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B_s^0 meson spectroscopy in the CMS experiment

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synopsis
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The main tasks of the Large Hadron Collider (LHC) at the time of its design planning were the search for and measurements of the Higgs boson properties, direct and indirect searches for New Physics, tests of supersymmetry theories, and precise measurements of the Standard Model (SM) parameters. Observation of the Higgs boson in 2012 by the ATLAS and CMS collaborations is one of the most remarkable achievements of the modern science. Despite this result, which finished experimental observations of the SM particles, the SM itself cannot be considered a complete theory. In particular, the SM does not describe the dark energy, neutrino mass nature, problem of fundamental particles mass hierarchy, and presence of more matter than antimatter in the universe. Therefore searches for physics beyond the standard model remain one of the main directions of work of the two largest LHC collaborations – ATLAS and CMS. The ALICE experiment is optimized for the heavy ion collision studies. The fourth large experiment LHCb is optimized for studies of particles containing heavy quarks, which provides opportunities to perform indirect NP searches and study the CP violation.

Hadron spectroscopy is important for tests of the models of strong interaction. In particular, measurements of masses, lifetimes, natural widths, searches for new decays and new states give important inputs for building theoretical models. During the last several years, the LHC experiments (mainly, LHCb) have discovered a number of new hadron states:

- Excited states of $\Xi_b^{\pm,0}$ baryons in the decays into $\Xi_b^{\pm,0}\pi^{\pm}$ and $\Lambda_b^0 K^-$;
- Excited states of Λ_b^0 baryon in the decays into $\Lambda_b^0 \pi^+ \pi^-$;
- Excited states of B^0 and B^+ mesons in the decays into $B^{+,0} \pi^{-,+}$;
- Excited states of B_c^+ meson in the decays into $B_c^{(*)+} \pi^+ \pi^-$;

- Excited states of Ω_c^0 baryon in the decays into $\Xi_c^+ K^-$;
- Doubly charmed baryon Ξ_{cc}^{++} in the decays into $\Lambda_c^0 K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$;
- Excited bottomonium states $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ in the decays into $\Upsilon(3S)\gamma$;
- Excited states of $\Sigma_b^\pm$ baryons in the $\Lambda_b^0 \pi^\pm$ decays.

Recently a number of so-called exotic states have been established, which are not described by the classical quark model which assumes existence only of mesons (quark-antiquark states) and baryons (3-quark states). In particular, in 2003 the $X(3872)$ particle was discovered, which cannot be described in the classic scheme of hadron spectroscopy, and its nature is not established to date. Later the CDF collaboration presented an evidence for the $X(4140)$ resonance decaying into $J/\psi\phi$, produced in the exclusive decay $B^+ \rightarrow J/\psi\phi K^+$, with the natural width of the state being significantly smaller than the natural width of a charmonium state with this mass. It was supposed that the $X(4140)$ can be a molecular state (bound state of two mesons) or a tetraquark, or a hybrid state. Belle and BaBar collaborations have not observed a significant signal, while the CMS and D0 collaborations have confirmed existence of this state. Even later, the LHCb collaboration has performed a full angular analysis of the $B^+ \rightarrow J/\psi\phi K^+$ decay which allowed to establish not only the $X(4140)$ state, but also 3 additional exotic states decaying into $J/\psi\phi$. Belle collaboration observed an exotic state $Z(4430)^\pm$ decaying into $\psi(2S)\pi^\pm$, which was later confirmed by the LHCb collaboration. In 2015 the LHCb collaboration claimed the observation of states consistent with pentaquarks decaying into $J/\psi p$. In 2016 the D0 collaboration observed $X(5568)$ — a tetraquark candidate decaying into $B_s^0 \pi^\pm$. The LHCb collaboration have not confirmed its existence, while

there are theoretical papers both explaining the state and questioning its existence.

This dissertation is devoted to the study of exotic states decaying into $B_s^0\pi^\pm$, and the study of P -wave excited B_s^0 meson states.

General dissertation information

Dissertation consists of two connected studies of excited B_s^0 meson states. The first is devoted to the search for the exotic state $X(5568)$ decaying into $B_s^0\pi^\pm$, where the B_s^0 meson is reconstructed in the $J/\psi\phi$ decay mode. In addition, a more general search is performed for the exotic states with mass between 5.5 and 5.9 GeV and the natural width between 10 and 50 MeV, decaying into $B_s^0\pi^\pm$. The second part of the research is dedicated to the study of the P -wave B_s^0 meson states $B_{s2}^*(5840)^0$ and $B_{s1}(5830)^0$. They are reconstructed both in the charged channels B^+K^- , and, for the first time, in the neutral channels $B^0K_S^0$. Using these decays, 6 mass differences are measured, 4 ratios of branching fractions, 2 ratios of cross sections multiplied by the branching fractions, and, finally, the B_{s2}^* meson natural width. Both studies are performed using the data collected by the CMS experiment at the LHC in 2012, in pp collisions at centre-of-mass energy of 8 TeV.

