Λ_{c}^{+}/Λ_{c}^{-} and Λ_{b}^{0}/Λ[over \text{ bar}_{b}^{0}] production asymmetry at the LHC from heavy quark recombination

W. K. Lai and A. K. Leibovich

Phys. Rev. D 91, 054022 — Published 18 March 2015

DOI: 10.1103/PhysRevD.91.054022
Λ⁺/Λ⁻ and Λ₀/Λ₀ production asymmetry at the LHC from heavy quark recombination

W. K. Lai* and A. K. Leibovich†

1Pittsburgh Particle Physics Astrophysics and Cosmology Center (PITT PACC)
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA

(Dated: February 24, 2015)

Abstract

The asymmetries in the forward region production cross section of Λ⁺/Λ⁻ and Λ₀/Λ₀ are predicted using the heavy quark recombination mechanism for pp collisions at 7 TeV and 14 TeV. Using non-perturbative parameters determined from various previous experiments, we find that $A_p(\Lambda_c^+/\Lambda_c^-) \sim 1-2\%$ in the region $2 < y < 5$ and $2 \text{ GeV} < p_T < 20 \text{ GeV}$ and $A_p(\Lambda_b^0/\bar{\Lambda}_b^0) \sim 1-3\%$ in the region $2 < y < 5$ and $5 \text{ GeV} < p_T < 20 \text{ GeV}$. The differential distributions of $A_p$ are significant at the high-rapidity and low-$p_T$ ends ($\sim 2-15\%$). Sensitivity of the integrated $A_p$ on the upper rapidity cut and lower $p_T$ cut is discussed.

* Electronic address: wal16@pitt.edu
† Electronic address: akl2@pitt.edu
Asymmetries in productions of heavy hadrons and antihadrons could provide clues to CP violation and physics beyond the standard model. At the LHC, since the initial state \( pp \) has a positive baryon number, it is not obvious that productions of heavy hadrons and antihadrons are symmetric even within QCD. In fact, the CERN Intersecting Storage Rings observed an asymmetry in the number of \( \Lambda_c^+ \) versus \( \Lambda_c^- \) \([1, 2]\), where production of \( \Lambda_c^+ \) was favored over \( \Lambda_c^- \) in proton-proton collisions. On the other hand, the lowest-twist QCD cross sections predict equal numbers of charm and anticharm baryons. More recently, the CMS detector has measured a small asymmetry in \( \Lambda_0^b \) and \( \Lambda_0^b \) productions \([3]\). There have been many models trying to explain this phenomenology, for instance \([4–9]\). However, the CMS data have relatively large error bars: \( \sigma(\Lambda_0^b)/\sigma(\Lambda_0^b) = 1.02 \pm 0.07 \pm 0.09 \). Data with more statistics at CMS, ATLAS, and LHCb are eagerly awaited. In this paper, we make predictions for the rapidity and transverse momentum distributions of the asymmetries of heavy baryon productions using the heavy quark recombination mechanism \([10–13]\) in the forward region. The LHCb experiment should see an asymmetry in both \( \Lambda_c^+ / \Lambda_c^- \) and \( \Lambda_0^b / \Lambda_0^b \) productions.

A similar asymmetry can be seen in the meson system. The asymmetry in \( D^{\pm} \) production has been observed in the forward region at LHCb \([14]\), and can be explained using the heavy quark recombination mechanism \([15]\). The heavy quark recombination mechanism also successfully explained production asymmetries of \( D^{\pm} \) and \( \Lambda_c^{\pm} \) in fixed-target experiments \([11–13, 16]\). Therefore, the prediction on production asymmetries of \( \Lambda_c^+ / \Lambda_c^- \) and \( \Lambda_0^b / \Lambda_0^b \) using the heavy quark recombination mechanism should give a sensible estimate for the contribution to the asymmetries from the standard model.

