Λ_{c}^{+}/Λ_{c}^{-} and Λ_{b}^{0}/Λ[over ¯]_{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_c^+/Λ_c^- and $\Lambda_b^0/\overline{\Lambda}_b^0$ production asymmetry at the LHC from heavy quark recombination

W. K. Lai*[1] and A. K. Leibovich†[1]

[1]*Pittsburgh 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_c^+/Λ_c^- and $\Lambda_b^0/\overline{\Lambda}_b^0$ 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 GeV $< p_T <$ 20 GeV and $A_p(\Lambda_b^0/\overline{\Lambda}_b^0) \sim 1-3\%$ in the region $2 < y < 5$ and 5 GeV $< p_T <$ 20 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 Λ_c^+ versus Λ_c^- [1, 2], where production of Λ_c^+ was favored over Λ_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 Λ_b^0 and $\overline{\Lambda}_b^0$ 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: $\sigma(\overline{\Lambda}_b^0)/\sigma(\Lambda_b^0) = 1.02 \pm 0.07 \pm 0.09$. 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 Λ_c^+/Λ_c^- and $\Lambda_b^0/\overline{\Lambda}_b^0$ 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 Λ_c^+/Λ_c^- and $\Lambda_b^0/\overline{\Lambda}_b^0$ 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 Λ_Q (udQ) baryon is defined by

$$A_p = \frac{d\sigma(\Lambda_Q) - d\sigma(\overline{\Lambda}_Q)}{d\sigma(\Lambda_Q) + d\sigma(\overline{\Lambda}_Q)}\,, \tag{1}$$

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 Λ_Q baryon in a pp collision, at leading order in a $1/p_T$ expansion, is given by

$$d\sigma[pp \to \Lambda_Q + X] = \sum_{i,j} f_{i/p} \otimes f_{j/p} \otimes d\hat{\sigma}[ij \to Q + X] \otimes D_{Q\to\Lambda_Q}\,, \tag{2}$$

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 Λ_Q baryon. The corresponding equation for $\overline{\Lambda}_Q$ is obtained by replacing Q by $\overline{Q}$ and Λ_Q by $\overline{\Lambda}_Q$. 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 $\Lambda_{\rm QCD}/m_Q$ and $\Lambda_{\rm QCD}/p_T$. 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 $\Lambda_{\rm QCD} m_Q/p_T^2$ relative to Eq. (2). In what follows, after a brief review of the heavy quark recombination mechanism,[1] we calculate A_p due to heavy quark recombination for Λ_c^+/Λ_c^- and $\Lambda_b^0/\overline{\Lambda}_b^0$ 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

$$(a) \qquad d\hat{\sigma}[\Lambda_Q] = d\hat{\sigma}[qg \to (Qq)^n + \overline{Q}]\eta[(Qq)^n \to \Lambda_Q]\,, \tag{3}$$

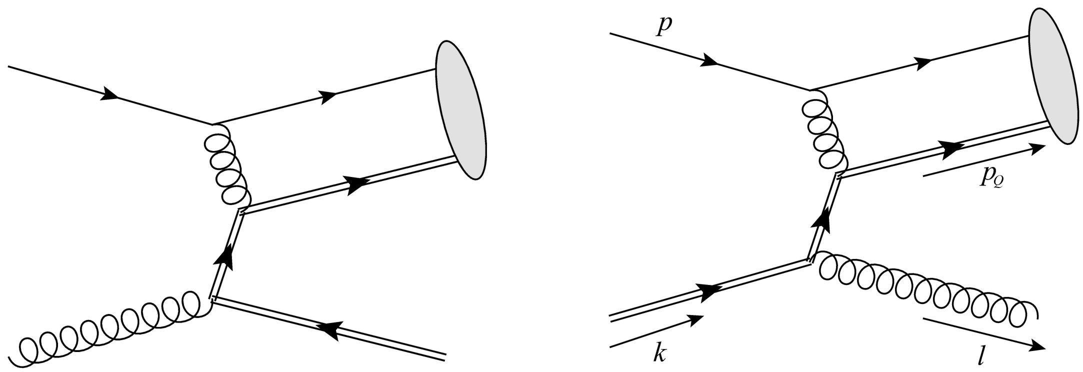
$$(b) \qquad d\hat{\sigma}[\Lambda_Q] = d\hat{\sigma}[Qq \to (Qq)^n + g]\eta[(Qq)^n \to \Lambda_Q]\,, \tag{4}$$