Relevance and scientific novelty of the thesis results

Heavy flavor spectroscopy studies in a relevant and modern field of high energy physics, as it allows to test various strong interaction models. From the time when the quark model was developed it became clear the it does not exclude existence of states consisting of more than three quarks. However, there were no significant evidence found for such exotic states consisting of light u, d, and s quarks. Exotic states having a heavy quark in their

components can be established with more confidence thanks to more clear decay signatures. In the beginning of 2016 the D0 collaboration claimed an observation of $X(5568)^-$ a tetraquark candidate. If its existence was confirmed, it would be the first particle consisting of four different quarks (b, s, u, d). However, the LHCb collaboration did not confirm its existence, therefore it is very important to search for this state at another independent experiment. In particular, the CMS experiment operates on the kinematic region (p_T, η) which is close to the D0 conditions, unlike the LHCb.

There is very little experimental information about the P -wave B_s^0 meson states, only their decays into $B^{(*)+}K^-$ have been observed. Precise measurements of their masses and natural widths, as well as observation of new decay modes, would significantly contribute to the summary of experimental knowledge of these states, which will, in turn, test the existing theoretical models and help to develop and tune parameters of the future models.

Goals and tasks of the presented research

The main goals of the work were:

- Search for the $X(5568)$ state decaying into $B_s^0\pi^\pm$, in case of positive result, measurement of its mass and production cross-section, multiplied by the decay probability $X(5568) \rightarrow B_s^0\pi^\pm$, in case of negative result – setting an upper limit on this quantity.
- Reconstruction of the P -wave B_s^0 meson states in the decays into $B^{(*)+}K^-$, measurements of the mass differences in these decays and the $B_{s2}^*(5840)^0$ natural width.
- Observation of the decay $B_{s2}^*(5840)^0 \rightarrow B^0K_S^0$ and search for the decay $B_{s1}(5830)^0 \rightarrow B^{*0}K_S^0$, as well as the measurements of their

relative branching fractions with respect to the corresponding decays into $B^{(*)+}K^-$, and the measurements of the mass differences in those decays.

Scientific results to be defended

- Method to check the $B_s^0\pi^\pm$ candidates reconstruction procedure with the use of decays of excited B^+ states;
- Calculation of the upper limit on the fraction of B_s^0 produced from $X(5568)$;
- Calculation of the upper limit on the fraction of B_s^0 produced in the decays of exotic states into $B_s^0\pi^\pm$, depending on their masses and natural widths;
- Method of the decay reconstruction for $B_{s1,2}^{(*)} \rightarrow B^{(*)+}K^-$;
- Method of the decay reconstruction for $B_{s1,2}^{(*)} \rightarrow B^{(*)0}K_S^0$;
- Measurement of the $B_{s2}^*(5840)^0$ natural width;
- Observation of the decay $B_{s2}^*(5840)^0 \rightarrow B^0K_S^0$ and evidence for the $B_{s1}(5830)^0 \rightarrow B^{*0}K_S^0$ decay, as well as the measurements of their branching fractions with respect to the corresponding decays into $B^{(*)+}K^-$;
- Mass difference measurements $M(B_{s2}^*) - m_{B^+}^{\text{PDG}} - m_{K^-}^{\text{PDG}}$, $M(B_{s1}) - m_{B^{*+}}^{\text{PDG}} - m_{K^-}^{\text{PDG}}$, $M(B_{s2}^*) - m_{B^0}^{\text{PDG}} - m_{K_S^0}^{\text{PDG}}$, $M(B_{s1}) - m_{B^{*0}}^{\text{PDG}} - m_{K_S^0}^{\text{PDG}}$, $M(B^0) - M(B^+)$ and $M(B^{*0}) - M(B^{*+})$.

Theoretical and practical significance of the work

The results of the performed work demonstrate the possibility to perform heavy flavor spectroscopy studies at the CMS experiment which was not initially optimized for this area of research. Obtained in the thesis upper limit on the $X(5568)$ is the most stringent among the results of other collaborations, and contradicts the D0 result, thus putting $X(5568)$ existence under serious doubt. The methods of analyzing the data and simulation samples are widely used in the other heavy flavor studies in the CMS experiment. The studies for the first time decays of P -wave B_s^0 mesons into a neutral B meson and a neutral kaon are important for filling up the experimental knowledge about these states. The measured masses and natural widths will help to obtain more precise world-average values and to test and tune the theoretical models.

The reliability of the results

Measured upper limit on the $X(5568)$ production is consistent with the conclusions of LHCb, ATLAS and CDF collaborations, while being more restrictive. The reconstruction algorithm is verified with a modification of the selection criteria so that the observed $]Bs\pi$ mass distributions presents evident peaks in from the excited B^+ meson decays into $B^{(*)0}\pi^+$. The measured masses of the $B_{s2}^*(5840)^0$ and $B_{s1}(5830)^0$ states are in agreement with the previous measurements, as well as the $B_{s2}^*(5840)^0$ natural width. Also the measured decay probability ratios are in agreement with the previous results, for those which exist. The ratios of excited B_s^0 branching fraction into neutral and charged BK are in agreement with theoretical predictions.