The production asymmetry \( A_p \) of a \( \Lambda_Q \ (udQ) \) baryon is defined by

\[
A_p = \frac{d\sigma(\Lambda_Q) - d\sigma(\bar{\Lambda}_Q)}{d\sigma(\Lambda_Q) + d\sigma(\bar{\Lambda}_Q)},
\]

where \( Q \) is either \( c \) or \( b \). Factorization theorems of perturbative QCD \([17]\) state that heavy hadron production cross section can be written in a factorized form. At the LHC, the cross section for producing a \( \Lambda_Q \) baryon in a \( pp \) collision, at leading order in a \( 1/p_T \) expansion, is given by

\[
d\sigma[pp \to \Lambda_Q + X] = \sum_{i,j} f_{i/p} \otimes f_{j/p} \otimes d\hat{\sigma}[ij \to Q + X] \otimes D_{Q \to \Lambda_Q},
\]

where \( f_{i/p} \) is the parton distribution function for parton \( i \) in the proton, \( d\hat{\sigma}(ij \to Q + X) \) is the partonic cross section and \( D_{Q \to \Lambda_Q} \) is the fragmentation function describing hadronization.
of a heavy quark $Q$ into a $\Lambda_Q$ baryon. The corresponding equation for $\bar{\Lambda}_Q$ is obtained by replacing $Q$ by $\bar{Q}$ and $\Lambda_Q$ by $\bar{\Lambda}_Q$. From charge conjugation symmetry and the fact that $f_{Q/p} = f_{\bar{Q}/p}$, we see that perturbative QCD Eq. (2) predicts that $A_p = 0$, up to corrections suppressed by $1/p_T$.

It should be noted that there are corrections to Eq. (2) that scale as powers of $\Lambda_{\text{QCD}}/m_Q$ and $\Lambda_{\text{QCD}}/p_T$. One should expect non-vanishing power-suppressed contributions to $A_p$ at low $p_T$. A QCD-based model for these power corrections is the heavy quark recombination mechanism [10–13]. In this scenario, a light quark and a heavy quark coming out from the hard scattering process combine to form the final state baryon. This process is of order $\Lambda_{\text{QCD}} m_Q/p_T^2$ relative to Eq. (2). In what follows, after a brief review of the heavy quark recombination mechanism, we calculate $A_p$ due to heavy quark recombination for $\Lambda^+_c/\Lambda^-_c$ and $\Lambda^0_b/\bar{\Lambda}^0_b$ productions at the LHC.

Figure 1 (a) and (b) show a diagram for the recombination process with initial state $qg$ and $Qq$ respectively. Their contributions to the cross section are given by

\begin{align}
(a) \quad & d\hat{\sigma}[\Lambda_Q] = d\hat{\sigma}[qg \rightarrow (Qq)^n + \bar{Q}]\eta[(Qq)^n \rightarrow \Lambda_Q], \\
(b) \quad & d\hat{\sigma}[\Lambda_Q] = d\hat{\sigma}[Qq \rightarrow (Qq)^n + g]\eta[(Qq)^n \rightarrow \Lambda_Q],
\end{align}

where $q$ is a light valence quark of $\Lambda_Q$. $(Qq)^n$ indicates that the light quark of flavor $q$ with momentum of order $\Lambda_{\text{QCD}}$ in the $Q$ rest frame is produced in the state $n$, where $n$ labels the color and angular momentum quantum numbers of the quark pair. The cross section is factored into a perturbatively calculable piece $d\hat{\sigma}$ and a nonperturbative factor $\eta[(Qq)^n \rightarrow \Lambda_Q]$ encoding the probability for the quark pair with quantum number $n$ to hadronize into a final state including a $\Lambda_Q$. $\eta[(Qq)^n \rightarrow \Lambda_Q]$ can be expressed as a matrix element of a HQET operator [18]. Equations (3) and (4) must then be convoluted with the proton parton distribution functions to get the final hadronic cross section.

The perturbative piece for process (a), was calculated to lowest order in [13]. Following the method in [13], we calculate the partonic cross sections for process (b), $Qq \rightarrow (Qq)^n + g$ (Fig. 1 (b)):

\begin{equation}
\frac{d\sigma}{dt}[Qq \rightarrow (Qq)^n + g] = -\frac{2\pi^2 \alpha_s^3 m_Q^2}{27 S^2 T} G(n|S, T), \tag{5}
\end{equation}

\footnote{For a full review, please see Refs. [10–13, 18].}
FIG. 1: Diagrams for production of a Λ_Q baryon by the heavy-quark recombination mechanism for (a) qg → (Qq)n + Q and (b) Qq → (Qq)n + g. Each process has five diagrams. Single lines represent light quarks, double lines heavy quarks, and the shaded blob the Λ_Q baryon.

