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Study of P-wave $B^0_S$ states at the CMS experiment

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Abstract. The observation of the $B^*_s(5840)^0 \rightarrow B^0_S K^0_S$ decay and the evidence for the $B_s^*(5830)^0 \rightarrow B^0 K^0_S$ decay are presented. The analysis uses the data collected by the CMS experiment at the LHC in proton-proton collisions at $\sqrt{s} = 8$ TeV. In addition, properties of the $P$-wave $B^0_S$ mesons are determined, as well as the mass differences $M(B^0) - M(B^+)$ and $M(B^*_0) - M(B^{*+})$, where the latter is measured for the first time.

1. Introduction

The CMS experiment [1] at the LHC continues to provide new important results in the area of Heavy Flavor physics. In this work, we report the study [2] of excited states of the $B^0_S$ meson, $B_s^1(5830)^0$ and $B^*_s(5840)^0$, including the first observation of the $B^*_s(5840)^0 \rightarrow B^0 K^0_S$ decay, the measurements of $B^*_s(5840)^0$ and $B_s(5830)^0$ properties, and the measurements of mass differences $M(B^*_s) - M(B^s) - M(K)$ and $M(B^0) - M(B^{*+})$. Here and in the following, $B^{(s)}_{1,2}$ refers to either $B_{s1}(5830)^0$ or $B^*_s(5840)^0$ and charge-conjugate states are implied throughout the text.

There are only a few experimental results on the excited $B^0_S$ mesons. In particular, the $P$-wave $B^0_S$ 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. Subsequently, the LHCb Collaboration at the LHC presented precise measurements of the $B^{(s)}_{1,2}$ properties [5], including the observation of the $B^*_s(5840)^0 \rightarrow B^{*+} K^-$ decay. The observation of this decay allowed to determine precisely the mass difference $M(B^{*+}) - M(B^+)$. More recently, using the full CDF run II sample, the CDF Collaboration released a study of orbitally excited B mesons [6], which included the updated measurements of the $B^{(s)}_{1,2}$ properties. All the described analyses used only the decays into a charged B meson and a kaon to reconstruct the $B^{(s)}_{1,2}$ candidates, while report the search for the decays into a neutral B meson and a neutral kaon.

2. Data and event selection

The analysis uses 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$^{-1}$. The $B^+$ and $B^0$ candidates are obtained using the decays $B^+ \rightarrow J/\psi K^+$ and $B^0 \rightarrow J/\psi K^{*}(892)^0 (K^{*0} \rightarrow K^+ \pi^-)$, where the $J/\psi$ meson is reconstructed via its dimuon decay, using the muon pairs that triggered the event readout. The standard requirements are applied on the muon and track quality and
mumon 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 case of $B^0 \rightarrow J/\psi K^{*0}$, additional selections are imposed, requiring the $K^+\pi^-$ candidate to be consistent with the $K^*(892)^0$ resonance and to be inconsistent with the $\phi(1020) \rightarrow K^+K^-$ decay (where one of the kaons is misreconstructed as a pion candidate). The $B^0K^-$ candidates are obtained by adding a track, originating from the same primary vertex as the $B^+$ candidate, to the selected $B^+$ candidate. The $K^0_S$ candidates are selected from significantly displaced from the pp interaction region two-track vertices, consistent with the $K_S^0 \rightarrow \pi^+\pi^-$ decay. The selected $K^0_S$ candidates are combined with $B^0$ candidates yielding the $B^0K^0_S$ candidates.

3. Study of the $B^+K^-$ invariant mass distribution

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, where the $m_{B^+\pi^-}$ is obtained in the same data set by assigning the pion mass to the selected $K^-$ candidate.

![Figure 1](image)

Figure 1. The two-dimensional distribution of $m_{B^+\pi^-}$ vs. $m_{B^+K^-}$ observed in data [2]. The vertical bands correspond to the decays $B_2^*(5840)^0 \rightarrow B^+K^-$, $B_2(5840)^0 \rightarrow B^{*+}K^-$, and $B_1(5830)^0 \rightarrow B^{*+}K^-$, while the horizontal bands are related to the decays $B_3^*(5747)^0 \rightarrow B^{*+}\pi^-$, $B_2(5747)^0 \rightarrow B^{*+}\pi^-$, and $B_1(5721)^0 \rightarrow B^{*+}\pi^-$. The selected $B^+K^-$ candidates are obtained by adding a track, originating from the three mentioned above excited $B^0$ decays, shown in Fig. 2. They are modelled by the smooth functions, and the obtained shapes are used in the fit to $B^+K^-$ invariant mass distribution in data. The magnitude of the contributions from the $B_3^*(5747)^0 \rightarrow B^{*+}\pi^-$, $B_2^*(5747)^0 \rightarrow B^{*+}\pi^-$, and $B_1(5721)^0 \rightarrow B^{*+}\pi^-$ decays are estimated from an unbinned maximum-likelihood fit to the $B^{+}\pi^-$ invariant mass distribution in data.