Personal contribution of the author

The defended results are obtained by author himself or with his key con-

tribution. The author has actively participated in the work of international B physics studies group of the CMS experiment. The results on the search for $X(5568) \rightarrow B_s^0 \pi^\pm$ are obtained with key contribution of the author. All the main results are obtained by the author, using the The P -wave B_s^0 meson study is performed fully solely by the author of the dissertation. Moreover, the author has participated in the data taking in the control room of the CMS experiment during 2016-2018 and participated in the trigger algorithms development.

Approbation of the work

The reported results are published in References [1, 2, 3, 4, 5], all of which satisfy the government requirements. Refs [1, 2] are the CMS collaboration papers published in the leading international peer-reviewed journals, while Refs [3, 4, 5] are the conference proceedings referenced in Web of Science and Scopus databases. The results have been discussed multiple times at the internal meetings of the CMS collaboration. Author has reported the results at 6 conferences, 5 of which were international.

Structure and the size of the thesis

Dissertation consists of an introduction, three main chapters, and conclusions. Size of the dissertation is 109 pages, including 30 figures and 29 tables. References list consists of 119 sources.

Brief summary of the dissertation

The introduction presents the recent results in the heavy flavor spectroscopy, including the classic and exotic spectroscopy measurements, and the general overview of the dissertation is given.

The second chapter describes the CMS experiment at the LHC, as

well as the standard for CMS particle reconstruction algorithms. Figure. 1

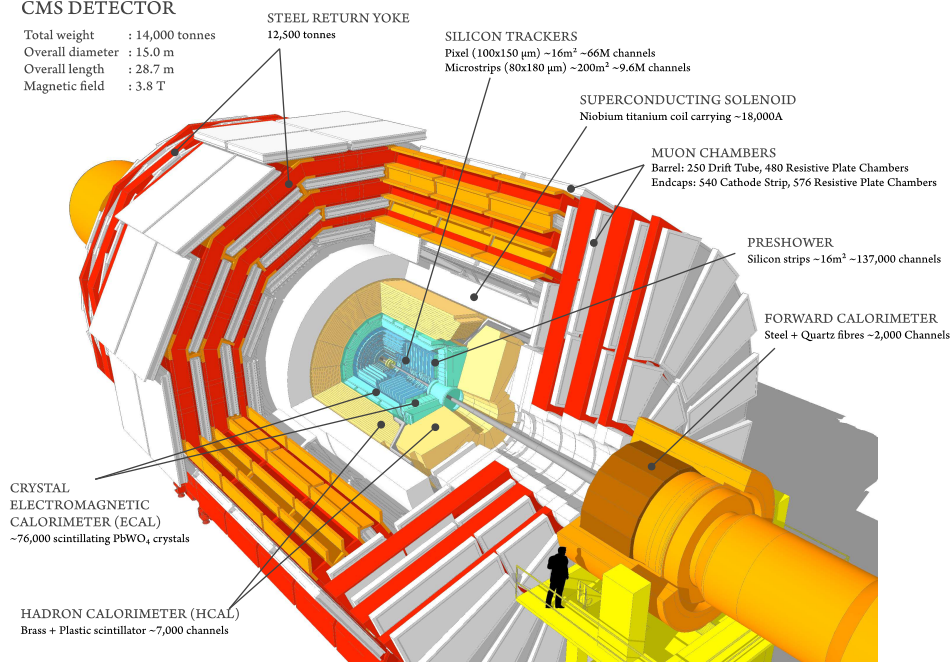


Figure 1: Schematic view of the CMS experiment layers.

presents a schematic view of the sensitive layers of the Compact Muon Solenoid (CMS) experiment. Different layers of the detector are grouped into barrel part and two endcap parts, covering the barrel from both sides. The total length is 28.7 m, and the diameter is 15 m, while the weight of the assembly equals to 14 000 ton. The key elements of the CMS experiment are the inner tracking system, electromagnetic and hadron calorimeters, and the muon system. A large superconducting solenoid is placed between the hadron calorimeter and the muon system, which provides a magnetic field of 3.8 T. The steel return yoke of the solenoid is put between the muon stations, also serving as absorber.