\[
G^{(1)S_0^{(3)}}|S, T) = -\frac{16S}{T} \left(1 - \frac{T U}{S^2}\right) - \frac{m_Q^2}{U} \left(3 + \frac{28S}{U} + \frac{16S^2}{U^2} - \frac{16U^2}{S^2}\right) + \frac{4m_Q^4 T}{SU^2} \left(3 + \frac{4U}{S} + \frac{8S}{U}\right),
\]

\[
G^{(3)S_1^{(3)}}|S, T) = 3G^{(1)S_0^{(3)}}|S, T) - 32 \left(\frac{U}{S} - \frac{S^2}{U^2}\right) - \frac{4m_Q^2}{U} \left(8 - \frac{6S}{U} - \frac{16S^2}{U^2} + \frac{13U}{S} + \frac{15U^2}{S^2}\right),
\]

\[
G^{(1)S_0^{(6)}}|S, T) = -\frac{4S}{T} \left(2 - \frac{5TU}{S^2}\right) - \frac{m_Q^2}{U} \left(27 + \frac{14S}{U} + \frac{8S^2}{U^2} - \frac{20U^2}{S^2}\right) + \frac{2m_Q^4 T}{SU^2} \left(9 + \frac{10U}{S} + \frac{8S}{U}\right),
\]

\[
G^{(3)S_1^{(6)}}|S, T) = 3G^{(1)S_0^{(6)}}|S, T) - \frac{8S}{T} \left(3 + \frac{5TU}{S^2} + \frac{5S}{U} + \frac{2S^2}{U^2}\right) + \frac{4m_Q^2 T}{SU^2} \left(27 - \frac{S}{U} - \frac{S^2}{U^2} - \frac{8S^3}{U^3}\right),
\]

(6)

where we have defined \( S = \hat{s} - m_Q^2 = (k + p)^2 - m_Q^2, T = \hat{t} = (k - p_Q)^2, \) and \( U = \hat{u} - m_Q^2 = (k - l)^2 - m_Q^2. \)

The heavy quark \( \bar{Q} \) in the final state of process (a) could fragment into a \( \bar{\Lambda}_Q \) baryon. Charge conjugation of this process gives the “opposite-side recombination”:

\[
(c) \quad d\tilde{\sigma}[\Lambda_Q] = \sum_n d\tilde{\sigma}[qg \to (Q\bar{q})^n + Q] \sum_{\pi_{meson}} \rho[(\bar{Q}q)^n \to \bar{H}_{meson}] \otimes D_{Q\to\bar{\Lambda}_Q},
\]

\[
(d) \quad d\tilde{\sigma}[\Lambda_Q] = \sum_n d\tilde{\sigma}[\bar{q}g \to (Q\bar{q})^n + Q] \sum_{\bar{H}_{baryon}} \eta[(\bar{Q}\bar{q})^n \to \bar{H}_{baryon}] \otimes D_{Q\to\bar{\Lambda}_Q}
\]

(7)

(8)

where \( H_{meson} \) and \( H_{baryon} \) are any heavy meson and heavy baryon respectively. We will assume charge conjugation symmetry and take \( \rho[(Q\bar{q})^n \to H_{meson}] = \rho[(\bar{Q}q)^n \to \bar{H}_{meson}] \) and \( \eta[(Qq)^n \to H_{baryon}] = \eta[(\bar{Q}\bar{q})^n \to \bar{H}_{baryon}] \). For simplicity, we will take \( H \) to be a
low-lying heavy hadron. Thus, for \( \Lambda_c \) production we will take \( H_{\text{meson}} \) to be either \( D \) or \( D^* \), and \( H_{\text{baryon}} \) be any baryon from the lowest mass \( J^p = \frac{1}{2}^+ \) and \( \frac{3}{2}^+ \) heavy baryon \( SU(3) \) flavor multiplets, and similarly for \( \Lambda_b \) production. We will also assume \( SU(3) \) flavor symmetry.