Figure 3 (left) presents the measured invariant mass distribution of the selected $B^+K^-$ candidates with the fit results overlaid. The combinatorial background is modelled with a smooth function, while the three signals, corresponding to the decays $B_2^*(5840)^0 \rightarrow B^{*+}K^-$, $B_2(5840)^0 \rightarrow B^{*+}K^-$, and $B_1(5830)^0 \rightarrow B^{*+}K^-$, are described with the relativistic Breit-Wigner (RBW) functions convolved with the resolution (found from the simulation). The results of the fit are used in the relative branching fraction measurements, as well as in the determination of the mass differences, as described below.
Figure 2. Shapes of the $B^+K^-$ invariant mass distributions reconstructed from the simulated decays [7]: (top left) $B_2^*(5747)^0 \rightarrow B^+\pi^-$, (top right) $B_2^*(5747)^0 \rightarrow B^+\pi^-$, (bottom) $B_2^*(5747)^0 \rightarrow B^+\pi^-$. Red lines show the results of the fits.

Figure 3. The $B^+K^-$ (a) and $B^0K^0_S$ (b) invariant mass distributions observed in data [2].

4. Study of the $B^0K^0_S$ invariant mass distribution
Figure 3 (right) shows the invariant mass distribution of the selected $B^0K^0_S$ 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: $B'_2(5840)^0 \rightarrow B^0K^0_S$, $B'_2(5840)^0 \rightarrow B^{*0}K^0_S$, and $B_3(5830)^0 \rightarrow B^{*0}K^0_S$. The charged pion and kaon may be swapped in the $B^0 \rightarrow J/\psi K^+\pi^-$ reconstruction, which leads to narrow peaks at the same $m_{B^0K^0_S}$ 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 the signal decays with swapped kaon and pion in the \(B^0\) reconstruction are included in \(m_{B^0K^0}\) fit model. The results of this fit are used in the calculation of the branching fraction ratios and in the measurements of the mass differences, as described below.

5. Measured quantities and corresponding systematic uncertainties

The signal yields extracted from the fits to the \(B^0K^0\) and \(B^0K^0\) invariant mass distributions are used to determine the relative branching fractions \(R_{2}^{0\pm}, R_{1}^{0\pm}, R_{2\pm}, R_{2\pm}, R_{\sigma}, R_{0\sigma}\), defined as:

\[
R_{2}^{0\pm} = \frac{B(B_{s2}^+ \rightarrow B^0 K^0)}{B(B_{s2}^+ \rightarrow B^+ K^-)} , \quad R_{1}^{0\pm} = \frac{B(B_{s1} \rightarrow B^0 K^0)}{B(B_{s1} \rightarrow B^+ K^-)} , \quad R_{2\pm} = \frac{B(B_{s2}^+ \rightarrow B^+ K^-)}{B(B_{s2}^+ \rightarrow B+ K^-)} ,
\]

\[
R_{2\pm} = \frac{B(B_{s2}^+ \rightarrow B^0 K^0)}{B(B_{s2}^+ \rightarrow B^+ K^-)} , \quad R_{\sigma} = \frac{\sigma(pp \rightarrow B_{s1}X) \times B(B_{s1} \rightarrow B^+ K^-)}{\sigma(pp \rightarrow B_{s2}^+X) \times B(B_{s2}^+ \rightarrow B+ K^-)} , \quad \text{and}
\]

\[
R_{0\sigma} = \frac{\sigma(pp \rightarrow B_{s1}X) \times B(B_{s1} \rightarrow B^0 K^0)}{\sigma(pp \rightarrow B_{s2}^+X) \times B(B_{s2}^+ \rightarrow B^0 K^0)}. \quad \text{and}
\]

These ratios are calculated as the ratios of the corresponding signal yields observed in data corrected for the ratio of total efficiencies and, in case of \(R_{0\pm}\) and \(R_{1}\), for the branching fractions of the intermediate decays involved \((B(B^+ \rightarrow J/\psi K^+), B(B^0 \rightarrow J/\psi K^0), B(K^0 \rightarrow K^+-\pi^-), \text{and } B(K^0_S \rightarrow \pi^+\pi^-)).\) For example,

\[
R_{2}^{0\pm} = \frac{B(B_{s2}^+ \rightarrow B^0 K^0)}{B(B_{s2}^+ \rightarrow B^+ K^-)} = \frac{N(B_{s2}^+ \rightarrow B^0 K^0)}{N(B_{s2}^+ \rightarrow B^+ K^-)} \times \frac{\epsilon(B_{s2}^+ \rightarrow B^+ K^-)}{\epsilon(B_{s2}^+ \rightarrow B^0 K^0)} \times \frac{B(B^+ \rightarrow J/\psi K^+)}{B(B^0 \rightarrow J/\psi K^0)B(K^0 \rightarrow K^+-\pi^-)B(K^0_S \rightarrow \pi^+\pi^-)}. \quad \text{and}
\]

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

\[
M(B^0) - M(B^+) = \Delta M_{B_{s2}}^\pm - \Delta M_{B_{s2}}^0 + M(K^-) - M(K_S^0) \quad \text{and}
\]

\[
M(B^0) - M(B^{*+}) = \Delta M_{B_{s1}}^\pm - \Delta M_{B_{s1}}^0 - M(K^-) - M(K_S^0),
\]

