Production asymmetries of $b$ and $c$ hadrons at LHCb

F Ferrari on behalf of the LHCb Collaboration

1Università di Bologna, Dipartimento di Fisica ed Astronomia, via Irnerio 46, (40126) Bologna, Italy
2INFN - Sezione di Bologna, viale B. Pichat 6/2, (40126) Bologna, Italy
E-mail: fabio.ferrari@cern.ch

Abstract. Using a data sample corresponding to an integrated luminosity of 1.0 fb$^{-1}$, collected by LHCb in $pp$ collisions at a centre-of-mass energy of 7 TeV, the $D^+_s$, $D^+$, $B^0$ and $B^0_s$ production asymmetries are determined. These quantities are measured by means of $D^+_s \to \phi(K^+K^-){\pi^+}$, $D^+_s \to K^0_S(\pi^+\pi^-){\pi^+}$, $B^0 \to J/\psi(\mu^+\mu^-)K^0(\pi^+\pi^-)$, $B^0 \to D^-(K^+\pi^-\pi^-){\pi^+}$ and $B^0_s \to D^-S(K^+K^-\pi^-){\pi^+}$ decays. Moreover, using the full LHCb Run 1 integrated luminosity, corresponding to 1.0 fb$^{-1}$ at 7 TeV and 2.0 fb$^{-1}$ at 8 TeV, the production and decay asymmetry of the $\Lambda^0_b$ baryon, $A_{P+D}(\Lambda^0_b)$, is determined by means of $\Lambda^0_b \to J/\psi(\mu^+\mu^-)pK^-$ decays. All asymmetries are measured as a function of $p_T$ and $y$ (or $\eta$ in the $D^+$, $B^0$ and $B^0_s$ cases) of the involved hadrons, in order to check if there is a dependence on kinematics.

1. Introduction

The production rates of $b(c)$- and $\bar{b}(\bar{c})$-hadrons in $pp$ collisions at the LHC are not expected to be identical. This phenomenon, commonly referred to as production asymmetry, is related to the fact that the $\bar{b}(\bar{c})$ quark produced in the hard scattering of the two colliding protons could coalesce with a $u$ or $d$ spectator quark in the proton remnants, whereas the opposite is not possible for a $b(c)$ quark. Some theoretical models also predict an enhancement of this effect in the forward region, where the produced $b\bar{b}(c\bar{c})$ pair is closer to the remnants of the colliding protons; finally, there are also predictions of other effects coming into play at high transverse momentum [1],[2],[3].

The determination of production asymmetries is very important, since in $CP$ violation measurements one needs to disentangle the physical asymmetry from other spurious effects, that could resemble the effect of $CP$ violation. The production asymmetries of $D^+_s$, $D^+$, $B^0$ and $B^0_s$ mesons are defined as

$$A_P(B^0_{(s)}) = \frac{\sigma(B^0_{(s)}) - \sigma(B^0_{(s)})}{\sigma(B^0_{(s)}) + \sigma(B^0_{(s)})}, \quad A_P(D^+_{(s)}) = \frac{\sigma(D^+_{(s)}) - \sigma(D^-_{(s)})}{\sigma(D^+_{(s)}) + \sigma(D^-_{(s)})},$$

where $\sigma$ stands for the production cross section.

The production and decay asymmetry for the $\Lambda^0_b \rightarrow J/\psi pK^-$ mode can be written as

$$A_{P+D}(\Lambda^0_b) = \frac{\sigma(\Lambda^0_b) - \sigma(\bar{\Lambda}^0_b)}{\sigma(\Lambda^0_b) + \sigma(\bar{\Lambda}^0_b)} + A_{CP}(\Lambda^0_b \rightarrow J/\psi pK^-)$$
Figure 1. Production asymmetry of $D_s^+$ mesons as a function of (a) rapidity and (b) transverse momentum for (red circles) magnet up and (blue squares) magnet down data. The results obtained for both magnet polarities are compatible. No significant trend is observed within the current experimental precision.

where the first term on the right hand side is the analogue of the terms in Equation (1) and the second term is the $CP$ asymmetry in the decay. If one assumes that $CP$ violation in the $\Lambda_b^0 \to J/\psi p K^-$ decay is zero, then $A_{P+D}(\Lambda_b^0) = A_P(\Lambda_b^0)$.

