b hadron production, spectroscopy and properties at CMS

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Abstract. Precise measurements of production and properties of hadrons containing a b quark, performed using data collected by the CMS experiment at the LHC, are reported. These are important to investigate underlying mechanisms in QCD describing heavy quarks. The dependencies on transverse momentum and rapidity are investigated. Comparisons with theory expectations and among different collision energies are provided.

1. Introduction
Since the start of the LHC, the CMS experiment has been producing interesting results in what is nowadays considered “low energy” physics. Taking into account that this area of research was not specifically among the CMS design goals, the number of new measurements is surprising. In this report we focus on the study of production, spectroscopy and properties of b-flavoured hadrons and on the recent results from CMS in this field as of Summer 2018.

The central feature of the CMS apparatus 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, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A detailed description of the CMS detector can be found in Ref. [1]. The events are collected using a two-level trigger system. Precisely the flexibility of the trigger system makes the study of b-flavoured hadrons possible at CMS. In particular, most analyses in this field rely on the double-muon trigger, which is able to identify the J/ψ originating from the decay of b hadrons with high purity and efficiency. In the following more details about a selection of recent analyses is presented.

2. Spectroscopy: P-wave B_s mesons and search for X(5568)
The spectroscopy of the B_s system is still poorly known. P-wave B_s mesons can exist in 4 different J^P states, from the possible couplings of the spin of the light quark with the total orbital angular momentum. The four states are known as B_s^*, B_s^+1, B_s^0 and B_s^*2 and collectively as B_s^{**}. The first two are believed to be broad resonances, while the second two are narrow
resonances because, by J and P conservation, they can decay to lower states only by the emission of a D-wave pion. In Ref. [2] CMS reports the first observation of the decays \( B^+_s \rightarrow B^0 K^0_s \) and the first evidence of \( B_{s1} \rightarrow B^{0*} K^0_S \). The \( B^0 \) is reconstructed via its \( J/\psi K^+ \pi^- \) decay, with the decay products required to originate from a vertex which is displaced with respect to the primary interaction vertex, and the \( K_s \) is reconstructed in the \( \pi^+ \pi^- \) final state. Figure 1 shows the \( B^0 K^0_S \) invariant mass spectrum. The \( B_{s1} \) and \( B_{s2}^0 \) peaks are clearly visible, with a statistical significance of 3.9\( \sigma \) and 6.3\( \sigma \) respectively. Several ratios of branching fractions, \( B(B_{s2}^0 \rightarrow B^0 K^0_S)/B(B_{s2}^0 \rightarrow B^+ K^-) \) and alike, are measured quantitatively together with several mass differences (e.g. \( m(B_{s2}^0) - m(B^0) - m(K^0_S) \)). The precision of these measurements is on par with the ones reported by the LHCb and CDF experiments, and almost all compatible. The agreement with theoretical predictions is good.

In Ref. [3] the CMS experiment reports on the search for the \( X(5568) \) exotic state, which was observed by the D0 collaboration in the \( B^0 \rightarrow J/\psi K^* \rightarrow J/\psi K^0_S \) channel but is so far unconfirmed [4]. The \( B_{s}^0 \) is reconstructed using the \( J/\psi(1020) \) decay using data acquired at 8 TeV. Figure 2 shows the \( B_{s}^0 \pi \) invariant mass spectrum published by CMS, in which no evidence of a resonant state appears. An upper limit to the fraction of \( B_{s}^0 \) originating from the decay of the supposed \( X(5568) \) of 1.0\% at 95\% CL is reported, while \( D^0 \) supports a value greater than 5\%.

![Figure 1. \( B^0 K^0_S \) invariant mass, showing the \( B_{s1} \) and \( B_{s2}^0 \) peaks [2].](image1)

![Figure 2. \( B_{s}^0 \pi \) invariant mass. No \( X(5568) \) peak is detected [3].](image2)

