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Study of the P-wave B_s^0 mesons at the CMS experiment in pp collisions at $\sqrt{s} = 8$ TeV

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We present the observation of the $B_{s2}^*(5840)^0 \to B^0 K_S^0$ decay and the evidence for the $B_{s1}(5830)^0 \to B^{*0} K_S^0$ decay by the CMS experiment at the LHC in proton-proton collisions at $\sqrt{s} = 8$ TeV. In addition, properties of the P-wave B_s^0 mesons are measured, as well as the mass differences $m_{B^0} - m_{B^+}$ and $m_{B^{*0}} - m_{B^{*+}}$, with the latter being measured for the first time.

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The CMS experiment [1] at the LHC continues to provide new important results in the Heavy Flavor physics sector. In this work, we report the study on excited B_s^0 mesons [2], including the first observation of the $B_{s2}^* \to B^0 K_S^0$ decay, the measurements of B_{s2}^* and B_{s1} properties, and the measurements of mass differences $M(B_{s1,2}^{(*)}) - M(B^{(*)}) - M(K)$ and $M(B^{(*)0}) - M(B^{(*)+})$. Here and in the following, the shorthand designations for particle names are used: $B_{s1} \equiv B_{s1}(5830)^0$, $B_{s2}^* \equiv B_{s2}^*(5840)^0$, $B_{s1,2}^{(*)}$ stands for either B_{s1} or B_{s2}^*, $K^{*0} \equiv K^*(892)^0$. Charge-conjugate states are implied throughout the text.

There are only a few experimental studies of excited B_s^0 mesons. In particular, the *P*-wave B_s^0 mesons were observed by the CDF and D0 collaborations at the Tevatron [3, 4] as the narrow peaks in the B^+K^- invariant mass distribution. Later, the LHCb collaboration at the LHC presented precise measurements of the $B_{s1,2}^{(*)}$ properties [5], including the observation of the $B_{s2}^* \to B^{*+}K^-$ decay. This decay allowed to determine the mass difference $M(B^{*+}) - M(B^+)$. Using the full CDF run II sample, the CDF collaboration released a study of orbitally excited B mesons [6], which included updated measurements of $B_{s1,2}^{(*)}$ properties. All these analyses used only the decays into charged B meson and a kaon to reconstruct the $B_{s1,2}^{(*)}$ candidates, while we report on the search result for the decays into a neutral B meson and a neutral kaon.

Using the data sample collected by the CMS experiment in proton-proton collisions at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of about 20 fb^{-1}, we reconstruct the B^+K^- and $B^0K_S^0$ candidates. The B^+ and B^0 candidates are obtained using the decays $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$ ($K^{*0} \to K^+\pi^-$), where the J/ψ meson is reconstructed in the decay $J/\psi \to \mu^+\mu^-$, and these muons are used to trigger the event readout. The standard requirements are applied on the muon and track quality and muon identification. The B meson vertices are required to be significantly displaced from the pp interaction vertex and the B meson momentum is required to be collinear with the direction from the pp interaction vertex to the B meson vertex. In order to build B^+K^- candidates, a track originating from the same primary vertex as the B^+ candidate is combined with the selected B^+ candidate. The K_S^0 candidates are selected from significantly displaced from the pp interaction region two-track vertices, consistent with the $K_S^0 \to \pi^+\pi^-$ decay, as described in Ref. [7]. The selected K_S^0 candidates are combined with B^0 candidates to obtain the $B^0K_S^0$ candidates.

The selected B^+K^- sample includes a contribution from the excited B^0 mesons decaying into B^+ and a charged pion, as illustrated in Fig. 1, obtained using the previously described B^+K^- data set, where the $m_{B^+\pi^-}$ is obtained by assigning the pion mass to the selected K^- candidate. In order to estimate the magnitude of these contributions, an unbinned maximum-likelihood fit is performed to the $B^+\pi^-$ invariant mass distribution, as shown in Fig. 1 (left). The three signals, corresponding to the decays $B_2^*(5747)^0 \to B^+\pi^-$, $B_2^*(5747)^0 \to B^{*+}\pi^-$, and $B_1(5721)^0 \to B^{*+}\pi^-$, are modelled with the relativistic Breit-Wigner (RBW) functions, convolved with the resolution obtained with Monte Carlo simulation. The combinatorial background is modelled with a smooth function. The fit yields in about 10,000 events for each of the three mentioned above signal contributions.