The leading nonperturbative parameters \( \rho[(c\bar{q})^n \rightarrow D] \) for \( D \) mesons are

\[
\begin{align*}
\rho_1 &= \rho[c\bar{q}^{(1)}S_0^{(1)} \rightarrow D], \\
\rho_8 &= \rho[c\bar{q}^{(1)}S_0^{(8)} \rightarrow D], \\
\tilde{\rho}_1 &= \rho[c\bar{q}^{(3)}S_1^{(1)} \rightarrow D], \\
\tilde{\rho}_8 &= \rho[c\bar{q}^{(3)}S_1^{(8)} \rightarrow D].
\end{align*}
\]

(9)

For \( D^* \) mesons, we can exploit heavy quark spin symmetry and get

\[
\begin{align*}
\rho[c\bar{q}^{(1)}S_0^{(c)} \rightarrow D] &= \rho[c\bar{q}^{(3)}S_1^{(c)} \rightarrow D^*], \\
\rho[c\bar{q}^{(3)}S_1^{(c)} \rightarrow D] &= \rho[c\bar{q}^{(1)}S_0^{(c)} \rightarrow D^*].
\end{align*}
\]

(10)

Similar relations are also true for \( B \) and \( B^* \). The leading nonperturbative parameters \( \eta[(Qq)^n \rightarrow \Lambda_Q] \) for \( \Lambda_Q \) baryons are

\[
\begin{align*}
\eta_3 &= \eta[Qq^{(1)}S_0^{(3)} \rightarrow \Lambda_Q], \\
\eta_6 &= \eta[Qq^{(1)}S_0^{(6)} \rightarrow \Lambda_Q], \\
\tilde{\eta}_3 &= \eta[Qq^{(3)}S_1^{(3)} \rightarrow \Lambda_Q], \\
\tilde{\eta}_6 &= \eta[Qq^{(3)}S_1^{(6)} \rightarrow \Lambda_Q].
\end{align*}
\]

(11)

All the \( \rho \)s and \( \eta \)s scale as \( \Lambda_{QCD}/m_Q \). Contributions of feeddown from heavier baryons in processes (a) and (b) can be taken into account by using the inclusive parameter \( \eta_{\text{inc}} \): \n
\[
\eta_{\text{inc}}[(Qq)^n \rightarrow \Lambda_Q] = \eta[(Qq)^n \rightarrow \Lambda_Q] + \sum_{H_{\text{baryon}} \neq \Lambda_Q} \eta[(Qq)^n \rightarrow H_{\text{baryon}}] B[H_{\text{baryon}} \rightarrow \Lambda_Q + X]
\]

(12)

Here again we assume \( H_{\text{baryon}} \) is a member of the lowest mass \( J^p = \frac{1}{2}^+ \) and \( \frac{3}{2}^+ \) heavy baryon \( SU(3) \) flavor multiplets. With our choice of possible \( H_{\text{baryon}} \) in the opposite-side recombination, by a simple quark counting and the fact that \( B[H_{\text{baryon}} \rightarrow \Lambda_Q + X] \approx 1 \) for \( H_{\text{baryon}} = \Sigma_Q \) or \( \Sigma_Q^* \), we have

\[
\sum_{\overline{H}_{\text{baryon}}} \eta[(\overline{Q}q')^n \rightarrow \overline{H}_{\text{baryon}}] \approx \frac{3}{2} \eta_{\text{inc}}[(Qq)^n \rightarrow \Lambda_Q],
\]

(13)

where \( q' = u, d, s \) and \( q = u, d \). From [15], a reasonable fit to \( D^\pm \) asymmetry at LHCb gives \( 0.055 < \rho_1 < 0.065, 0.65 < \rho_8 < 0.8, 0.24 < \tilde{\rho}_1 < 0.3 \) and \( 0.24 < \tilde{\rho}_8 < 0.3 \) for \( \rho[(c\bar{d})^n \rightarrow D^+] \).

Best single-parameter fit to \( \Lambda_c^{\pm} \) asymmetry in fixed target experiments gives \( \tilde{\eta}_{3,\text{inc}} = 0.058 \) for \( \Lambda_c [13] \). We will take \( \eta_{3,\text{inc}} = \eta_{6,\text{inc}} = \tilde{\eta}_{6,\text{inc}} = 0 \) and \( 0.052 < \tilde{\eta}_{3,\text{inc}} < 0.064 \) for \( \Lambda_c \). For
the $\eta$s for $\Lambda_b$ and $\rho$s for $B$, we simply multiply the $\Lambda_c$ and $D$ counterparts by the theoretical scaling factor $m_c/m_b$. We use MSTW 2008 LO central PDFs with $m_c = 1.275$ GeV and $m_b = 4.18$ GeV. The fragmentation function $D_{Q \to \Lambda_Q}$ is taken as