2. $D_s^+$ production asymmetry

The $D_s^+$ production asymmetry [4] can be written as the sum of its various contributions

$$A_P(D_s^+) = A_{RAW}(D_s^+ \to \phi \pi^+) - A_{CP}(D_s^+ \to \phi \pi^+) - A_D(\pi^+) + A_D(K^+ K^-),$$

where $A_{RAW}(D_s^+ \to \phi \pi^+)$ is defined as the difference between $D_s^+$ and $D_s^-$ signal yields divided by their sum. The $CP$ asymmetry in the decay is neglected, as this mode is Cabibbo favoured and no significant $CP$ violation is expected [5],[6]. As the final state is symmetric with respect to charges of the kaons, the detection asymmetry of the kaon pair, $A_D(K^+ K^-)$, is zero. Hence the only correction that needs to be applied is due to the $\pi^\pm$ detection asymmetry. This latter quantity can be derived by taking the ratio of the pion detection efficiencies $\varepsilon(\pi^+)/\varepsilon(\pi^-)$.

In order to measure the pion efficiencies, the decay sequence $D_s^*+ \to \pi^+ s D_0(K^- \pi^+ \pi^+ \pi^-)$ is employed. Assuming that the $D_s^{*+}$ comes from the primary vertex, there are enough constraints to allow for the detection of this decay even if one pion from the $D_s^0$ decay is missed. One can also fully reconstruct this decay, if no charged track is missed. The ratio of fully to partially reconstructed $D_s^0$ decays gives a measurement of the pion detection efficiency.

The signal yield is obtained performing binned maximum likelihood fits to the invariant mass spectrum. The signal model employed is composed of triple Gaussians where all parameters are free to vary, except that two of the three Gaussians that are required to have a common mean. The background is parameterised by means of a second order polynomial.

The overall production asymmetry in the ranges $2.0 < y < 4.5$ and $p_T > 2$ GeV is

$$A_P(D_s^+) = (−0.33 \pm 0.22 \pm 0.10)\%$$

where the first error is statistical and the second systematic. The production asymmetry as a function of $y$ and $p_T$ of the $D_s^+$ meson is shown in Figure 1. No significant dependence on these variables is observed within the current experimental uncertainties.
Figure 2. Production asymmetry of $D^+$ mesons as a function of (a) transverse momentum and (b) pseudorapidity. Although non-zero slopes are found as central values, the uncertainties are still too large to draw any conclusion on the presence of a kinematic dependence.

3. $D^+$ production asymmetry

The $D^+$ production asymmetry [7] can be obtained by

$$A_P(D^+) = A_{\text{RAW}}(D^+ \rightarrow K^0_S \pi^+) - A_{\text{CP}}(D^+ \rightarrow K^0_S \pi^+) + A_D(\pi^+) + A_\epsilon,$$  \hspace{1cm} (4)

where the raw asymmetry is defined taking the difference of $D^+$ and $D^-$ signal yields divided by their sum. The number of signal candidates is obtained by means of binned maximum likelihood fits to the $K^0_S \pi^+$ invariant mass distribution. The signal component is parameterised using Crujiff functions [8], while the background is described by a linear function plus a Gaussian function accounting for $D^+ \rightarrow K^0_S \pi^+ \pi^0$ decays, where the neutral pion is not reconstructed.

$CP$ violation in the decay, $A_{\text{CP}}(D^+ \rightarrow K^0_S \pi^+)$, is estimated to be at most $1 \times 10^{-4}$ [9] and thus neglected. The pion detection asymmetry, $A_D(\pi^+)$, is corrected for using the results obtained in the $D^+$ production asymmetry measurement.

The asymmetry due to $CP$ violation in the neutral kaon system, $A_\epsilon$, depends on the decay time acceptance for $K^0_S$ mesons. This quantity is obtained by fitting the $K^0_S$ decay time distribution with an empirical function. The value obtained for the asymmetry is $A_\epsilon = (2.831^{+0.003}_{-0.004}) \times 10^{-4}$, where the quoted uncertainty is statistical only.

The $D^+$ production asymmetry is obtained in the kinematic range $2.0 < p_T < 18.0$ GeV and $2.20 < \eta < 4.75$, excluding the region with $2.0 < p_T < 3.2$ GeV and $2.20 < \eta < 2.80$, and is found to be

$$A_P(D^+) = (-0.96 \pm 0.26 \pm 0.18)\%.$$

The production asymmetry as a function of $D^+$ meson $p_T$ and $\eta$ is shown in Figure 2. No dependence is observed within the current experimental uncertainties.