The third chapter describes the search for the exotic state $X(5568)$

decaying into $B_s^0\pi^\pm$. The chapter starts with the discussion about the results of other experiments on the $X(5568)$. In the beginning of 2016 the D0 collaboration claimed an observation of a new state decaying into $B_s^0\pi^\pm$, called $X(5568)$, with measured mass and natural width of $M_X = 5567.8 \pm 2.9 \text{ (stat.)}_{-1.9}^{+0.9} \text{ (syst.) MeV}$ and $\Gamma_X = 21.9 \pm 6.4 \text{ (stat.)}_{-2.5}^{+5.0} \text{ (syst.) MeV}$. Its decay products consist of four different quarks (b, s, u, d), which can possibly be explained by the molecular hypothesis (tightly bound B^0 and $K^\pm$), or a bound state of four quarks (tetraquark). The measured $X(5568)$ mass is 200 MeV below the $B^0K^\pm$ threshold, therefore a molecular hypothesis is very unlikely to be true. The D0 collaboration had also measured ρ_X – the fraction of B_s^0 mesons produced from the $X(5568) \rightarrow B_s^0\pi^\pm$ decays, to be $8.6 \pm 2.4\%$ ($8.2 \pm 3.1\%$) for $p_T(B_s^0) > 10(15)$ GeV. $X(5568)$ is the first tetraquark candidate consisting of 4 different quarks. The LHCb collaboration had quickly investigated the $B_s^0\pi^\pm$ spectrum and had not find any evidence for the $]Xm$ state, putting an upper limits $\rho_X^{LHCb} < 2.4\%$ at 95% confidence level for $p_T(B_s^0) > 10$ GeV and $\rho_X^{LHCb} < 2.0\%$ @ 95% CL for $p_T(B_s^0) > 15$ GeV. These limits are in contradiction with the D0 result, however, they are obtained in a different kinematic region. After that, the CMS collaboration presented their search result for $X(5568)$, this work was done with a key contribution of the author and is described in chapter 3.

An upper limit on ρ_X (fraction of B_s^0 produced in $X(5568)$ decays), is estimated using the relation

$$\rho_X \equiv \frac{\sigma(pp \rightarrow X(5568) + \dots) \times \mathcal{B}(X(5568) \rightarrow B_s^0\pi^\pm)}{\sigma(pp \rightarrow B_s^0 + \dots)} = \frac{N_{X(5568)}}{N_{B_s^0} \times \epsilon_{rel}},$$

where $N_{X(5568)}$ ($N_{B_s^0}$) is the number of the $X(5568)$ (B_s^0) signal events measured in data, and $\epsilon_{rel} = \epsilon_{X(5568)}/\epsilon_{B_s^0}$ is the relative efficiency.

The third part of the third chapter describes the event reconstruc-

tion and selection, as well as the details of the simulated event samples. The reconstruction requires to opposite-sign muons consistent with the J/ψ candidate that triggered the event readout. The dimuon candidate is then combined with two opposite-sign tracks with an invariant mass $M(K^+K^-)$ around the known ϕ meson mass forming the $B_s^0 \rightarrow J/\psi\phi$ -candidate. Its vertex is required to be significantly displaced from the interaction region, and its momentum vector is required to be aligned with the measured displacement vector. The fit to B_s^0 candidate mass distribution is applied to extract the mass resolution and define the signal and control regions of the B_s^0 mass. The simulation samples are described: the signal one, $X(5568) \rightarrow B_s^0\pi^\pm$, where $B_s^0 \rightarrow J/\psi K^+K^-$, and the normalization one, inclusive $B_s^0 \rightarrow J/\psi\phi$.

In the fourth part of the third chapter studies of the $B_s^0\pi^\pm$ mass distribution are presented. In particular, the distribution from the B_s^0 signal region is compared to that from the B_s^0 sidebands, and no significant difference between them is observed, with both not showing any peak around the $X(5568)$ mass. In order to verify the $B_s^0\pi^\pm$ candidates reconstruction procedure, the mass window requirement on the kaon pair is removed, allowing the $B^0 \rightarrow J/\psi K^+\pi^-$ decays (with pion reconstructed as a kaon) to contribute to the selected B_s^0 sample, consequently, allowing the excited B^+ meson decays into $B^{(*)0}\pi^\pm$ to appear in the $B_s^0\pi^\pm$ mass spectrum. Such process has exactly the same topology and close kinematics to the searched for $X(5568) \rightarrow B_s^0\pi^\pm$ decay, and thus the clear signals from excited B^+ decays in the observed distribution verify the reconstruction procedure. To obtain the numerical limits on the $X(5568)$, the observed $B_s^0\pi^\pm$ mass distribution is fit with a sum of a smooth background function and a signal component, as shown in Fig. 2 for the two studied kinematic ranges. The fit results in the signal yield consistent with zero.

