\mathrm{PDG}}_{\psi(2S)}$. The K^0_S candidates are required to have $p_{\mathrm{T}}(K^0_S) > 1\,\mathrm{GeV}$, 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: $P_{\mathrm{vtx}}(\mu^+\mu^-K^0_S) > 5\%$, $\cos(\vec{D}_{xy}(B), \vec{p}_{\mathrm{T}}(B)) > 0.99$, 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 $p_{\mathrm{T}} > 0.9\,\mathrm{GeV}$, 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 (left). 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.

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 Section 7.

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

As shown in Fig. 1 (right), 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.

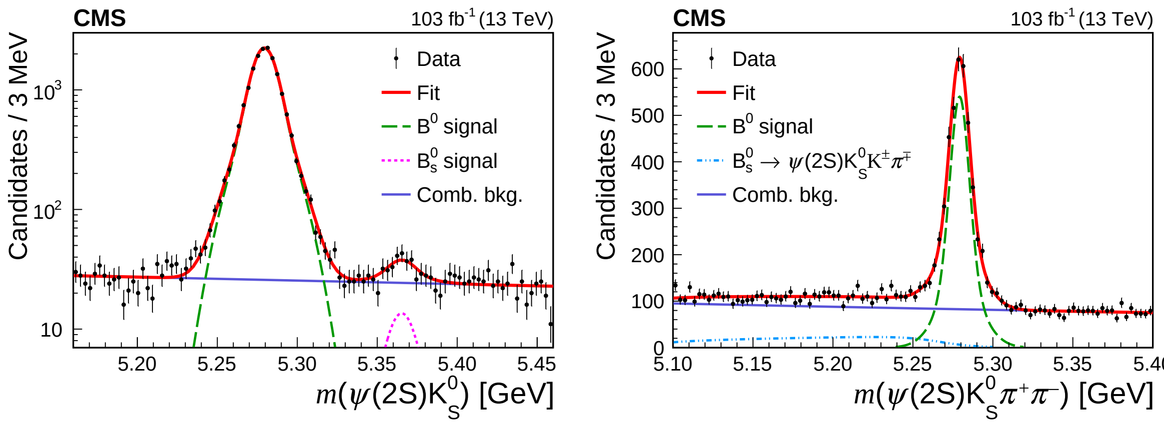

Figure 1: Measured invariant mass distributions of $\psi(2S)K^0_S$ (left) and $\psi(2S)K^0_S\pi^+\pi^-$ (right) candidates. The overlaid results from the fit are described in the text.

Studies of simulated events show that the $B_s^0 \to \psi(2S) K_S^0 K^{\mp}\pi^{\pm}$ 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, right).

The signal yield $N(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)$ 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 $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ signal, evaluated as described in Section 4, exceeds 30 standard deviations.

The intermediate invariant mass distributions, corresponding to the four-body $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decay, are produced using the ${}_s\mathcal{P}$lot [48] technique to subtract the non-B^0 background, using the $m(\psi(2S)K_S^0\pi^+\pi^-)$ 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 Section 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.

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

$$\frac{\epsilon(B^0 \to \psi(2S)K_S^0)}{\epsilon(B_s^0 \to \psi(2S)K_S^0)} = 1.019 \pm 0.013 \text{ and } \frac{\epsilon(B^0 \to \psi(2S)K_S^0)}{\epsilon(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)} = 2.288 \pm 0.026,$$

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 $\epsilon(B_s^0 \to \psi(2S)K_S^0)$. 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.