where q is a light valence quark of Λ_Q. $(Qq)^n$ indicates that the light quark of flavor q with momentum of order $\Lambda_{\rm QCD}$ 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 $\eta[(Qq)^n \to \Lambda_Q]$ encoding the probability for the quark pair with quantum number n to hadronize into a final state including a Λ_Q. $\eta[(Qq)^n \to \Lambda_Q]$ 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), $Qq \to (Qq)^n + g$ (Fig. 1 (b)):

$$\frac{d\sigma}{d\hat{t}}[Qq \to (Qq)^n + g] = -\frac{2\pi^2\alpha_s^3 m_Q^2}{27 S^2 T} G(n|S,T), \tag{5}$$

[1] For a full review, please see Refs. [10–13, 18].



(a) (b)

FIG. 1: Diagrams for production of a Λ_Q baryon by the heavy-quark recombination mechanism for (a) $qg \to (Qq)^n + \overline{Q}$ and (b) $Qq \to (Qq)^n + g$. Each process has five diagrams. Single lines represent light quarks, double lines heavy quarks, and the shaded blob the Λ_Q baryon.

$$
\begin{aligned}
G({}^1S_0^{(\bar{3})}|S,T) &= -\frac{16S}{T}\left(1-\frac{TU}{S^2}\right)-\frac{m_Q^2}{U}\left(3+\frac{28S}{U}+\frac{16S^2}{U^2}-\frac{16U^2}{S^2}\right)+\frac{4m_Q^4T}{SU^2}\left(3+\frac{4U}{S}+\frac{8S}{U}\right),\\
G({}^3S_1^{(\bar{3})}|S,T) &= 3G({}^1S_0^{(\bar{3})}|S,T)-32\left(\frac{U}{S}-\frac{S^2}{U^2}\right)-\frac{4m_Q^2}{U}\left(8-\frac{6S}{U}-\frac{16S^2}{U^2}+\frac{13U}{S}+\frac{15U^2}{S^2}\right),\\
G({}^1S_0^{(6)}|S,T) &= -\frac{4S}{T}\left(2-\frac{5TU}{S^2}\right)-\frac{m_Q^2}{U}\left(27+\frac{14S}{U}+\frac{8S^2}{U^2}-\frac{20U^2}{S^2}\right)+\frac{2m_Q^4T}{SU^2}\left(9+\frac{10U}{S}+\frac{8S}{U}\right),\\
G({}^3S_1^{(6)}|S,T) &= 3G({}^1S_0^{(6)}|S,T)-\frac{8S}{T}\left(3+\frac{5TU}{S^2}+\frac{5S}{U}+\frac{2S^2}{U^2}\right)+\frac{4m_Q^2T}{S^2}\left(27-\frac{S}{U}-\frac{S^2}{U^2}-\frac{8S^3}{U^3}\right),
\end{aligned}
\tag{6}
$$

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 $\overline{Q}$ in the final state of process (a) could fragment into a $\overline{\Lambda}_Q$ baryon. Charge conjugation of this process gives the "opposite-side recombination":

$$(c) \qquad d\hat{\sigma}[\Lambda_Q] = \sum_n d\hat{\sigma}[qg \to (\overline{Q}q)^n + Q] \sum_{\overline{H}_{meson}} \rho[(\overline{Q}q)^n \to \overline{H}_{meson}] \otimes D_{Q\to\Lambda_Q}\,, \tag{7}$$

$$(d) \qquad d\hat{\sigma}[\Lambda_Q] = \sum_n d\hat{\sigma}[\bar{q}g \to (\overline{Q}\bar{q})^n + Q] \sum_{\overline{H}_{baryon}} \eta[(\overline{Q}\bar{q})^n \to \overline{H}_{baryon}] \otimes D_{Q\to\Lambda_Q} \tag{8}$$