Figure 2 (left) shows the invariant mass distribution of the selected B^+K^- candidates with the fit results overlaid. The background model includes the smooth combinatorial background component and the three components accounting for the above discussed contributions from the $B_2^*(5747)^0 \to B^+\pi^-$, $B_2^*(5747)^0 \to B^{*+}\pi^-$, and $B_1(5721)^0 \to B^{*+}\pi^-$ decays, with shapes obtained

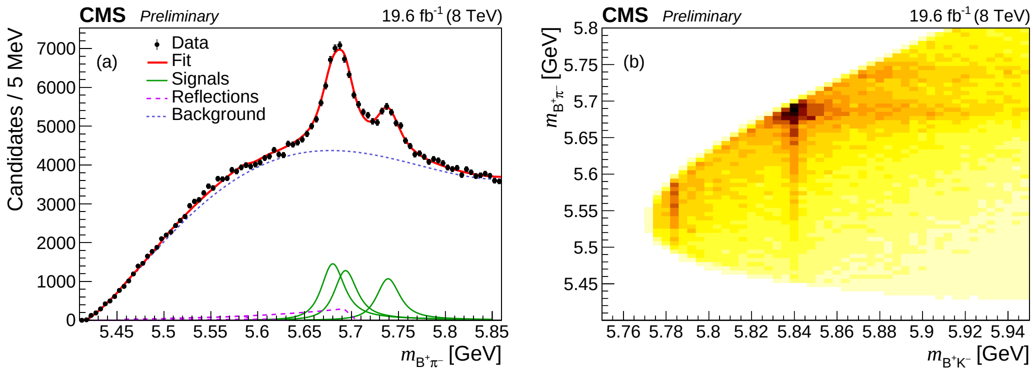

Figure 1: The $B^+\pi^-$ invariant mass distribution (left) and the two-dimensional distribution of $m_{B^+\pi^-}$ versus $m_{B^+K^-}$ (right) [2].

in Monte Carlo simulation and yields fixed to those obtained from the fit to the $B^+\pi^-$ invariant mass distribution. The three signals, corresponding to the decays $B_{s2}^* \to B^+K^-$, $B_{s2}^* \to B^{*+}K^-$, and $B_{s1} \to B^{*+}K^-$, are modelled with RBW functions convolved with the resolution.

Figure 2 (right) shows the invariant mass distribution of the selected $B^0K_S^0$ candidates with the fit results overlaid. Similar to the B^+K^- channel, the three RBW functions convolved with resolution functions are used to describe the three signals: $B_{s2}^* \to B^0K_S^0$, $B_{s2}^* \to B^{*0}K_S^0$, and $B_{s1} \to B^{*0}K_S^0$. The charged pion and kaon may be swapped in the $B^0 \to J/\psi K^+\pi^-$ reconstruction, which leads to narrow peaks at the same $m_{B^0K_S^0}$ value, as found in simulation. The fraction of events where this happens is estimated from the fit to $J/\psi K^+\pi^-$ invariant mass distribution to be around 19%. The contributions from from the signal decays with swapped kaon and pion in the B^0 reconstruction are included in $m_{B^0K_S^0}$ fit model.

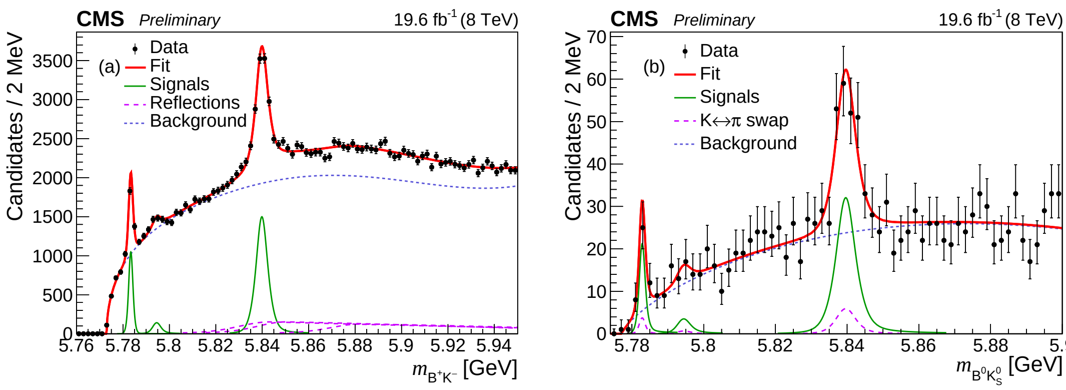

Figure 2: The B^+K^- (left) and $B^0K_S^0$ (right) invariant mass distributions [2].