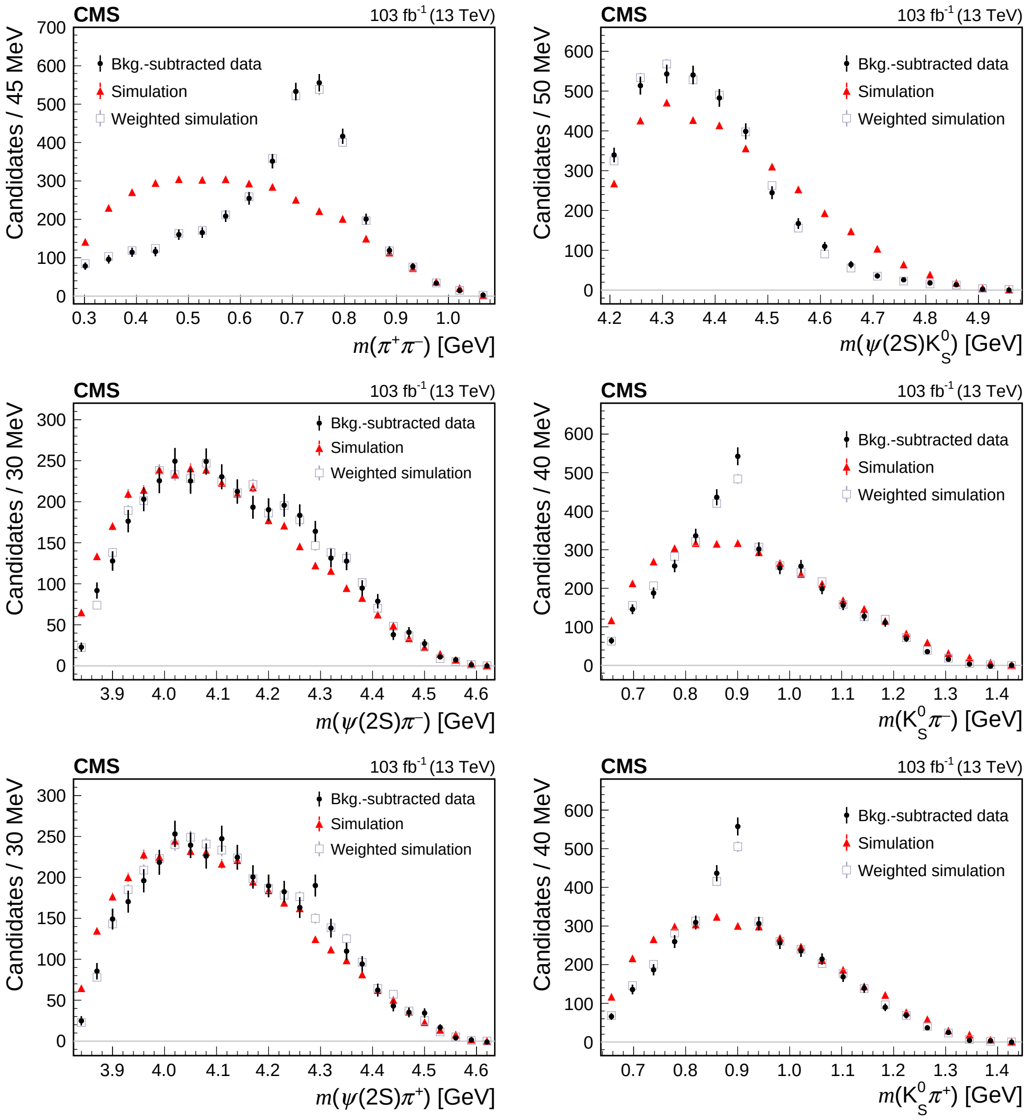

Figure 2: Distributions of 2-body intermediate invariant masses from the $B^0 \to \psi(2S) K^0_S \pi^+\pi^-$ decay. The data distributions (black dots) are background subtracted. Overlaid are the predictions of phase space simulations (red triangles), as well as the predictions after applying the reweighting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

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 $B^0_s \to \psi(2S) K^0_S$ and $B^0 \to \psi(2S) K^0_S$ 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

