Heavy Flavor Physics at ATLAS and CMS

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Abstract. In this talk I report recent results on heavy flavor physics from ATLAS and CMS. It includes two topics: spectroscopy of open or hidden beauty hadrons and studies of rare B decays of the type $b \rightarrow s \mu^+\mu^-$. The former one is aimed to collect new information on the properties of beauty hadrons which helps to gain better understanding of QCD. And the latter one provides a good opportunity of searching for New Physics, the effects beyond the Standard Model. The discussed results were obtained with the Run 1 data ($\sqrt{s} = 8$ TeV) or Run 2 data ($\sqrt{s} = 13$ TeV).

1. Introduction
The ATLAS [1] and CMS [2] experiments at LHC are designed mainly for high-$p_t$ physics (studies of the Higgs boson, precision measurements of the Standard Model processes and parameters and numerous searches for New Physics including Dark Matter particles and SUSY particles). Nevertheless, both experiments are contributing intensively in heavy flavor physics. This is possible due to several universal features of these experiments. First of all, the redundant muon system with large rapidity coverage provides high-purity muon-ID with standalone $\delta p_t/p_t = 10\%$. Secondly, this is a very efficient hardware Level 1 trigger and highly flexible High Level Trigger with paths dedicated to $b$-hadron specific decays with muons in the final state. Then it is good $p_t$ resolution in tracker with high efficiency (> 99% in CMS) and good secondary vertex reconstruction with the impact parameter resolution down to $\approx 15 \mu m$.

In this article I will discuss the results on $b$-hadrons recently obtained by ATLAS and CMS from the analyses of the Run 1 data as well as Run 2 data. These results fall into two topics: heavy flavor spectroscopy and search for New Physics in rare B meson decays.

2. New results on the spectroscopy of beauty hadrons
2.1. Search for exotic $X(5568)^+ \rightarrow B_s^0\pi^+$ in ATLAS and CMS
15 years ago the Belle Collaboration discovered the first exotic charmonium-like state, the X(3872), decaying into $J/\psi\pi^+\pi^-$. During all following 15 years, many charmonium-like states were observed including charged states. There are several theoretical interpretations of these states. Among them one can mention hadrocharmonium, tetraquarks and molecular states. No one is sufficient for describing all properties of all observed states. So we need in more information about already observed states. And of course observation of new states will widen our understanding of dynamics of quarks in different configurations. It also helps to test various QCD inspired phenomenological models.

Fortunately, new information about the exotic hadrons in beauty sector is coming: in 2016 the D0 Collaboration announced the evidence of a new structure, $X(5568)$, decaying into $B_s^0\pi^+$ [3].
If confirmed, this state would be unique with 4 different flavors: $b\bar{s}ud\bar{d}$. For $p_t(B_{s}^{0}) > 10$, the measured value of the ratio of production cross-sections times $B(X(5568) \rightarrow B_{s}^{0}\pi^{+})$, $\rho_{X} = \frac{\sigma(\bar{p}p\rightarrow X+\text{anything}) \times B(X(5568) \rightarrow B_{s}^{0}\pi^{+})}{\sigma(\bar{p}p\rightarrow B_{s}^{0}\pi^{+})}$, was measured to be $(8.6 \pm 1.9 \pm 1.4)\%$ resulting in an active further research. Shortly after the first announcement about $X(5568)$, the LHCb Collaboration published the results of a search for this state for different intervals on $p_t(B_{s}^{0})$, > 5, > 10 and > 15 GeV/c. No evidence for the signal was found and upper limits on the $\rho_{X}$ value were set for $p_t(B_{s}^{0}) > 10$ $\rho_{X} < 2.1\% @ 90\% \text{ CL}$ [4]. Of course, analogous search for the $X(5568)$ in ATLAS and CMS was very actual because of different $\eta$ interval with LHCb. Also, B-hadron production conditions are similar in D0 and ATLAS and CMS. In 2018 both experiments published their results: no signals were found and stringent upper limits on the $\rho_{X}$ value for different Mass($B_{s}^{0}\pi^{+}$) in the interval [5.550-5.700] GeV in ATLAS and [5.500-5.900] GeV in CMS for two $p_t(B_{s}^{0})$ intervals, > 10 and > 15 GeV, were set. Particularly, at the mass 5568 GeV the Upper Limits @ 90\% CL on $\rho_{X}$ for $p_t(B_{s}^{0}) > 10$ were obtained to be < 1.5\% and < 1.1\% in ATLAS [5] and CMS [6], respectively. These limits much lower than the $\rho_{X}$ reported by the D0 Collaboration. So, LHC experiments have found no evidence for the $X(5568)$ production in pp collisions at $\sqrt{s} = 7,8$ TeV.