### 3. Lifetime measurements

In Ref. [5] the CMS collaboration describes the measurement of the lifetime of \( B^0 \), \( B_{s}^0 \), \( \Lambda_b^0 \), and \( B_{s}^+ \) hadrons using the decay channels \( B^0 \rightarrow J/\psi K^*(892)^0 \), \( B^0 \rightarrow J/\psi K^0_S^\pm \), \( B_{s}^0 \rightarrow J/\psi \pi^+ \pi^- \), \( B_{s}^0 \rightarrow J/\psi(1020) \), \( \Lambda_b^0 \rightarrow J/\psi \Lambda \), and \( B_{s}^+ \rightarrow J/\psi \pi^+ \). The data sample was acquired at 8 TeV. The measurements are based on the reconstruction of the transverse decay length \( L_{xy} \), where \( L_{xy} \) is defined as the flight distance vector from the primary vertex to the decay vertex of the b hadron, projected onto the transverse component \( \vec{p}_T \) (perpendicular to the beam axis) of the b hadron momentum. The b hadrons are reconstructed from decays containing a \( J/\psi \) meson. The lifetime extraction analysis technique consists in applying a 3D maximum likelihood fit to the data using invariant mass, proper decay length and proper decay length uncertainty as dimensions. An example of fit is shown in Fig. 3. The \( B^0 \) lifetime is measured to be \( 453.0 \pm 1.6 \) (stat.) \( \pm 1.8 \) (syst.) \( \mu \) in \( J/\psi K^*(892)^0 \) and \( 457.8 \pm 2.7 \) (stat.) \( \pm 2.8 \) (syst.) \( \mu \) in \( J/\psi K^0_S \), which results in a combined measurement of \( c \tau_{B^0} = 454.1 \pm 1.4 \) (stat.) \( \pm 1.7 \) (syst.) \( \mu \). The effective lifetime of the \( B_{s}^0 \) meson is measured in two decay modes, with contributions from different amounts of the heavy and light eigenstates. This results in two different measured lifetimes: \( c \tau_{B_{s}^0 \rightarrow J/\psi \pi^+ \pi^-} = \)
502.7 ± 10.2 (stat) ± 3.4 (syst) µm and $c\tau_{B_s^+ \to J/\psi \phi(1020)} = 443.9 ± 2.0$ (stat) ± 1.5 (syst) µm. The $\Lambda_b^0$ lifetime is found to be 442.9 ± 8.2 (stat) ± 2.8 (syst) µm. The precision from each of these channels is as good as or better than previous measurements. The $B^+_c$ lifetime, measured with respect to the $B^+$ to reduce the systematic uncertainty, is 162.3 ± 7.8 (stat) ± 4.2 (syst) ± 0.1 (τ_{B^+}) µm.

Figure 3. The lifetime of the $B_s^0$ is measured in two different channels, using a 3D fit to the invariant mass (right), proper decay length (right) and proper decay length uncertainty [5].

4. Production
Notable recent CMS results on production of b hadrons have been published both in pp, pPb and PbPb collisions. The measurement of $B_c$ and $B^+$ production cross sections at 7 TeV and $B^+$ cross section at 13 TeV in pp collisions are presented in Ref. [7] and [8] respectively. The $B^+$ production cross sections in PbPb collisions at 5.02 TeV is presented in Ref. [9] and reports the first direct reconstruction of B mesons in heavy ion collisions. Figure 4 shows the $B_s^0$ peak detected in PbPb collisions. The $B^+$ yield is significantly suppressed in PbPb collisions compared to pp collisions. An interesting result is presented in Ref. [6], where the $B_s^0$ suppression in PbPb with respect to pp is measured to be of smaller magnitude with respect to the suppression of $B^+$. Figure 5 shows the nuclear modification factor $R_{AA}$ for the $B_s^0$ and the $B^0$, providing convincing hints of the fact that the $B_s^0$ is less suppressed than the $B^0$. This is in fact an effect which was theoretically predicted and ascribed to the strangeness enhancement and quark recombination mechanisms. The $B^+$, $B^0$ and $B_s^0$ production cross sections in pPb collisions at 5.02 TeV are presented in Ref. [10].
5. $Λ_b$ polarization
The study of the $Λ_b → J/ψΛ$ decay can provide deep insight about the effect of strong interactions in hadronic decays. Perturbative quantum chromodynamics can be applied and the effect of the polarization of the $b$ quark can be calculated using several techniques. The decay can be parameterized in terms of four parameters, the most interesting of which are $P$, the $Λ_b$ polarization, and $α_{Λ_b}$, the parity-violating decay asymmetry. Acceptance and efficiency are evaluated using simulation. Exploiting about 6000 $Λ_b$ candidates acquired at $\sqrt{s} = 7$ TeV and 8 TeV, CMS reports, in Ref. [11], a $Λ_b$ polarization compatible with zero ($0.00 ± 0.06$ (stat) ± 0.06 (syst)), as the asymmetry parameter ($0.14 ± 0.14$ (stat) ± 0.10 (syst)). These results are in line with LHCb results and theoretical predictions.

6. Conclusions
CMS is a multi-purpose experiment which was not expressly designed for B physics. With this consideration in mind, the quantity and quality of results published in this field, often competing with the world best, is quite impressive. At BEACH 2018 CMS results concerning spectroscopy, properties and production of $b$ hadrons were presented. This contribution only listed a few of them, whereas the topics of quarkonium studies, rare decays of $b$ hadrons, rare decays of $H$ and $Z$ bosons to quarkonia and dilepton exclusive production were beautifully explained by other CMS speakers.

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References
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