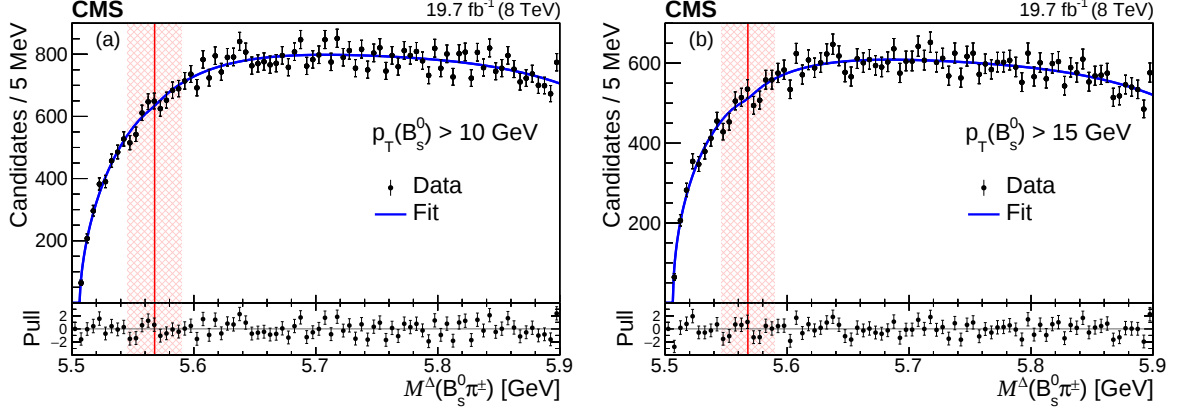


Figure 2: $B_s^0\pi^\pm$ invariant mass distribution in the B_s^0 signal region with the fit results overlaid: (a) $p_T(B_s^0) > 10$ GeV and (b) $p_T(B_s^0) > 15$ GeV. Bottom insets show the pull distributions, i.e. the difference between the data and the fit, divided by the data uncertainty. Vertical shaded areas display the region $M_X \pm \Gamma_X$ around the $X(5568)$ mass.

The fifth part of the third chapter presents the calculation of the upper limit on the fraction of B_s^0 mesons produced in the $X(5568) \rightarrow B_s^0\pi^\pm$ decays. The obtained limit is $\rho_X < 1.1\%(1.0\%)$ at 95% CL for the kinematic region $p_T(B_s^0) > 10(15)$ GeV, which is in evident contradiction with the D0 result. Moreover, the result is obtained in the ranges of p_T and η), close to the D0 experiment conditions, unlike the LHCb experiment. In addition, an upper limit is set on the fraction of B_s^0 mesons produced in the decays of an exotic particle, decaying into $B_s^0\pi^\pm$, as a function of the mass and the natural width of that particle, and get these results, the dependencies of the efficiency and the mass resolution on the mass of the exotic state are obtained.

Sixth part of the third chapter summarizes the $X(5568)$ search results. Existence of the $X(5568)$ state is not confirmed. The upper limit set in the thesis on the fraction of B_s^0 mesons produced in the $X(5568)$

decays, is the most stringent limit to date.

The fourth chapter describes the study of the P -wave B_s^0 meson states $B_{s2}^*(5840)^0$ and $B_{s1}(5830)^0$. An overview of the previous results and a summary of a large number of various theoretical predictions on the excited B_s^0 states are given, proving the relevance of the presented research. **The third part of the fourth chapter** gives a brief overview of the analysis, including the definitions of the measured quantities and the used methods to measure them.

In the fourth part of the fourth chapter the reconstruction procedures are discussed. As in the third chapter, the reconstruction starts with finding the $J/\psi \rightarrow \mu^+\mu^-$ candidates, which are then combined with one or two tracks to form, respectively, $B^+ \rightarrow J/\psi K^+$ or $B^0 \rightarrow J/\psi K^+\pi^-$ candidates. To suppress background, the reconstructed B meson vertex is required to be significantly displaced from the interaction region, and B meson momentum vector is required to be aligned with the measured displacement vector. B^+K^- candidates are obtained by attaching a prompt track to the selected B^+ candidate, and $B^0K_S^0$ candidates are obtained by combining the B^0 candidates with significantly displaced from the interaction region two-prong vertices consistent with the $K_S^0 \rightarrow \pi^+\pi^-$ decays.

The fifth part of the fourth chapter lists the details about the used simulated event samples. In total 9 decay samples are used: $B_{s2}^* \rightarrow B^+K^-$, $B_{s2}^* \rightarrow B^{*+}K^-$, $B_{s1} \rightarrow B^{*+}K^-$, $B_{s2}^* \rightarrow B^0K_S^0$, $B_{s2}^* \rightarrow B^{*0}K_S^0$, $B_{s1} \rightarrow B^{*0}K_S^0$, $B_2^* \rightarrow B^+\pi^-$, $B_2^* \rightarrow B^{*+}\pi^-$ and $B_1 \rightarrow B^{*+}\pi^-$.