2.2. Study of $B_{s1}(5830)^{0}$ and $B_{s2}^{*}(5840)$ decaying into $B^{+}K^{-}$ and $B^{0}K_{s}^{0}$ in CMS

In 2018 the CMS Collaboration published results from a study of excited $B_{s}^{0}$ states, the $B_{s2}^{*}(5840)^{0}$ and $B_{s1}(5830)^{0}$, using 19.6 fb$^{-1}$ of pp data at $\sqrt{s} = 8$ TeV. Previously these states were observed by the CDF [7] and D0 [8] Collaborations and confirmed by the LHCb Collaboration [9] in the charged decay mode $B^{+}K^{-}$. In the present work CMS confirmed all previous measurements and observed new decay mode $B_{s2}^{*}(5840)^{0} \rightarrow B_{s}^{0}K_{s}^{0}$ and obtain evidence for the analogous neutral mode for the $B_{s1}(5830)^{0}$ state (see figure 1). Various mass and mass difference measurements along with the ratios of production cross-sections times branching fractions were measured[10]. As a by-product of this analysis, the first measurement of the mass difference between spin excited B-meson states was obtained: $M(B^{*0}) - M(B^{*+}) = (0.91 \pm 0.24 \pm 0.09 \pm 0.02(PDG))$ MeV.

Figure 1. Invariant mass distributions of $B^{0}K_{s}^{0}$ candidates with the results of the fit overlaid [10]. The points represent the data, the thick solid curves are the results of the overall fits, and the thin solid lines display the signal contributions. The short-dashed lines show the combinatorial background contributions. The long-dashed lines show the contributions from swapping $K^{\pm} \rightarrow \pi^{\pm}$ in the reconstruction of the $B^{0}$ mesons.

2.3. Study of $X(3872)$ Production Properties in ATLAS

In 2017 the ATLAS Collaboration published the study of $\psi(2S)$ and $X(3872)$ production properties, both prompt and non-prompt, and the corresponding $X(3872)/\psi(2S)$ cross-
sections times branching fractions ratios were measured [11]. Such a study is aimed to compare existing theoretical predictions concerning the $X(3872)$ and $\psi(2S)$ production properties with experimental observations. These studies could shed light on the nature of $X(3872)$.

By using the data collected in pp collisions at $\sqrt{s} = 8$ TeV, ATLAS reconstructed in several $p_t$ bins, from 10 to 70 GeV, the $X(3872)$ and $\psi(2S)\!\!\!\rightarrow J/\psi\pi^+\pi^-$. Then in each $p_t$ bin the data were further subdivided in bins on pseudo-proper decay time. It was done to disentangle prompt and non-prompt contributions.

As a result, the differential prompt production cross-sections for $\psi(2S)$ and $X(3872)$ were measured to be consistent with the prediction from NLO NRQCD. This model considers the $X(3872)$ to be a mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{*0}$ molecular state, with the production being dominated by the $\chi_{c1}(2P)$ component. For the non-prompt case the data also in an agreement with theoretical predictions of FONLL in case of $\psi(2S)$. But for the $X(3872)$ case, the FONLL prediction of non-prompt production overestimates data by a factor from 4 to 8.