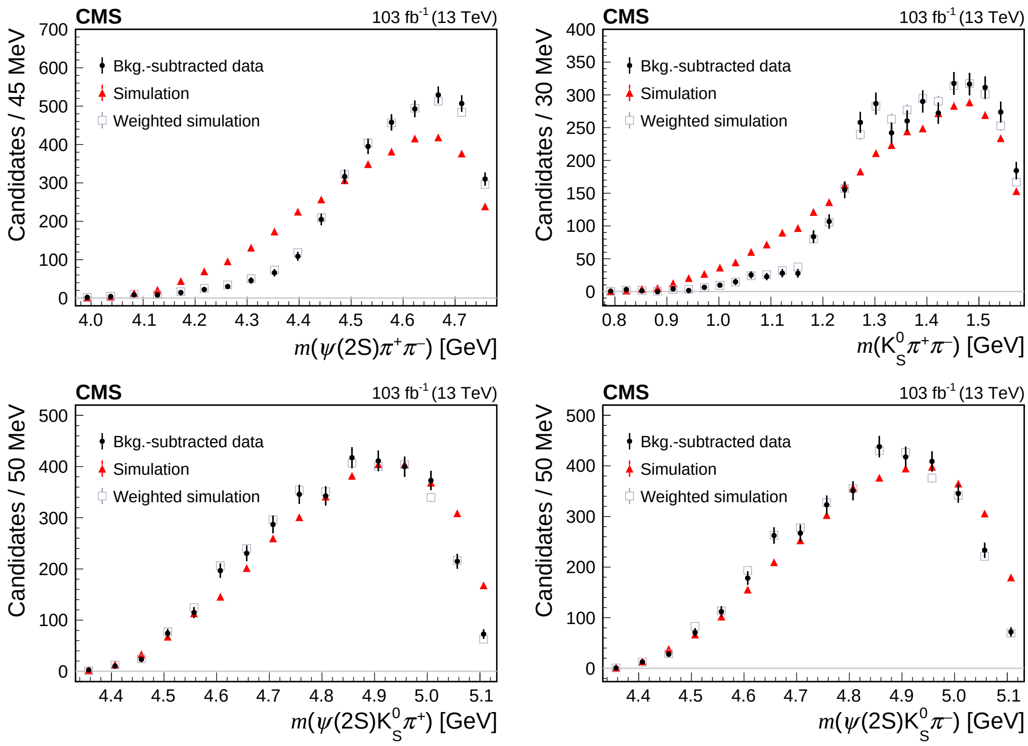

Figure 3: Distributions of 3-body intermediate invariant masses from the $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ decay. Data distributions (black dots) are background subtracted. Overlaid are the predictions of phase space simulations (red triangles), as well as the predictions after applying the reweighting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

and B^0_s 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 all cases the background shape parameters are free to vary in the fits.

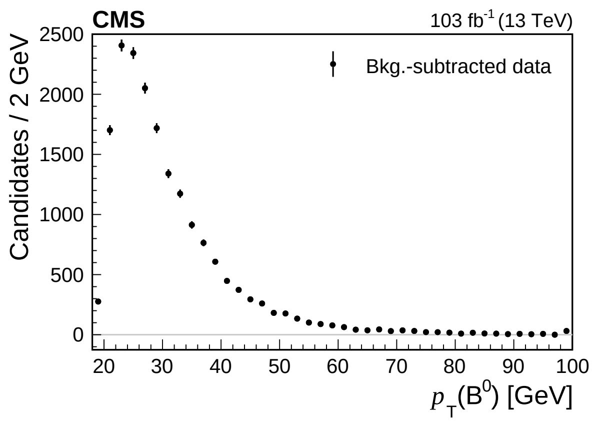

Figure 4: Background-subtracted $p_T(B^0)$ distribution in data for the $B^0 \to \psi(2S)K^0_S$ signal. The last bin includes the overflow.

The uncertainty related to the finite size of the simulation samples (used to measure the efficiencies in Section 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 Section 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 Section 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.

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

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

$p_T > 20\,\text{GeV}$. 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 $103\,\text{fb}^{-1}$. 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.

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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** (2003) 262001, doi: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** (2009) 242002, doi: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** (2017) 1750139, doi: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** (2014) 261, doi: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** (2017) 012002, doi: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** (2005) 142001, doi: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** (2017) 092001, doi: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** (2008) 142001, doi: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** (2009) 031104, doi: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** (2013) 074026, doi: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** (2014) 222002, doi: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** (2016) 062C01, doi: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** (2020) 083C01, doi:10.1093/ptep/ptaa104.

[14] N. Cabibbo, "Unitary symmetry and leptonic decays", *Phys. Rev. Lett.* **10** (1963) 531, doi:10.1103/PhysRevLett.10.531.