The sixth part of the fourth chapter details the study of the selected B^+ and B^0 candidates. In case of the $B^0 \rightarrow J/\psi K^+\pi^-$ decay, the kaon and the pion might be swapped in the reconstruction ($K^\pm \leftrightarrow \pi^\pm$), and this effect is studied with the use of the simulated samples. According to the results of those studies, an additional component is included into

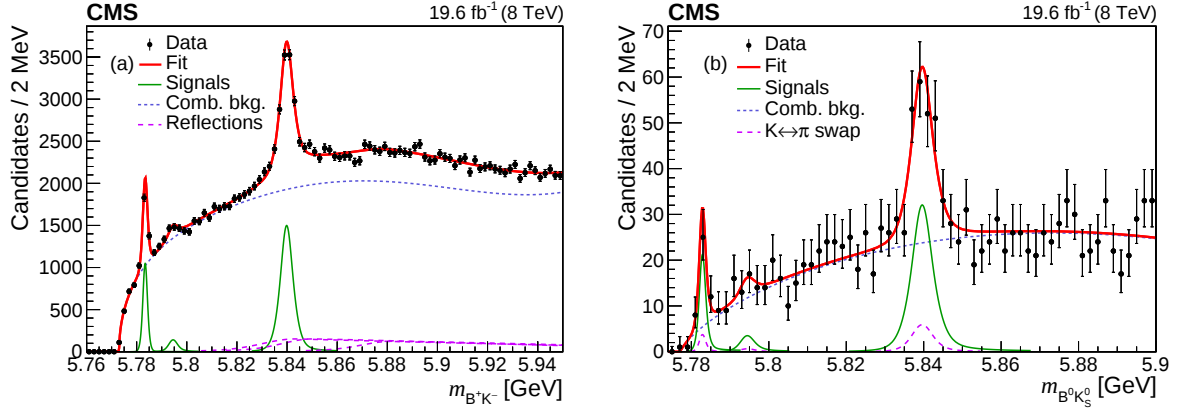


Figure 3: Invariant mass distributions B^+K^- (a) and $B^0K_S^0$ (b), measured in data.

the fit model, with the shape determined from simulation. The fraction of $K^\pm \leftrightarrow \pi^\pm$ events in the B^0 signal region is measured to be about 19%.

The seventh part of the fourth chapter presents an analysis of the $B_{s1,2}^{(*)}$ meson decays into $B^{(*)}K^-$. A special technique to account for the decays of excited B^0 mesons into $B^{(*)}\pi^-$ is designed, which uses both simulation and the $B^+\pi^-$ distribution measured in data. The simulated samples are used to obtain all the necessary B^+K^- mass resolutions. The observed B^+K^- mass distribution, shown in Fig. 3 (a), is modelled with a sum of signal and background contributions. The signal yields of the $B_{s2}^* \rightarrow B^+K^-$, $B_{s2}^* \rightarrow B^{*+}K^-$ and $B_{s1} \rightarrow B^{*+}K^-$ decays are obtained, as well as the mass differences $M(B_{s2}^*) - m_{B^+}^{\text{PDG}} - m_{K^-}^{\text{PDG}}$ and $M(B_{s1}) - m_{B^{*+}}^{\text{PDG}} - m_{K^-}^{\text{PDG}}$, and the B_{s2}^* meson natural width.

The eights part of the fourth chapter studies the obtained mass distribution of the selected $B^0K_S^0$ candidates, shown in Fig. 3 (b). The fit to this distribution accounts for the mass resolution extracted from the simulation and for probability of $K^\pm \leftrightarrow \pi^\pm$ in the B^0 reconstruction. The obtained statistical significances of the $B_{s2}^* \rightarrow B^0K_S^0$ and $B_{s1} \rightarrow B^{*0}K_S^0$

signals are 6.3σ and 3.6σ , allowing to claim the first observation and the first evidence for these decays.

The ninth part of the fourth chapter contains the calculation of the total efficiencies of the studied P -wave B_s^0 meson decays, which are necessary for the branching fraction measurements. **Tenth part of the fourth chapter** details the in-depth study of the potential systematic uncertainties. For each systematic uncertainty source, the details on the estimation of its magnitude are given, and total systematic uncertainties are summarized in the Tables at the end.

The last part of the fourth chapter gives the results of the P -wave B_s^0 meson studies. The decay $B_{s2}^* \rightarrow B^0 K_S^0$ is observed for the first time and the first evidence is found for the decay $B_{s1} \rightarrow B^{*0} K_S^0$. The ratios of branching fractions are measured to be

$$\begin{aligned} R_2^{0\pm} &= \frac{\mathcal{B}(B_{s2}^* \rightarrow B^0 K_S^0)}{\mathcal{B}(B_{s2}^* \rightarrow B^+ K^-)} = 0.432 \pm 0.077 \text{ (stat.)} \pm 0.075 \text{ (syst.)} \pm 0.021(\mathcal{B}), \\ R_1^{0\pm} &= \frac{\mathcal{B}(B_{s1} \rightarrow B^{*0} K_S^0)}{\mathcal{B}(B_{s1} \rightarrow B^{*+} K^-)} = 0.492 \pm 0.122 \text{ (stat.)} \pm 0.068 \text{ (syst.)} \pm 0.024(\mathcal{B}), \\ R_{2*}^{\pm} &= \frac{\mathcal{B}(B_{s2}^* \rightarrow B^{*+} K^-)}{\mathcal{B}(B_{s2}^* \rightarrow B^+ K^-)} = 0.081 \pm 0.021 \text{ (stat.)} \pm 0.015 \text{ (syst.)}, \\ R_{2*}^0 &= \frac{\mathcal{B}(B_{s2}^* \rightarrow B^{*0} K_S^0)}{\mathcal{B}(B_{s2}^* \rightarrow B^0 K_S^0)} = 0.093 \pm 0.086 \text{ (stat.)} \pm 0.014 \text{ (syst.)}. \end{aligned}$$