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

\[
\Delta M_{B_{s2}}^\pm = M(B_{s2}^+ - m_{PDG}^B - m_{PDG}^{K^-}) , \quad \Delta M_{B_{s2}}^0 = M(B_{s2}^0 - m_{PDG}^B - m_{PDG}^{K^-}) ,
\]

\[
\Delta M_{B_{s1}}^\pm = M(B_{s1}^+ - m_{PDG}^B - m_{PDG}^{K^+}) , \quad \Delta M_{B_{s1}}^0 = M(B_{s1}^0 - m_{PDG}^B - m_{PDG}^{K^+}).
\]

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

- The choice of the fit model;
- The track reconstruction efficiency;
- The invariant mass resolution uncertainty;
- The uncertainty in the fraction of events where kaon and pion are swapped in the \(B^0 \rightarrow J/\psi K^+\pi^-\) decay reconstruction;
The fraction of non-$K^*(892)^0$ contribution in the selected $B^0 \rightarrow J/\psi K^+ \pi^-$ 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 the measured natural width $\Gamma_{B_s^0(5840)^0}$.

6. Results
The measured branching fraction ratios are

\[
R_{2s}^{0\pm} = \frac{B(B_s^0 \rightarrow B^{0K_S^0}_{s2})}{B(B_s^0 \rightarrow B^+K^-)} = 0.432 \pm 0.077 \text{ (stat)} \pm 0.075 \text{ (syst)} \pm 0.021 \text{ (PDG)},
\]

\[
R_{1s}^0 = \frac{B(B_s^0 \rightarrow B^{0K_S^0}_{s1})}{B(B_s^0 \rightarrow B^{+K^-})} = 0.492 \pm 0.122 \text{ (stat)} \pm 0.068 \text{ (syst)} \pm 0.024 \text{ (PDG)},
\]

\[
R_{2s}^+ = \frac{B(B_s^0 \rightarrow B^{+K^-})}{B(B_s^0 \rightarrow B^+K^-)} = 0.081 \pm 0.021 \text{ (stat)} \pm 0.015 \text{ (syst)},
\]

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

\[
\begin{align*}
\Delta M_{B_s^0}^{\pm} &= M(B_s^0) - m_{B^{*+}}^{\text{PDG}} - m_{K^-}^{\text{PDG}} = 66.870 \pm 0.093 \text{ (stat)} \pm 0.073 \text{ (syst)} \text{ MeV}, \\
\Delta M_{B_s^0}^{\pm} &= M(B_s^0) - m_{B^{*0}}^{\text{PDG}} - m_{K^-}^{\text{PDG}} = 10.452 \pm 0.089 \text{ (stat)} \pm 0.063 \text{ (syst)} \text{ MeV}, \\
\Delta M_{B_s^0}^{0} &= M(B_s^0) - m_{B^{*0}}^{\text{PDG}} - m_{K^0_S}^{\text{PDG}} = 62.37 \pm 0.48 \text{ (stat)} \pm 0.07 \text{ (syst)} \text{ MeV}, \\
\Delta M_{B_s^0}^{0} &= M(B_s^0) - m_{B^{*0}}^{\text{PDG}} - m_{K^0_S}^{\text{PDG}} = 5.61 \pm 0.23 \text{ (stat)} \pm 0.06 \text{ (syst)} \text{ MeV},
\end{align*}
\]

where the second, fourth, and sixth mass differences are measured for the first time. The first two of these values are used together with the known masses of B and K mesons to obtain the $B_{s1,2}^{(*)}$ masses:

\[
\begin{align*}
M(B_s^0) &= 5839.857 \pm 0.093 \text{ (stat)} \pm 0.073 \text{ (syst)} \pm 0.151 \text{ (PDG)} \text{ MeV}, \\
M(B_s^0) &= 5828.779 \pm 0.089 \text{ (stat)} \pm 0.063 \text{ (syst)} \pm 0.275 \text{ (PDG)} \text{ MeV},
\end{align*}
\]

where the last uncertainties are from the uncertainties in the world-average masses and mass differences. The $B_s^0(5840)^0$ natural width is determined to be

\[
\Gamma_{B_s^0(5840)^0} = 1.52 \pm 0.34 \text{ (stat)} \pm 0.30 \text{ (syst)} \text{ MeV}.
\]
7. Summary
In summary, the excited states of the $B^0_s$ meson are studied in the $B^+K^-$ and $B^0K^0_S$ decay channels 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 $B^*_s(5840)^0 \rightarrow B^0K^0_S$ decay is observed for the first time and the evidence for the $B_{s1}(5830)^0 \rightarrow B^{*0}K^0_S$ decay is found. The measured properties of $B^{(s)}_s$ mesons include masses, mass differences with respect to the sum of $B$ meson and kaon mass, branching fraction ratios, and the $B^*_s(5840)^0$ natural width. We also report the first measurement of $M(B^{*0}) - M(B^{*+})$.

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