Then, at low $p_t$ it was observed that the effective decay time of non-prompt $X(3872)$ is somewhat shorter than that in all other $p_t$ bins (see figure 2). It suggests possible different mechanism of $X(3872)$ production at low $p_t$. Therefore, the pseudo-proper decay time distribution was considered as a sum of two distinctive contributions with two different effective lifetimes, long-lived and short-lived. The long-lived part of the non-prompt contribution originates from the mix of $B(s)$-mesons and $b$-baryons while short-lived part would be due to the contribution of $B_c$-mesons.

As a result, the fraction of non-prompt $X(3872)$ from short-lived sources, integrated over the $p_t$ range $p_t > 10$ GeV was obtained to be

$$\frac{\sigma(pp\rightarrow B_c)[B_c\rightarrow X(3872)]}{\sigma(pp\rightarrow non-prompt X(3872))} = (25 \pm 13(stat.) \pm 2(sys.) \pm 5(spin))\%.$$  

This ratio would mean that the production of $X(3872)$ in $B_c$ decays is enhanced compared to its production from other $b$-hadrons.

2.4. Observation of two Resolved States $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ in CMS

The bottomonium system plays very important role in our understanding of the dynamics of quarks inside the hadrons and permits to performed thorough tests of various theoretical models describing the potential between the $b$ and $\bar{b}$ quarks within the bottomonium system. The $\chi_{bJ}(3P)$ triplet attract a special attention since sits near the open beauty threshold. In charmonium system such a proximity of $\chi_{cJ}(2P)$ state to the $D^0\bar{D}^{*0}$ threshold leads to the existence of the famous $X(3872)$. The question about whether this state is just the ordinary
χ_c(2P) which mass is modified by the interaction with the D^0\overline{D}^{*0} threshold or it is a mixture of χ_c(2P) and D^0\overline{D}^{*0} molecular remains open. So, the study of the χ_b(3P) triplet could shed light on the existence or absence of the X_b state, possible beauty analogue of X(3872). Beside it, this study is aimed to test theoretical models describing the spin-orbit interaction term of the inter-quark potential within the bottomonium system.

In 2018, by using the data collected at \( \sqrt{s} = 13 \) TeV (from 2015 to 2017 years with the integrated luminosity of 80 fb\(^{-1} \)), the CMS Collaboration published the first observation of resolved χ_b1(3P) and χ_b2(3P) states along with the measurement of their masses and mass difference between them [12]. These measurements become possible due to the good mass resolution in χ_b1,2(3P) \( \rightarrow \Upsilon(3S)\gamma \) decay, where \( \Upsilon(3S) \rightarrow \mu^+\mu^- \) and photons are detected through the conversion into the e^+e^- pairs figure 3 shows the \( \Upsilon(3S)\gamma \) invariant mass distribution after the photon energy correction as well as the overlaid fit. The χ_b1,2(3P) masses were measured to be \( M_1 = 10513.42 \pm 0.41 \pm 0.18 \) MeV, \( M_2 = 10524.02 \pm 0.57 \pm 0.18 \) MeV. The mass difference was obtained to be \( \Delta M = 10.6 \pm 0.64 \pm 0.17 \) MeV. From 20 theoretical predictions for \( \Delta M \), 19 of them fall into the interval [8–18] MeV and only 1 gives for the \( \Delta M \) the value of −2 MeV. The negative sign, i.e. unnatural mass hierarchy, is due to the regarding by that model of the coupling with open-beauty threshold. The obtained experimental result favors the natural mass hierarchy when the J=2 state is heavier than the J=1 state.

![Figure 3. The invariant mass distribution of the χ_b(3P) \( \rightarrow \Upsilon(3S)\gamma \) candidates [12]. The vertical bars are the statistical uncertainties. The curves represent the fitted contributions of the two signal peaks, the background, and their sum.](image)

### 3. New Results on a Search for New Physics in Rare B Decays

The flavor changing neutral current (FCNC) decays \( b \rightarrow s l^+l^- \) are promising places for New Physics searches. In the Standard Model (SM) these decays proceed through suppressed penguin or box diagrams. Therefore, the measurements of FCNC decays are sensitive to the phenomena beyond the SM.

