Latest results on B_c^+ at ATLAS and CMS

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Summary. — The present report summarizes recent results on the B_c^+ meson at the CMS and ATLAS experiments at the LHC: aspects such as the B_c^+ production, its decay mechanisms, and the observation of excited states are investigated.

Introduction

The B_c^+ production is a unique probe for heavy flavour physics as it requires the collinear production of two heavy quarks of different flavour, namely a beauty and a charm quark. At the Large Hadron Collider (LHC) the B_c^+ production is accessible via gluon-gluon fusion process, which is proportional to α_S^4 (α_S, strong coupling constant).

Recent results from the CMS [1] and ATLAS [2] experiments on the B_c^+ production in both the proton-proton (pp) and lead-lead (PbPb) collisions are presented.

The B_c^+ decays are interesting as they can proceed through three different mechanisms: b-quark decay, c-quark decay, and annihilation. Improved precision on branching fraction measurements allows a better understanding of heavy quark interactions.

The increasing amount of data produced at the LHC results in a large sample of collected B_c^+ mesons: this allows as well to study the spectroscopy of excited B_c^+ states decaying to the ground state B_c^+.

1. – B_c^+ production in pp collisions at ATLAS

The ATLAS Collaboration performed the measurement of the B_c^+ differential production cross section relative to the B^+ using data at a centre-of-mass energy $\sqrt{s} = 8$ TeV by reconstructing the decay[1] $B_c^\pm \to J/\psi\pi^\pm$ and its analogous $B^\pm \to J/\psi K^\pm$ [3].

The measurement is provided in bins of transverse momentum $p_T(B)$ and rapidity $y(B)$ of the beauty meson:

- $13 < p_T(B) < 22$ GeV and $p_T(B) > 22$ GeV

[1] The inclusion of charge-conjugate decay modes is implied throughout the paper.

- $|y(B)| < 0.75$ and $0.75 < |y(B)| < 2.3$

The B_c^+ and B^+ signal yields are extracted independently by means of an Unbinned Maximum Likelihood (UML) fit on the final state invariant mass, either in the whole detector fiducial region or in a specific bin.

The total production cross section ratio is

$$\frac{\sigma(B_c^+)\cdot\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)} = (0.34\pm 0.04_{stat}\ {}^{+0.06}_{-0.02}\ {}_{syst} \pm 0.01_{lifetime})\% \tag{1}$$

where the last term comes from the effect on the selection efficiency of the B_c^+ lifetime (its world average lifetime is known with an uncertainty of 2%, while for the B^+ it is 4 times smaller).

A decreasing dependence on $p_T(B)$ is observed for the first time, while no significant trend is observed in rapidity (fig. 1). The result can be compared with previous measurements from CMS [4] and LHCb [5, 6] with slightly overlapping fiducial regions: while the CMS result is reasonably compatible with the ATLAS result, at LHCb a larger cross section is measured. Nevertheless the more forward fiducial region of LHCb must be taken into account, as it leads to a sample populated by softer B_c^+ mesons.