The fit results to the invariant mass distributions of the selected B^+K^- and $B^0K_S^0$ candidates are given in Table 1. They are used to measure the relative branching fractions $R_2^{0\pm}$, $R_1^{0\pm}$, $R_{2*}^{\pm}$, R_{2*}^{0},

$R_\sigma^\pm$, and R_σ^0, defined as:

$$R_2^{0\pm} = \frac{\mathscr{B}(B_{s2}^* \to B^0 K_S^0)}{\mathscr{B}(B_{s2}^* \to B^+ K^-)}, \quad R_1^{0\pm} = \frac{\mathscr{B}(B_{s1} \to B^{*0} K_S^0)}{\mathscr{B}(B_{s1} \to B^{*+} K^-)},$$
$$R_{2*}^{\pm} = \frac{\mathscr{B}(B_{s2}^* \to B^{*+} K^-)}{\mathscr{B}(B_{s2}^* \to B^+ K^-)}, \quad R_{2*}^{0} = \frac{\mathscr{B}(B_{s2}^* \to B^{*0} K_S^0)}{\mathscr{B}(B_{s2}^* \to B^0 K_S^0)},$$
$$R_\sigma^\pm = \frac{\sigma(pp \to B_{s1} X) \times \mathscr{B}(B_{s1} \to B^{*+} K^-)}{\sigma(pp \to B_{s2}^* X) \times \mathscr{B}(B_{s2}^* \to B^+ K^-)},$$
$$R_\sigma^0 = \frac{\sigma(pp \to B_{s1} X) \times \mathscr{B}(B_{s1} \to B^{*0} K_S^0)}{\sigma(pp \to B_{s2}^* X) \times \mathscr{B}(B_{s2}^* \to B^0 K_S^0)}.$$

These ratios are obtained as the ratios of the corresponding signal yields observed in data corrected for the ratio of total efficiencies and, in case of $R_2^{0\pm}$ and $R_1^{0\pm}$, for the branching fractions of the intermediate decays involved ($\mathscr{B}(B^+ \to J/\psi K^+)$, $\mathscr{B}(B^0 \to J/\psi K^{*0})$, $\mathscr{B}(K^{*0} \to K^+\pi^-)$, and $\mathscr{B}(K_S^0 \to \pi^+\pi^-)$). For example,

$$R_2^{0\pm} = \frac{\mathscr{B}(B_{s2}^* \to B^0 K_S^0)}{\mathscr{B}(B_{s2}^* \to B^+ K^-)} = \frac{N(B_{s2}^* \to B^0 K_S^0)}{N(B_{s2}^* \to B^+ K^-)} \times \frac{\varepsilon(B_{s2}^* \to B^+ K^-)}{\varepsilon(B_{s2}^* \to B^0 K_S^0)} \times$$
$$\times \frac{\mathscr{B}(B^+ \to J/\psi K^+)}{\mathscr{B}(B^0 \to J/\psi K^{*0}) \mathscr{B}(K^{*0} \to K^+\pi^-) \mathscr{B}(K_S^0 \to \pi^+\pi^-)}.$$

Table 1: Results from the fits to the m_{BK} distributions: signal yields (N), natural widths (Γ) and mass differences.