Recently, the LHCb Collaboration found a 3σ deviation from SM in the angular parameter \( P'_5 \). Therefore it is important to perform independent measurements of this parameter. And in 2018 both, ATLAS and CMS published the results of the angular analysis in the \( B^0 \rightarrow K^{*0}\mu^+\mu^- \) decay.

#### 3.1. Angular Analysis of \( B^0 \rightarrow K^{*0}\mu^+\mu^- \) in CMS and ATLAS

The LHCb and Belle measured the \( P'_5 \) angular parameter where a potential discrepancy with the Standard Model was found. With 20.5 fb\(^{-1} \) of Run 1 data collected at \( \sqrt{s} = 8 \) TeV CMS analyzed the \( B^0 \rightarrow K^{*0}\mu^+\mu^- \) decay and performed measurement of the \( P_1 \) and \( P'_5 \) parameters [13].
The \( q^2 \) (dimuon invariant mass squared) spectrum for the selected \( B^0 \to K^{*0} \mu^+ \mu^- \) candidates has been divided in 9 bins from 1 to 19 GeV^2. Then angular parameters \( P_1 \) and \( P'_5 \) are determined via fit of the distributions of events as a function of three angular variables, independently in each \( q^2 \) bin. The angular variables are the following: the decay angle of the dimuon system, \( \theta_l \), the decay angle of the \( K^{*0}, \theta_K \), and the angle between these two decay planes, \( \phi \). The projection of the fit result for the second \( q^2 \) bin, are shown in figure 4. The final results for \( P_1 \) and \( P'_5 \) are shown in figure 5 left and right, respectively, along with the SM predictions and the results from LHCb and Belle. The CMS results are consistent with the predictions based on the SM and qualitatively agree with other experiments.

By using 20.3 fb\(^{-1}\) of data collected at \( \sqrt{s} = 8 \) TeV the analogous analysis has been performed by the ATLAS Collaboration. An extended unbinned maximum-likelihood fit of the angular distribution of the \( B^0 \to K^{*0} \mu^+ \mu^- \) decay was performed and several angular parameters, including \( P_1 \) and \( P'_5 \), has been extracted in 6 bins of \( q^2 \) [14]. The results are within 3 \( \sigma \) of the range covered by the different theoretical predictions. Also, these results are compatible with the results of the LHCb, Belle and CMS Collaborations.

**Figure 4.** Invariant mass and angular distributions of \( K^+ \pi^- \mu^+ \mu^- \) events for \( 4.3 < q^2 < 6 \) GeV [13]. The projection of the results from the total fit, as well as for correctly tagged signal events, misstated signal events, and background events, are also shown. The vertical bars indicate the statistical uncertainties.

**Figure 5.** Left (Right): CMS measurements of the \( P_1 \) (\( P'_5 \)) angular parameter versus \( q^2 \) for \( B^0 \to K^{*0} \mu^+ \mu^- \) decays [13], in comparison to results from the LHCb and Belle Collaborations. The statistical uncertainties are shown by the inner vertical bars, while the outer vertical bars give the total uncertainties. The horizontal bars show the bin widths. The vertical shaded regions correspond to the \( J/\psi \) and \( \psi' \) resonances. The hatched region shows the predictions from two SM calculations described in the text, averaged over each \( q^2 \) bin.

3.2. **Angular Analysis of \( B^+ \to K^+ \mu^+ \mu^- \) in CMS**

The angular distribution for the decay \( B^+ \to K^+ \mu^+ \mu^- \) can be described as a function of the \( q^2 \) (see above) and the decay angle of the dimuon system, \( \theta_l \). The \( \theta_l \) dependence of the decay rate
can be expressed in terms of the $A_{FB}$ and $F_H$ angular parameters. ($A_{FB}$ is the forward-backward asymmetry of the dimuon system and $F_H$ is the contribution from the pseudoscalar, scalar, and tensor amplitudes to the decay width.) In the SM, $A_{FB}$ is zero up to small corrections, and $F_H$ is also small. Because SM amplitudes may interfere with the contributions from BSM particles in loop diagrams, this decay can probe the presence of yet-unobserved particles and processes.