$$D_{Q \to \Lambda_Q}(z) = f_{\Lambda_Q} \delta(1 - z),$$

where $f_{\Lambda_Q}$ is the inclusive fragmentation probability. This form of fragmentation function was found to be better than the Peterson form when fitting to fixed target $\Lambda^+_c/\Lambda^-_c$ asymmetry data [13]. We take $f_{\Lambda^+_c} = 0.101$, which is the average of the values listed in [19]. $f_{\Lambda^-_c}$ is taken to be 0.09 from [20]. We use the LO cross section for the perturbative QCD rate Eq. (2). The factorization scale is set to be $\mu_f = \sqrt{p_T^2 + m_Q^2}$.

For $\Lambda^+_c/\Lambda^-_c$ production, the kinematic region is taken to be $2 < y < 5$ and $2$ GeV $< p_T < 20$ GeV. The integrated $A_p$ is found to be $2.0\% < A_p(\Lambda^+_c/\Lambda^-_c) < 2.4\%$ for $\sqrt{s} = 7$ TeV and $1.2\% < A_p(\Lambda^+_c/\Lambda^-_c) < 1.5\%$ for $\sqrt{s} = 14$ TeV. For $\Lambda^0_b/\bar{\Lambda}^0_b$ production, the kinematic region is taken to be $2 < y < 5$ and $5$ GeV $< p_T < 20$ GeV. The integrated $A_p$ is found to be $2.2\% < A_p(\Lambda^0_b/\bar{\Lambda}^0_b) < 2.6\%$ for $\sqrt{s} = 7$ TeV and $1.1\% < A_p(\Lambda^0_b/\bar{\Lambda}^0_b) < 1.4\%$ for $\sqrt{s} = 14$ TeV. Figures 2 and 3 show the rapidity and transverse momentum distributions of $A_p$ for $\Lambda^+_c/\Lambda^-_c$ and $\Lambda^0_b/\bar{\Lambda}^0_b$ respectively. The asymmetry is significant at the high-rapidity and low-$p_T$ ends ($\sim 2 - 15\%$). Because of this, the integrated $A_p$ is sensitive to the upper rapidity cut and lower $p_T$ cut. Figures 4 and 5 show the dependence of the integrated $A_p$ on the upper rapidity cut and lower $p_T$ cut for $\Lambda^+_c/\Lambda^-_c$ and $\Lambda^0_b/\bar{\Lambda}^0_b$ respectively. The kinematic regions are the same as in Figs. 2 and 3 except for the variations in the upper rapidity cut and lower $p_T$ cut. In order to give an idea of the size of the recombination cross section relative to the standard perturbative QCD cross section, the ratio of the two cross sections is plotted in Fig. 6 as a function of rapidity and transverse momentum respectively for $\Lambda^+_c$ and $\Lambda^-_c$ productions in 7 TeV $pp$ collisions.

It should also be noted that Eqs. (3), (4), (7) and (8) have corrections suppressed by powers of $\Lambda_{QCD}/p_T$ and $m_Q/p_T$, which we have neglected in our calculations. As a result, in principle our calculations should have large theoretical uncertainties for $p_T \sim m_Q$. However, as shown in [15], the heavy quark recombination works reasonably well at regions of $p_T$ as low as $p_T \sim 2$ GeV in explaining the $D^\pm$ asymmetries at LHCb. Therefore, it seems reasonable to include the $p_T \sim m_Q$ region in our calculations.