where H_{meson} and H_{baryon} are any heavy meson and heavy baryon respectively. We will assume charge conjugation symmetry and take $\rho[(Q\bar{q})^n \to H_{meson}] = \rho[(\overline{Q}q)^n \to \overline{H}_{meson}]$ and $\eta[(Qq)^n \to H_{baryon}] = \eta[(\overline{Q}\bar{q})^n \to \overline{H}_{baryon}]$. For simplicity, we will take H to be a low-lying heavy hadron. Thus, for Λ_c production we will take H_{meson} to be either D or D^*, and H_{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 Λ_b production. We will also assume $SU(3)$ flavor symmetry.

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

$$\begin{aligned} \rho_1 &= \rho[c\bar{q}(^1S_0^{(1)}) \to D]\,, & \tilde{\rho}_1 &= \rho[c\bar{q}(^3S_1^{(1)}) \to D]\,, \\ \rho_8 &= \rho[c\bar{q}(^1S_0^{(8)}) \to D]\,, & \tilde{\rho}_8 &= \rho[c\bar{q}(^3S_1^{(8)}) \to D]\,. \end{aligned} \tag{9}$$

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

$$\begin{aligned} \rho[c\bar{q}(^1S_0^{(c)}) \to D] &= \rho[c\bar{q}(^3S_1^{(c)}) \to D^*]\,, \\ \rho[c\bar{q}(^3S_1^{(c)}) \to D] &= \rho[c\bar{q}(^1S_0^{(c)}) \to D^*]\,. \end{aligned} \tag{10}$$

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

$$\begin{aligned} \eta_3 &= \eta[Qq(^1S_0^{(\bar{3})}) \to \Lambda_Q]\,, & \tilde{\eta}_3 &= \eta[Qq(^3S_1^{(\bar{3})}) \to \Lambda_Q]\,, \\ \eta_6 &= \eta[Qq(^1S_0^{(6)}) \to \Lambda_Q]\,, & \tilde{\eta}_6 &= \eta[Qq(^3S_1^{(6)}) \to \Lambda_Q]\,. \end{aligned} \tag{11}$$

All the ρs and ηs scale as Λ_{QCD}/m_Q. Contributions of feeddown from heavier baryons in processes (a) and (b) can be taken into account by using the inclusive parameter η_{inc}:

$$\eta_{inc}[(Qq)^n \to \Lambda_Q] = \eta[(Qq)^n \to \Lambda_Q] + \sum_{H_{baryon} \neq \Lambda_Q} \eta[(Qq)^n \to H_{baryon}] B[H_{baryon} \to \Lambda_Q + X] \tag{12}$$

Here again we assume H_{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 $\overline{H}_{baryon}$ in the opposite-side recombination, by a simple quark counting and the fact that $B[H_{baryon} \to \Lambda_Q + X] \approx 1$ for $H_{baryon} = \Sigma_Q$ or Σ_Q^*, we have

$$\sum_{\overline{H}_{baryon}} \eta[(\overline{Q}\bar{q}')^n \to \overline{H}_{baryon}] \approx \frac{3}{2}\eta_{inc}[(Qq)^n \to \Lambda_Q]\,, \tag{13}$$

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 $\rho[(c\bar{d})^n \to D^+]$. Best single-parameter fit to $\Lambda_c^\pm$ asymmetry in fixed target experiments gives $\tilde{\eta}_{3,inc} = 0.058$ for Λ_c [13]. We will take $\eta_{3,inc} = \eta_{6,inc} = \tilde{\eta}_{6,inc} = 0$ and $0.052 < \tilde{\eta}_{3,inc} < 0.064$ for Λ_c. For the ηs for Λ_b and ρs for B, we simply multiply the Λ_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

$$D_{Q\to\Lambda_Q}(z) = f_{\Lambda_Q}\delta(1-z)\,, \tag{14}$$

where f_{Λ_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 Λ_c^+/Λ_c^- asymmetry data [13]. We take $f_{\Lambda_c^+} = 0.101$, which is the average of the values listed in [19]. $f_{\Lambda_b^0}$ 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 $\mu_f = \sqrt{p_T^2 + m_Q^2}$.