	B^+K^-	$B^0K_S^0$
$N(B_{s2}^* \to BK)$	5424 ± 269	128 ± 22
$N(B_{s2}^* \to B^*K)$	455 ± 119	12 ± 11
$N(B_{s1} \to B^*K)$	1329 ± 83	34.5 ± 8.3
$\Gamma(B_{s2}^*)$ [MeV]	1.52 ± 0.34	2.1 ± 1.3
$\Gamma(B_{s1})$ [MeV]	0.10 ± 0.15	0.4 ± 0.4
$M(B_{s2}^*) - M(B) - M(K)$ [MeV]	66.926 ± 0.093	62.42 ± 0.48
$M(B_{s1}) - M(B^*) - M(K)$ [MeV]	10.495 ± 0.089	5.65 ± 0.23

In addition, we measure the mass differences between the neutral and charged B mesons, using the following equations:

$$m_{B^0} - m_{B^+} = \Delta M_{B_{s2}^*}^{\pm} - \Delta M_{B_{s2}^*}^{0} + M(K^-) - M(K_S^0) \text{ and}$$
$$m_{B^{*0}} - m_{B^{*+}} = \Delta M_{B_{s1}}^{\pm} - \Delta M_{B_{s1}}^{0} + M(K^-) - M(K_S^0),$$

where the mass differences $\Delta M_{B_{s2}^*}^{\pm}$, $\Delta M_{B_{s1}}^{\pm}$, $\Delta M_{B_{s2}^*}^{0}$, and $\Delta M_{B_{s1}}^{0}$ denote the values obtained from the fits to the B^+K^- and $B^0K_S^0$ invariant mass distributions (and given in Table 1):

$$\Delta M_{B_{s2}^*}^{\pm} = M(B_{s2}^*) - M(B^+) - M(K^-), \quad \Delta M_{B_{s1}}^{\pm} = M(B_{s1}) - M(B^{*+}) - M(K^-),$$
$$\Delta M_{B_{s2}^*}^{0} = M(B_{s2}^*) - M(B^0) - M(K_S^0), \quad \Delta M_{B_{s1}}^{0} = M(B_{s1}) - M(B^{*0}) - M(K_S^0).$$

The considered systematic uncertainties in the measured branching fraction ratios, mass differences and the B_{s2}^* natural width, are related to:

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- The choice of the fit model;
- The track reconstruction efficiency;
- The invariant mass resolution uncertainty;
- The fraction of events where kaon and pion are swapped in the $B^0 \to J/\psi K^+\pi^-$ reconstruction;
- The fraction of non-$K^*(892)^0$ contribution in the selected $B^0 \to J/\psi K^+\pi^-$ candidates;
- Finite size of the simulation samples;
- The uncertainties in the known mass differences $M(B^{*+}) - M(B^+)$ and $M(B^{*0}) - M(B^0)$;
- The possible misalignment of the detector;
- The shift in the measured masses introduced by the reconstruction algorithms.

The obtained systematic uncertainties are up to 20% for the ratios of branching fractions, up to 0.1 MeV for the measured mass differences, and 0.3 MeV for $\Gamma(B^*_{s2})$.

The resulting branching fraction ratios are

$$R_2^{0\pm} = \frac{\mathscr{B}(B^*_{s2} \to B^0 K^0_S)}{\mathscr{B}(B^*_{s2} \to B^+ K^-)} = 0.432 \pm 0.077\,(\text{stat}) \pm 0.075\,(\text{syst}) \pm 0.021\,(\text{PDG}),$$

$$R_1^{0\pm} = \frac{\mathscr{B}(B_{s1} \to B^{*0} K^0_S)}{\mathscr{B}(B_{s1} \to B^{*+} K^-)} = 0.492 \pm 0.122\,(\text{stat}) \pm 0.068\,(\text{syst}) \pm 0.024\,(\text{PDG}),$$

$$R_{2*}^{\pm} = \frac{\mathscr{B}(B^*_{s2} \to B^{*+} K^-)}{\mathscr{B}(B^*_{s2} \to B^+ K^-)} = 0.081 \pm 0.021\,(\text{stat}) \pm 0.015\,(\text{syst}),$$

$$R_{2*}^{0} = \frac{\mathscr{B}(B^*_{s2} \to B^{*0} K^0_S)}{\mathscr{B}(B^*_{s2} \to B^0 K^0_S)} = 0.093 \pm 0.086\,(\text{stat}) \pm 0.014\,(\text{syst}),$$

$$R_{\sigma}^{\pm} = \frac{\sigma(pp \to B_{s1} X) \times \mathscr{B}(B_{s1} \to B^{*+} K^-)}{\sigma(pp \to B^*_{s2} X) \times \mathscr{B}(B^*_{s2} \to B^+ K^-)} = 0.233 \pm 0.019\,(\text{stat}) \pm 0.018\,(\text{syst}),$$

$$R_{\sigma}^{0} = \frac{\sigma(pp \to B_{s1} X) \times \mathscr{B}(B_{s1} \to B^{*0} K^0_S)}{\sigma(pp \to B^*_{s2} X) \times \mathscr{B}(B^*_{s2} \to B^0 K^0_S)} = 0.266 \pm 0.079\,(\text{stat}) \pm 0.063\,(\text{syst}).$$

where the first uncertainties are statistical, the second systematic, and the third are due to the uncertainties in the world-average branching fractions. The third and fifth ratios are consistent with the previous measurements of LHCb [5] and CDF [6] Collaborations.