Shown in Fig. 7 are the CMS data [3], which are the rapidity and transverse momentum
distributions of $\sigma(\Lambda^0_b)/\sigma(\Lambda^0_b)$ for 7 TeV $pp$ collisions in the kinematic region $0 < y < 2$ and $10 \text{ GeV} < p_T < 50 \text{ GeV}$. The CMS data, despite of the large error bars, do have a slight trend of surplus of $\Lambda^0_b$ over $\bar{\Lambda}^0_b$ in the regions of high rapidity and low transverse momentum respectively. However, with the values of $\eta$s we used above, the asymmetry predicted from the heavy quark recombination mechanism is negligible in this kinematic region. To see the limit of the heavy quark recombination mechanism in explaining the data, in Fig. 7 we also plot the prediction with larger values of $\eta$s. Here all $\eta_{\text{inc}}$s are set equal to each other, with the range being $\Lambda_{\text{QCD}}/m_b \sim 0.2 < \eta_{\text{inc}} < 1$. The ranges of the $\rho$s are as those used in Fig. 3. Although the prediction shows a significant asymmetry $\sim 10\%$ at the high-rapidity and low-$p_T$ ends, it still fails to hit the bin with the largest rapidity. Fig. 8 shows the prediction in the forward region $2 < y < 5$ and $5 \text{ GeV} < p_T < 20 \text{ GeV}$ for 7 TeV $pp$ collisions with the ranges of $\eta$s and $\rho$s as in Fig. 7. The asymmetry is huge ($\sim 50\%$). We believe that our previous predictions with smaller $\eta_{\text{inc}}$s (Figs. 2-5) are more reasonable since those values of $\eta$s were obtained from better fit to fixed-target experiments. Moreover, the surplus of $\bar{\Lambda}^0_b$ over $\Lambda^0_b$ at $y \sim 1$ and $p_T > 20 \text{ GeV}$ in the CMS data cannot be explained by any existing model. We hope that data from LHCb in the future will settle the issue.

An appealing feature of the heavy quark recombination mechanism is that it has its basis in perturbative QCD and thus is model-independent [18]. However, it should be emphasized that the heavy quark recombination mechanism is not the only possible way to give rise to production asymmetries of heavy hadrons at the LHC. Other models for soft processes in QCD also give qualitatively similar asymmetries. While a quantitative analysis of the differences of these models is beyond the scope of this paper, we discuss the qualitative properties of a few of the models below.

The first example of another model is the valon model [4]. In this model, initial-state hadrons involved in soft scatterings are composed of valons, which are valence quarks dressed by gluons and quark-antiquark pairs. A heavy quark induced by fluctuations in a valon would combine with light quarks in the valons from the same initial-state hadron to form a heavy hadron. The valon distributions are non-perturbative and were obtained by fitting to data of soft hadronic scattering, so are the distributions of light valence and sea quarks inside a valon. Since a heavy quark-antiquark pair is a tightly bound system in a valon, it has a wide momentum spread. The probability to find a heavy quark in a valon is therefore assumed to be uniform in momentum fraction. The probability for a heavy quark and quarks to
FIG. 2: Asymmetry in $\Lambda_c^+/\Lambda_c^-$ production as a function of (a) rapidity $y$ and (b) transverse momentum $p_T$ in the kinematic region $2 < y < 5$ and $2 \text{ GeV} < p_T < 20 \text{ GeV}$ in 7 TeV (grey band) and 14 TeV (black band) $pp$ collisions.

FIG. 3: Asymmetry in $\Lambda_b^0/\bar{\Lambda}_b^0$ production as a function of (a) rapidity $y$ and (b) transverse momentum $p_T$ in the kinematic region $2 < y < 5$ and $5 \text{ GeV} < p_T < 20 \text{ GeV}$ in 7 TeV (grey band) and 14 TeV (black band) $pp$ collisions.
FIG. 4: Integrated asymmetry in $\Lambda_c^+ / \Lambda_c^-$ production as a function of (a) upper $y$ cut and (b) lower $p_T$ cut in the kinematic region $2 < y < 5$ and $2 \text{ GeV} < p_T < 20 \text{ GeV}$ in 7 TeV (grey band) and 14 TeV (black band) $pp$ collisions.

FIG. 5: Integrated asymmetry in $\Lambda_b^0 / \Lambda_b^0$ production as a function of (a) upper $y$ cut and (b) lower $p_T$ cut in the kinematic region $2 < y < 5$ and $5 \text{ GeV} < p_T < 20 \text{ GeV}$ in 7 TeV (grey band) and 14 TeV (black band) $pp$ collisions.
(a) 

FIG. 6: Distributions in (a) rapidity and (b) transverse momentum of ratio of recombination cross section to standard perturbative QCD cross section for $\Lambda_c^+$ and $\Lambda_c^-$ productions in 7 TeV $pp$ collisions. $\rho s$ and $\eta s$ are taken to be central values of those used in Fig. 2.