[15] Belle Collaboration, "Observation of large *CP* violation in the neutral B meson system", *Phys. Rev. Lett.* **87** (2001) 091802, doi: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** (2001) 091801, doi: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** (2008) 021801, doi: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** (2009) 072009, doi: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** (2012) 171802, doi: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** (2015) 38, doi: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** (2015) 031601, doi: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** (2015) 131, doi: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** (2017) 170, doi: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** (2018) 112008, doi:10.1103/PhysRevD.98.112008, arXiv:1810.01356.

[25] LHCb Collaboration, "Updated measurement of time-dependent *CP*-violating observables in $B^0_s \to J/\psi K^+K^-$ decays", *Eur. Phys. J. C* **79** (2019) 706, doi:10.1140/epjc/s10052-019-7159-8, arXiv:1906.08356. [Erratum: doi:10.1140/epjc/s10052-020-7875-0].

[26] CMS Collaboration, "Measurement of the *CP*-violating phase ϕ_s in the $B^0_s \to J/\psi\,\phi(1020) \to \mu^+\mu^-K^+K^-$ channel in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Phys. Lett. B* **816** (2021) 136188, doi:10.1016/j.physletb.2021.136188, arXiv:2007.02434.

[27] ATLAS Collaboration, "Measurement of the *CP*-violating phase ϕ_s in $B^0_s \to J/\psi\phi$ decays in ATLAS at 13 TeV", *Eur. Phys. J. C* **81** (2021) 342, doi: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. doi:10.17182/hepdata.114370.

[31] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[32] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi: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** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.

[34] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi: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) doi: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** (2001) 152, doi:10.1016/S0168-9002(01)00089-4.

[37] E. Barberio, B. van Eijk, and Z. Wąs, “PHOTOS — a universal Monte Carlo for QED radiative corrections in decays”, *Comput. Phys. Commun.* **66** (1991) 115, doi:10.1016/0010-4655(91)90012-A.

[38] E. Barberio and Z. Wąs, “PHOTOS – a universal Monte Carlo for QED radiative corrections: version 2.0”, *Comput. Phys. Commun.* **79** (1994) 291, doi:10.1016/0010-4655(94)90074-4.

[39] GEANT4 Collaboration, “GEANT4—A simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi: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** (2018) P06015, doi: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** (2010) 1165, doi:10.1140/epjc/s10052-010-1491-3, arXiv:1007.1988.

[42] CMS Collaboration, “Search for the X(5568) state decaying into $\mathrm{B_s^0}\pi^{\pm}$ in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *Phys. Rev. Lett.* **120** (2018) 202005, doi:10.1103/PhysRevLett.120.202005, arXiv:1712.06144.

[43] CMS Collaboration, “Study of the $\mathrm{B}^+ \to \mathrm{J}/\psi\overline{\Lambda}\mathrm{p}$ decay in proton-proton collisions at $\sqrt{s} =$ 8 TeV”, *JHEP* **12** (2019) 100, doi:10.1007/JHEP12(2019)100, arXiv:1907.05461.

[44] CMS Collaboration, "Observation of the $\Lambda_b^0 \to J/\psi\Lambda\phi$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Phys. Lett. B* **802** (2020) 135203, doi: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** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[46] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics", *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

[47] S. S. Wilks, "The large-sample distribution of the likelihood ratio for testing composite hypotheses", *Annals Math. Statist.* **9** (1938) 60, doi:10.1214/aoms/1177732360.

[48] M. Pivk and F. R. Le Diberder, "${}_s\mathcal{P}$lot: a statistical tool to unfold data distributions", *Nucl. Instrum. Meth. A* **555** (2005) 356, doi: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". John Wiley & Sons, New Jersey, USA, 2009. doi: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** (2021) 032005, doi:10.1103/PhysRevD.104.032005, arXiv:2103.06810.

[52] LHCb Collaboration, "Observation of the $B_s^0 \to J/\psi K_S^0 K^{\pm}\pi^{\mp}$ decay", *JHEP* **07** (2014) 140, doi:10.1007/JHEP07(2014)140, arXiv:1405.3219.

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