In addition, the cross sections multiplied by the branching fraction ratios are measured

$$\begin{aligned} R_{\sigma}^{\pm} &= \frac{\sigma(\text{pp} \rightarrow B_{s1} \dots) \times \mathcal{B}(B_{s1} \rightarrow B^{*+} K^-)}{\sigma(\text{pp} \rightarrow B_{s2}^* \dots) \times \mathcal{B}(B_{s2}^* \rightarrow B^+ K^-)} = 0.233 \pm 0.019 \text{ (stat.)} \pm 0.018 \text{ (syst.)}, \\ R_{\sigma}^0 &= \frac{\sigma(\text{pp} \rightarrow B_{s1} \dots) \times \mathcal{B}(B_{s1} \rightarrow B^{*0} K_S^0)}{\sigma(\text{pp} \rightarrow B_{s2}^* \dots) \times \mathcal{B}(B_{s2}^* \rightarrow B^0 K_S^0)} = 0.266 \pm 0.079 \text{ (stat.)} \pm 0.063 \text{ (syst.)}. \end{aligned}$$

The measured mass differences are

$$\begin{aligned}
\Delta M_{B_{s2}^*}^\pm &= M(B_{s2}^*) - m_{B^+}^{\text{PDG}} - m_{K^-}^{\text{PDG}} = 66.870 \pm 0.093 \text{ (stat.)} \pm 0.073 \text{ (syst.) MeV,} \\
\Delta M_{B_{s2}^*}^0 &= M(B_{s2}^*) - m_{B^0}^{\text{PDG}} - m_{K_S^0}^{\text{PDG}} = 62.370 \pm 0.478 \text{ (stat.)} \pm 0.071 \text{ (syst.) MeV,} \\
\Delta M_{B_{s1}}^\pm &= M(B_{s1}) - m_{B^{*+}}^{\text{PDG}} - m_{K^-}^{\text{PDG}} = 10.452 \pm 0.089 \text{ (stat.)} \pm 0.063 \text{ (syst.) MeV,} \\
\Delta M_{B_{s1}}^0 &= M(B_{s1}) - m_{B^{*0}}^{\text{PDG}} - m_{K_S^0}^{\text{PDG}} = 5.612 \pm 0.225 \text{ (stat.)} \pm 0.057 \text{ (syst.) MeV.}
\end{aligned}$$

Using the first and the third of these measurements, the masses of $B_{s1,2}^{(*)}$ mesons are calculated:

$$\begin{aligned}
M(B_{s2}^*) &= 5839.857 \pm 0.093 \text{ (stat.)} \pm 0.073 \text{ (syst.)} \pm 0.151 \text{ (PDG) MeV,} \\
M(B_{s1}) &= 5828.779 \pm 0.089 \text{ (stat.)} \pm 0.063 \text{ (syst.)} \pm 0.275 \text{ (PDG) MeV.}
\end{aligned}$$

Also using the relations above, the mass differences between neutral and charged mesons are measured

$$\begin{aligned}
M(B^0) - M(B^+) &= 0.566 \pm 0.487 \text{ (stat.)} \pm 0.098 \text{ (syst.)} \pm 0.020 \text{ (PDG) MeV,} \\
M(B^{*0}) - M(B^{*+}) &= 0.906 \pm 0.242 \text{ (stat.)} \pm 0.085 \text{ (syst.)} \pm 0.020 \text{ (PDG) MeV.}
\end{aligned}$$

The mass difference $M(B^{*0}) - M(B^{*+})$ is measured for the first time and this work presents a new method to measure these mass differences.

Finally, the B_{s2}^* meson natural width is measured:

$$\Gamma(B_{s2}^*) = 1.52 \pm 0.34 \text{ (stat.)} \pm 0.30 \text{ (syst.) MeV.}$$

Measured mass differences $\Delta M_{B_{s2}^*}^\pm$ and $\Delta M_{B_{s1}}^\pm$ and the $\Gamma(B_{s2}^*)$ are in agreement with the previous experimental measurements of the LHCb and CDF collaborations. The measured ratios $R_{2*}^\pm$ and $R_\sigma^\pm$ are in agreement with the values measured by the LHCb collaboration.