(b) 

FIG. 7: $\sigma(\Lambda_b^0)/\sigma(\Lambda_b^0)$ as a function of (a) rapidity $y$ and (b) transverse momentum $p_T$ in the kinematic region $0 < y < 2$ and $10 \text{ GeV} < p_T < 50 \text{ GeV}$ for 7 TeV $pp$ collisions. The data are from CMS [3]. The grey band is our prediction from the heavy quark recombination mechanism with all $\eta_{inc}$s set equal to each other, the range being $0.2 < \eta_{inc} < 1$. The ranges of $\rho s$ are as those used in Fig. 3.
FIG. 8: $\sigma(\Lambda_0^0)/\sigma(\Lambda^0)$ as a function of (a) rapidity $y$ and (b) transverse momentum $p_T$ in the kinematic region $2 < y < 5$ and $5 \text{ GeV} < p_T < 20 \text{ GeV}$ for 7 TeV pp collisions. The grey band is our prediction from the heavy quark recombination mechanism with all $\eta_{incs}$ set equal to each other, the range being $0.2 < \eta_{inc} < 1$. The ranges of $\rho$s are as those used in Fig. 3.

combine and form a heavy hadron has its dependence on momentum fractions determined by a counting rule. The model predicts a surplus of the produced $\Lambda$ over $\bar{\Lambda}$ in pp collisions since the light valence quarks of the $\Lambda$ or $\bar{\Lambda}$ come from the valons of the initial-state protons. This model has the nice feature of the absence of free parameters in the prediction of $A_p$. However, it makes no prediction on the $p_T$ distribution of the produced heavy hadron since the effect of a transverse kick is neglected [4].

The second model is the intrinsic heavy quark model [7]. In this model, an initial-state proton is in a superposition of fock states $|uud\ldots\rangle$, where “…” denotes an arbitrary number of quark-antiquark pairs and gluons. The heavy quark $Q$ in $|uudQ\bar{Q}\rangle$ can combine with the valence quarks $ud$ to form a $\Lambda Q$. The probability for fock state $|uudQ\bar{Q}\rangle$ with a given momentum fraction distribution among the quarks is assumed a simple form proportional to $\alpha_s^4(m_{Q\bar{Q}})$. The produced $\Lambda Q$ has momentum fraction given simply by the sum of those of the $u$, $d$ and $Q$ forming it. The idea is therefore very similar to that of the valon model. Formally, this model gives an asymmetry suppressed by an extra power of $\alpha_s$ relative to that predicted by the heavy quark recombination mechanism.

The third model is the string-drag model [9], in which a heavy quark produced by parton
fusion is dragged toward the spectator quarks by color strings connecting them. The surplus of the produced $\Lambda$ over $\bar{\Lambda}$ is due to the surplus of spectator valence quarks over the sea quarks. The dragging effect is non-perturbative and can only be taken into account by Monte Carlo simulations.

Comparison of predictions on the asymmetry from the heavy quark recombination mechanism and these three models will be an interesting work to follow up. Qualitatively all the models are similar since in order to have any asymmetry, some type of interaction that distinguishes the initial state is necessary. The interaction is with a spectator quark or the proton remnant, giving rise to the possibility of a hadron-antihadron asymmetry. Given the fact that we are dealing with hadronic initial and final states, there will always be some nonperturbative input into any calculation. Of note, however, is that the heavy quark recombination model only has standard PDFs in the initial state. The other models mentioned above must include additional nonperturbative inputs for the initial state.

In summary, we have used the heavy quark recombination mechanism to calculate the production asymmetries for $\Lambda_c^+ / \Lambda_c^-$ and $\Lambda_b^0 / \bar{\Lambda}_b^0$ at the LHCb experiment. The heavy quark recombination mechanism is a correction of order $\Lambda_{QCD} m_Q / p_T^2$ to the leading order QCD prediction. Therefore, we expect large effects at small $p_T$ and/or large rapidity. Our calculation confirms this expectation, where the differential distributions are significant at the high-rapidity and low-$p_T$ ends ($\sim 2 - 15\%$). The integrated asymmetries in the LHCb region are of the order of $\sim 1 - 3\%$ and should be measurable.

Acknowledgements

AKL and WKL are supported in part by the National Science Foundation under Grant No. PHY-1212635.