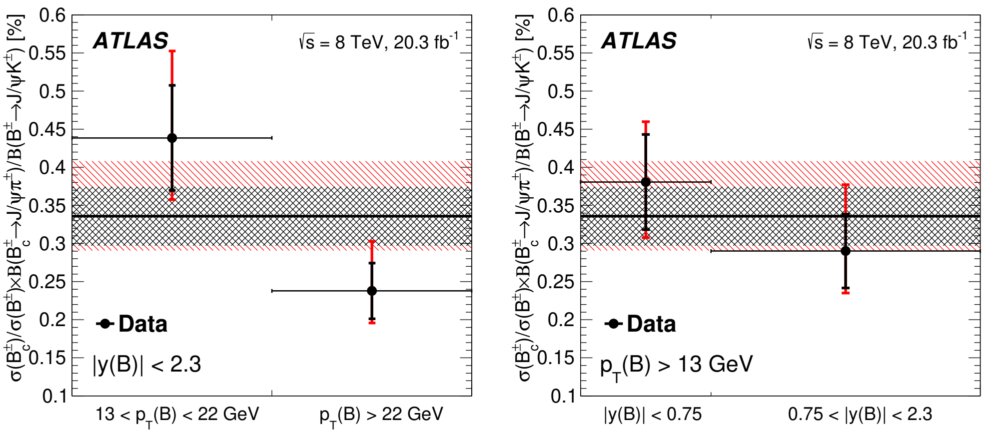

Fig. 1. – Black points in the left (right) plot are the differential B_c^+ production cross section relative to B^+ in transverse momentum $p_T(B)$ (rapidity $y(B)$) bins measured by ATLAS [3]. The black (red) error bars are statistical (systematic) uncertainties. The shaded area represents the result in the entire fiducial region. A dependence on p_T is observed for the first time, while no significant dependence is observed on rapidity.

2. – B_c^+ production in PbPb collisions at CMS

The CMS Collaboration recently observed the B_c^+ meson in PbPb collisions for the first time [7]. In this analysis, the B_c^+ is partially reconstructed in the $B_c^+ \to J/\psi(\to \mu^+\mu^-)\mu^+\nu_\mu$ decay in both pp and PbPb collisions. The measurement uses 1.61 nb^{-1} of PbPb collisions data at a centre-of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV per nucleon pair, and 302 pb^{-1} of pp collisions at a centre-of-mass energy $\sqrt{s} = 13$ TeV.

A Boosted Decision Tree is trained to discriminate the signal from the different background sources: *i.e.* fake J/ψ, contributions from other beauty hadrons, and J/ψ + an uncorrelated third particle.

The signal yields are extracted using a 1D UML fit and converted into production cross sections. The B_c^+ meson is observed also in PbPb data, where it shows a smaller production cross section dependence on p_T, compared to the pp environment, suggesting a larger recombination effect.

The nuclear modification factor R_{AA}, which equals 1 when there is no medium-induced modification, is computed. The R_{AA} is found to be greater than 1 in the low p_T region with a significance of 1.2σ and also larger than the value in the high p_T bin with a significance of 1.8σ (fig. 2, left). No dependence on the centrality is observed instead (fig. 2, right).

Except for the B_s^0 meson, other heavy meson systems (*e.g.* charmonia, bottomonia, light hadrons) show greater suppression than B_c^+: further investigation of this aspect can shed light on the contribution of heavy-quark recombination in the B_c^+ production.

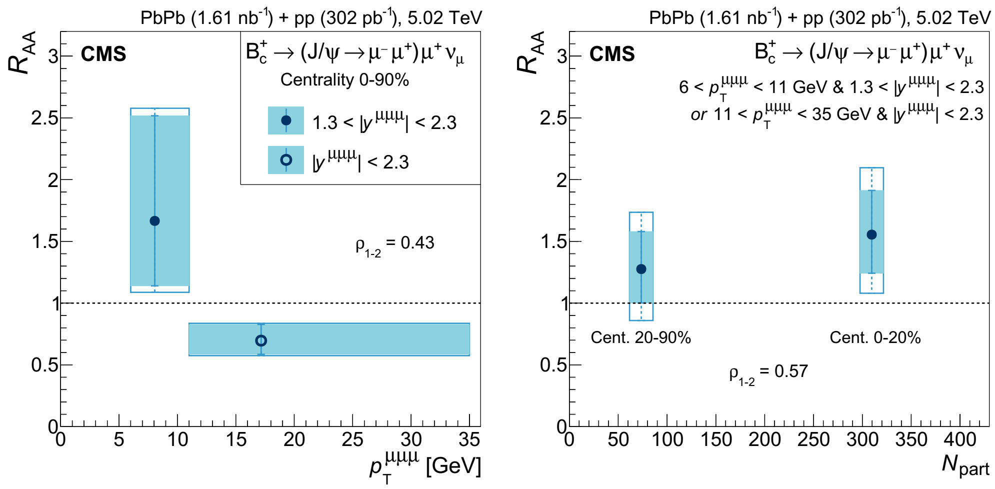

Fig. 2. – Black points in the left (right) plot are the nuclear modification factor R_{AA} in visible transverse momentum $p_T^{\mu\mu\mu}$ (centrality) bins measured by CMS [7]. The filled (empty) rectangles show the bin-to-bin-uncorrelated (total) uncertainties. The larger uncertainty in the low-p_T bin is induced by the effect of the different B_c^+ kinematics in PbPb and pp on the efficiency corrections.