In the conclusions, the main thesis results are listed. The work was done using the data collected by the CMS experiment in proton-proton collisions at the LHC at the centre-of-mass energy of $\sqrt{s} = 8 \text{ TeV}$ and corresponding to an integrated luminosity of about 20 fb^{-1} . The following goals are achieved:

- A search for the $X(5568)$ state decaying into $B_s^0 \pi^\pm$ is carried out, an upper limit is set on the fraction of B_s^0 mesons produced in the $X(5568)$ decays. Obtained upper limit is the most stringent to date and is in a strong contradiction with the result of the D0 collaboration.
- An upper limit is set on the fraction of B_s^0 mesons produced in the decays of an exotic particle, decaying into $B_s^0 \pi^\pm$, as a function of the mass and the natural width of that particle.
- The P -wave B_s^0 meson decays $B_{s2}^* \rightarrow B^+ K^-$, $B_{s2}^* \rightarrow B^{*+} K^-$, $B_{s1} \rightarrow B^{*+} K^-$ are reconstructed, and the ratios $\frac{\mathcal{B}(B_{s2}^* \rightarrow B^{*+} K^-)}{\mathcal{B}(B_{s2}^* \rightarrow B^+ K^-)}$ and $\frac{\sigma(\text{pp} \rightarrow B_{s1} \dots) \times \mathcal{B}(B_{s1} \rightarrow B^{*+} K^-)}{\sigma(\text{pp} \rightarrow B_{s2}^* \dots) \times \mathcal{B}(B_{s2}^* \rightarrow B^+ K^-)}$ are measured. These decays are used to determine the mass differences $M(B_{s2}^*) - m_{B^+}^{\text{PDG}} - m_{K^-}^{\text{PDG}}$ and $M(B_{s1}) - m_{B^{*+}}^{\text{PDG}} - m_{K^-}^{\text{PDG}}$, masses of the B_{s2}^* and B_{s1} mesons, and the natural width $\Gamma(B_{s2}^*)$.
- The decay $B_{s2}^* \rightarrow B^0 K_S^0$ is observed for the first time, and a first evidence is found for the decay $B_{s1} \rightarrow B^{*0} K_S^0$; the ratios $\frac{\mathcal{B}(B_{s2}^* \rightarrow B^0 K_S^0)}{\mathcal{B}(B_{s2}^* \rightarrow B^+ K^-)}$, $\frac{\mathcal{B}(B_{s1} \rightarrow B^{*0} K_S^0)}{\mathcal{B}(B_{s1} \rightarrow B^{*+} K^-)}$, $\frac{\mathcal{B}(B_{s2}^* \rightarrow B^{*0} K_S^0)}{\mathcal{B}(B_{s2}^* \rightarrow B^0 K_S^0)}$, and $\frac{\sigma(\text{pp} \rightarrow B_{s1} \dots) \times \mathcal{B}(B_{s1} \rightarrow B^{*0} K_S^0)}{\sigma(\text{pp} \rightarrow B_{s2}^* \dots) \times \mathcal{B}(B_{s2}^* \rightarrow B^0 K_S^0)}$ are measured.

In addition, the mass difference measurements $M(\text{B}_{\text{s}2}^*) - m_{\text{B}^0}^{\text{PDG}} - m_{\text{K}_S^0}^{\text{PDG}}$ and $M(\text{B}_{\text{s}1}) - m_{\text{B}^{*0}}^{\text{PDG}} - m_{\text{K}_S^0}^{\text{PDG}}$ are reported.

- Using a new approach, the mass differences $M(\text{B}^0) - M(\text{B}^+)$ and $M(\text{B}^{*0}) - M(\text{B}^{*+})$ are measured, where the latter one is measured for the first time.

Author's publications related to the thesis (to the date of defense)

- [1] CMS Collaboration, Sirunyan A. M. et al. 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. — 2018. — Vol. **120**. — no. 20. — P. 202005, arXiv:1712.06144, DOI: 10.1103/PhysRevLett.120.202005.
- [2] CMS Collaboration, Sirunyan Albert M et al. Studies of $B_{s2}^*(5840)^0$ and $B_{s1}(5830)^0$ mesons including the observation of the $B_{s2}^*(5840)^0 \rightarrow B^0 K_s^0$ decay in proton-proton collisions at $\sqrt{s} = 8$ TeV // Eur. Phys. J. C. — 2018. — Vol. **78**. — P. 939, arXiv:1809.03578, DOI: 10.1140/epjc/s10052-018-6390-z.
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- [4] Polikarpov S. Recent CMS B physics results // EPJ Web of Conferences. — Vol. 182. — 2018. — n. 02098, DOI: 10.1051/epjconf/201818202098.
- [5] Polikarpov S. Study of the P -wave B_s^0 mesons at the CMS experiment in pp collisions at $\sqrt{s} = 8$ TeV // Proceedings of Science. — Vol. 321. — 2018. — Journal reference: PoS(LHCP2018)184, DOI: 10.22323/1.321.0184.