By using 20.5 fb$^{-1}$ of data in pp collisions at $\sqrt{s} = 8$ TeV, CMS performed the measurements of $A_{FB}$ and $F_H$ as a function of the $q^2$ based on an angular fit of the decay $B^+ \rightarrow K^+ \mu^+ \mu^-$. The $q^2$ spectrum has been divided in 9 bins from 1 to 22 GeV. The $A_{FB}$ and $F_H$ angular parameters are obtained from two-dimensional unbinned extended maximum-likelihood fit to the $B^+$ candidate mass, $m$, and to the $\cos\theta_l$ distributions, in each $q^2$ bin. The measured values of the $A_{FB}$ and $F_H$ are shown in figure 6. For both parameters the results are consistent with the SM predictions. The results are also in agreement with the measurements from other experiments.

![Figure 6](image.png)

**Figure 6.** Left (Right): Results of the $A_{FB}$ ($F_H$) measurements in ranges of $q^2$ [15]. The statistical uncertainties are shown by the inner vertical bars, while the outer vertical bars give the total uncertainties. The horizontal bars show the $q^2$ range widths. The vertical shaded regions are 8.68-10.09 and 12.86-14.18 GeV, corresponding to the $J/\psi$- and $\psi(2S)$-dominated control regions, respectively. The horizontal lines in the right plot show the DHMV SM theoretical predictions, whose uncertainties are smaller than the line width.

### 4. Summary

Recently, ATLAS and CMS have performed a search for exotic $X(5568) \rightarrow B_s^0 \pi^+$ and obtained the null result. Together with the analogous result from LHCb, it implies that LHC experiments see no evidence for the production of such an exotic state.

CMS observed new decay mode of excited $B_s^0$ state, $B_{s2}^0(5840)^0 \rightarrow B^0 K_s^0$ and obtain evidence for $B_{s1}(5830)^0 \rightarrow B^0 K_s^0$.

ATLAS performed measurements of $\psi(2S)$ and $X(3872)$ production properties. From the study of non-prompt pseudo-proper decay time distributions in different $p_t$ bins, first hint on the enhanced branching fraction of $B_c^+ \rightarrow X(3872) + \text{anything}$ was obtained.

CMS observed for the first time two resolved states $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$, measured their masses and mass difference between these two states. The latter supports the standard mass hierarchy ($J=2$ state is heavier than the $J=1$ one).

As for the search for the New Physics in $B \rightarrow K(\ast) \mu^+ \mu^-$ decays, both ATLAS and CMS performed measurements of angular distributions in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays using 8 TeV data. It was found that the results are consistent with previous measurements and with the existing calculations within the framework of SM.
Although designed for high-$p_t$ physics, ATLAS and CMS are good experiments for heavy flavor physics.

References

[1] ATLAS Collaboration 2008 *JINST* 3 S08003
[2] CMS Collaboration 2008 *JINST* 3 S08004
[3] D0 Collaboration 2016 *Phys. Rev. Lett.* 117 022003
[4] LHCb Collaboration 2016 *Phys. Rev. Lett* 117 152003
[5] ATLAS Collaboration 2018 *Phys. Rev. Lett* 120 202007
[6] CMS Collaboration 2018 *Phys. Rev. Lett* 120 202005
[7] CDF Collaboration 2008 *Phys. Rev. Lett* 100 082001
[8] D0 Collaboration 2008 *Phys. Rev. Lett* 100 082002
[9] LHCb Collaboration 2013 *Phys. Rev. Lett* 110 151803
[10] CMS Collaboration 2018 *Eur. Phys. J. C* 78 939
[11] ATLAS Collaboration 2017 *JHEP* 01 117
[12] CMS Collaboration 2018 *Phys. Rev. Lett* 121 092002
[13] CMS Collaboration 2018 *Phys. Lett.* B 781 517
[14] ATLAS Collaboration 2018 *JHEP* 10 047
[15] CMS Collaboration 2018 *Preprint* arXiv:1806.00636