4. $B^0$ and $B^0_s$ production asymmetries

The $B^0$ and $B^0_s$ production asymmetries [10] are obtained by means of two dimensional maximum likelihood invariant mass and decay time fits to the relevant distributions.

The signal mass component is parameterised by two Gaussians with the same mean and different widths. The partially reconstructed contributions are described by shapes obtained from a kernel estimation technique [11] based on invariant mass distributions obtained from fully simulated events. The combinatorial component is fitted using an exponential function.

As for the decay time, the signal is parameterized by a theoretical function describing the time dependent decay rate of a $B^0_{(s)}(\overline{B}^0_{(s)})$ to a flavour specific final state $f \bar{f}$ convolved with a
The production asymmetries as a function of the $b$-mesons $p_T$ and $\eta$ are shown in Figure 3. The $B^0$ and $B^0_s$ production asymmetries, integrated in the ranges $4 < p_T < 30$ GeV/$c$ and $2.5 < \eta < 4.5$, are found to be

$$A_P(B^0) = (-0.35 \pm 0.76 \pm 0.28)\%$$
$$A_P(B^0_s) = (1.09 \pm 2.61 \pm 0.66)\%$$

where the first uncertainties are statistical, and the second uncertainties are systematic. No evidence of production asymmetry is found within the current precision.

5. $\Lambda^0_b$ production asymmetry

The $\Lambda^0_b$ production and decay asymmetry [12] can be obtained as the sum of various terms

$$A_{P+D}(\Lambda^0_b) = A_{RAW}(\Lambda^0_b \to J/\psi pK^-) + A_{PID}(\Lambda^0_b \to J/\psi pK^-) + A_D(p) + A_D(K),$$

where $A_{RAW}(\Lambda^0_b \to J/\psi pK^-)$ is the raw asymmetry defined as the difference between $\Lambda^0_b$ and $\bar{\Lambda}^0_b$ signal yields divided by their sum, $A_{PID}(\Lambda^0_b \to J/\psi pK^-)$ is the asymmetry between the particle identification asymmetries of $\Lambda^0_b$ and $\bar{\Lambda}^0_b$, and $A_D(p)(A_D(K))$ is the proton (kaon) detection asymmetry.

The signal yields are obtained from unbinned extended maximum likelihood fits to the invariant mass distributions of $\Lambda^0_b$ and $\bar{\Lambda}^0_b$. The signal component is parameterised using an
Figure 4. Production and decay asymmetry as a function of (left) transverse momentum and (right) rapidity of the b-hadrons.

double sided Crystal Ball function, that is composed by a Gaussian shape with power-law tails. The combinatorial background is modelled using an exponential function, while the contribution from $\Lambda^0_b \to J/\psi K^+\bar{p}$ decays is taken into account using the same shape as for the signal.

The particle identification correction is calculated using samples of data with tracks from the decays $J/\psi \to \mu^+\mu^-$, $D^{*+} \to D^0(K^-\pi^+)\pi^+$ and $\Lambda^+_c \to pK^-\pi^+$, which can be identified without requiring any particle identification cut on the daughters.

The kaon detection asymmetry is obtained from a previous LHCb publication [13], while the proton detection asymmetry is estimated from simulated events.

The quantity $A_{P+D}$ as a function of $p_T$ and $y$ is shown in Figure 4. The $p_T$ result is consistent with a null slope, whereas the combined result for $A_{P+D}(y)$ gives

$$A_{P+D}(y) = (-0.001 \pm 0.007) + (0.058 \pm 0.014)(y - \langle y \rangle),$$

where $\langle y \rangle = 3.1$ is the average rapidity of the $\Lambda^0_b$ in the sample. The quoted error is the combination of the statistical and systematic contributions to the uncertainty.

6. Conclusion

Thanks to the unprecedented amount of $b$- and $c$-hadrons produced in the LHC $pp$ collisions, LHCb is in an excellent position to perform high-precision CP violation measurements. One key ingredient to perform such measurements is the determination of the $b$- and $c$-hadron production asymmetries. These proceedings summarise the present status at LHCb for $D^+_s$, $D^+_c$, $B^0$, $B^0_s$ and $\Lambda^0_b$ hadrons. LHCb will continue to produce results in this sector as more data are being collected.

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