The results for the mass differences are

$$\Delta M^{\pm}_{B^*_{s2}} = M(B^*_{s2}) - M(B^+) - M(K^-) = 66.870 \pm 0.093\,(\text{stat}) \pm 0.073\,(\text{syst})\,\text{MeV},$$

$$\Delta M^{0}_{B^*_{s2}} = M(B^*_{s2}) - M(B^0) - M(K^0_S) = 62.37 \pm 0.48\,(\text{stat}) \pm 0.07\,(\text{syst})\,\text{MeV},$$

$$\Delta M^{\pm}_{B_{s1}} = M(B_{s1}) - M(B^{*+}) - M(K^-) = 10.452 \pm 0.089\,(\text{stat}) \pm 0.063\,(\text{syst})\,\text{MeV},$$

$$\Delta M^{0}_{B_{s1}} = M(B_{s1}) - M(B^{*0}) - M(K^0_S) = 5.61 \pm 0.23\,(\text{stat}) \pm 0.06\,(\text{syst})\,\text{MeV},$$

$$m_{B^0} - m_{B^+} = 0.57 \pm 0.49\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.02\,(\text{PDG})\,\text{MeV},$$

$$m_{B^{*0}} - m_{B^{*+}} = 0.91 \pm 0.24\,(\text{stat}) \pm 0.09\,(\text{syst}) \pm 0.02\,(\text{PDG})\,\text{MeV},$$

where the second, fourth, and sixth mass differences are measured for the first time, and the last uncertainties in $m_{B^{(*)0}} - m_{B^{(*)+}}$ are due to the uncertainty in the mass difference between K^- and K_S^0. The first four of these values are used together with the known masses of B and K mesons to obtain the $B_{s1,2}^{(*)}$ masses:

$$M(B_{s2}^*) = 5839.857 \pm 0.093\,(\text{stat}) \pm 0.073\,(\text{syst}) \pm 0.151\,(\text{PDG})\,\text{MeV, in the } B^+K^- \text{ channel,}$$
$$M(B_{s2}^*) = 5839.60 \pm 0.48\,(\text{stat}) \pm 0.07\,(\text{syst}) \pm 0.15\,(\text{PDG})\,\text{MeV, in the } B^0K_S^0 \text{ channel,}$$
$$M(B_{s1}) = 5828.779 \pm 0.089\,(\text{stat}) \pm 0.063\,(\text{syst}) \pm 0.275\,(\text{PDG})\,\text{MeV, in the } B^+K^- \text{ channel,}$$
$$M(B_{s1}) = 5828.02 \pm 0.23\,(\text{stat}) \pm 0.06\,(\text{syst}) \pm 0.28\,(\text{PDG})\,\text{MeV, in the } B^0K_S^0 \text{ channel,}$$

where the last uncertainties are from the uncertainties in the world-average masses and mass differences. The $B_{s2}^*(5840)^0$ natural width is determined to be $1.52 \pm 0.34\,(\text{stat}) \pm 0.30\,(\text{syst})$ MeV.

In summary, the $B_{s2}^*(5840)^0 \to B^0K_S^0$ decay is observed for the first time and the evidence for the $B_{s1}(5830)^0 \to B^{*0}K_S^0$ decay is found. The analysis was performed using the data sample of about 20 fb^{-1} collected by the CMS experiment at the LHC in proton-proton collisions at $\sqrt{s} =$ 8 TeV. The measured properties of $B_{s1,2}^{(*)}$ include masses, mass differences with respect to the sum of B meson and kaon mass, and the $B_{s2}^*(5840)^0$ natural width. We also report the first measurement of $m_{B^{*0}} - m_{B^{*+}}$.

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