3. – $B_c^+ \to J/\psi D_s^{(*)+}$ decays at ATLAS

The ATLAS Collaboration recently measured the branching fraction of the $B_c^+ \to J/\psi D_s^{(*)+}$ decays using 139 fb^{-1} of pp collisions data at a centre-of-mass energy $\sqrt{s} = 13$ TeV [8]. A pseudoscalar decaying into two vector states is described with three helicity amplitudes: two transverse (A_{++}, A_{--}) and one longitudinal A_{00} polarizations.

An angular analysis is performed in order to distinguish between the longitudinal polarization A_{00} and the total traverse polarization $A_{\pm\pm}$. The two decays are reconstructed in the same final state, due to the non-reconstructable soft photon(s) in the the

D_s^{*+} decay.

The well-established $B_c^+ \to J/\psi\pi^+$ decay is considered as normalization channel: a large sample of $N(B_c^+) = 8440^{+550}_{-470}$ candidates is reconstructed in the considered fiducial region ($p_T(B_c^+) > 15$ GeV, $|\eta(B_c^+)| < 2.0$).

The yields for the two decay modes are extracted simultaneously with a 2D UML fit in the $J/\psi D_s^+$ invariant mass and the muon helicity angle.

The signal yields enter the branching fraction ratios after being corrected by an overall efficiency, that is determined with Monte Carlo studies. The results, summarized in fig. 3, are in agreement with those previously obtained by LHCb [9] and ATLAS [10] using the Run 1 (2012 - 2015) data sample, but with improved precision. The ratio $R_{D_s^{*+}/\pi^+}$ is in good agreement with theoretical predictions, while other ratios show consistent deviation from predicted values. The fraction of transverse polarization relative to the total is compatible with a naive 2/3 spin counting.

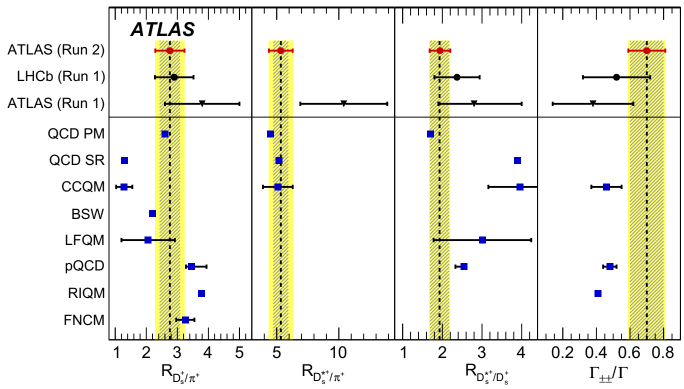

Fig. 3. – Comparison between ATLAS new results [8] and previous LHCb [9] and ATLAS [10] results using the Run 1 data sample. The new ATLAS measurement improves the available precision on the branching fraction ratios. Different theoretical predictions show good agreement with the ratio $R_{D_s^{*+}/\pi^+}$, while predictions for the other ratios consistently deviate from data.

4. – B_c^+ spectroscopy at CMS

The CMS Collaboration firstly reported the observation of two well resolved peaks in the $B_c^+\pi^+\pi^-$ invariant mass spectrum using 143 fb^{-1} of pp collisions data at a centre-of-mass energy $\sqrt{s} = 13$ TeV [11]: the two structures have been interpreted as the $B_c(2S)^+$ and $B_c^*(2S)^+$ excitations. This observation superseeded the previous measurement from the ATLAS experiment, where the two states were observed as a merged single peak [12].

The excited states both decay via di-pion transition. The $B_c^*(2S)^+$ reconstruction includes an unreconstructed soft photon (γ_{lost}) in its decay chain. The two decay chains are

1. $B_c^*(2S)^+ \to B_c^{*+}\pi^+\pi^-$, with $B_c^{*+} \to B_c^+\gamma_{lost}$;

2. $B_c(2S)^+ \to B_c^+\pi^+\pi^-$;

thus both states are reconstructed in the same $B_c^+\pi^+\pi^-$ final state, with the B_c^+ reconstructed in the $B_c^+ \to J/\psi(\to \mu^+\mu^-)\pi^+$ decay. Two peaks in the $B_c^+\pi^+\pi^-$ invariant mass are well resolved (fig. 4, left): as the lost photon is predicted to be of 55 MeV and the mass difference between the peaks is of 29 MeV, the lower mass peak is the higher mass state $B_c^*(2S)^+$.

CMS subsequently published a second paper with the measurement of the differential production cross sections for the two excitations [13]. The production cross section ratios are determined from the signal yields once they are corrected by relative efficiencies, derived from Monte Carlo studies. The production cross section ratios are also computed differentially in three B_c^+ transverse momentum and three B_c^+ rapidity bins: no significant dependence on these two variables is observed. The invariant mass of the di-pion system is also investigated for both $B_c(2S)^+$ and $B_c^*(2S)^+$ (fig. 4, right): the di-pion invariant mass distributions are compatible within the uncertainties and have shapes different from the rather flat distributions predicted from the phase space simulations.

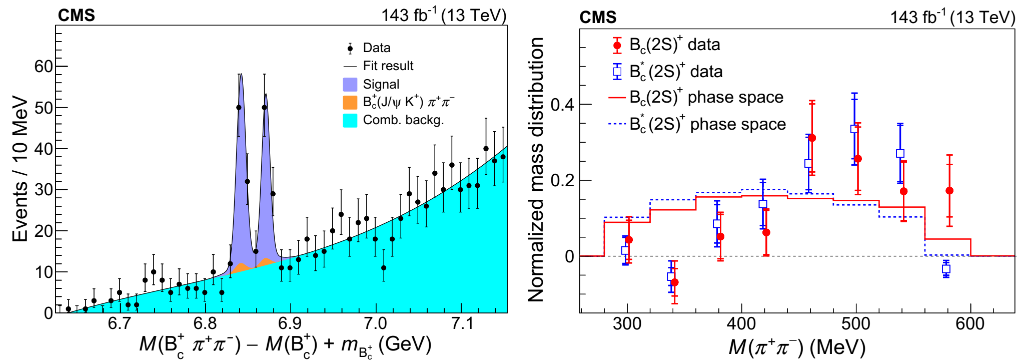

Fig. 4. – Left: Two peaks are well resolved in the $B_c^+\pi^+\pi^-$ invariant mass distribution with a mass resolution of 6 MeV and a mass distance of 29 MeV (from [13], superseeding [11]). The higher (lower) mass peak corresponds to the $B_c^{(*)}(2S)^+$ meson. Right: Invariant mass distribution with background substraction of the di-pion system for $B_c^{(*)}(2S)^+$.

REFERENCES

[1] CMS Collaboration, *JINST*, **3** (2008) S08004.
[2] ATLAS Collaboration, *JINST*, **3** (2008) S08003.
[3] ATLAS Collaboration, *Phys. Rev. D*, **104** (2021) 012010.
[4] CMS Collaboration, *Journal of High Energy Physics*, **2015** (2015) 63.
[5] LHCb Collaboration, *Phys. Rev. Lett.*, **109** (2012) 232001.
[6] LHCb Collaboration, *Phys. Rev. Lett.*, **114** (2015) 132001.
[7] CMS Collaboration, *Phys. Rev. Lett.*, **128** (2022) 252301.
[8] ATLAS Collaboration, *Journal of High Energy Physics*, **2022** (2022) 87.
[9] LHCb Collaboration, *Phys. Rev. D*, **128** (2013) 112012.
[10] ATLAS Collaboration, *Eur. Phys. J. C*, **76** (2016) 4.
[11] CMS Collaboration, *Phys. Rev. Lett.*, **122** (2019) 132001.
[12] ATLAS Collaboration, *Phys. Rev. Lett.*, **113** (2014) 212004.
[13] CMS Collaboration, *Phys. Rev. D*, **102** (2020) 092007.