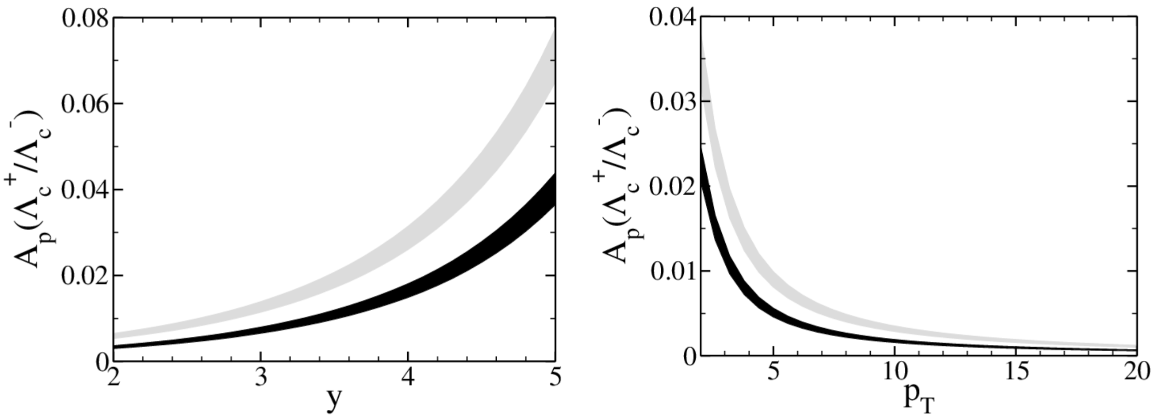
For Λ_c^+/Λ_c^- production, the kinematic region is taken to be $2 < y < 5$ and 2 GeV $< p_T <$ 20 GeV. The integrated A_p is found to be $2.0\% < A_p(\Lambda_c^+/\Lambda_c^-) < 2.4\%$ for $\sqrt{s} = 7$ TeV and $1.2\% < A_p(\Lambda_c^+/\Lambda_c^-) < 1.5\%$ for $\sqrt{s} = 14$ TeV. For $\Lambda_b^0/\overline{\Lambda}_b^0$ 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 $2.2\% < A_p(\Lambda_b^0/\overline{\Lambda}_b^0) < 2.6\%$ for $\sqrt{s} = 7$ TeV and $1.1\% < A_p(\Lambda_b^0/\overline{\Lambda}_b^0) < 1.4\%$ for $\sqrt{s} = 14$ TeV. Figures 2 and 3 show the rapidity and transverse momentum distributions of A_p for Λ_c^+/Λ_c^- and $\Lambda_b^0/\overline{\Lambda}_b^0$ 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 Λ_c^+/Λ_c^- and $\Lambda_b^0/\overline{\Lambda}_b^0$ 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 Λ_c^+ and Λ_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 Λ_{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 $\sigma(\overline{\Lambda}_b^0)/\sigma(\Lambda_b^0)$ for 7 TeV pp collisions in the kinematic region $0 < y < 2$ and 10 GeV $< p_T <$ 50 GeV. The CMS data, despite of the large error bars, do have a slight trend of surplus of Λ_b^0 over $\overline{\Lambda}_b^0$ in the regions of high rapidity and low transverse momentum respectively. However, with the values of ηs 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 ηs. Here all η_{inc}s are set equal to each other, with the range being $\Lambda_{QCD}/m_b \sim 0.2 < \eta_{inc} < 1$. The ranges of the ρs 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 GeV $< p_T <$ 20 GeV for 7 TeV pp collisions with the ranges of ηs and ρs as in Fig. 7. The asymmetry is huge ($\sim$ 50%). We believe that our previous predictions with smaller η_{inc}s (Figs. 2-5) are more reasonable since those values of ηs were obtained from better fit to fixed-target experiments. Moreover, the surplus of $\overline{\Lambda}_b^0$ over Λ_b^0 at $y \sim 1$ and $p_T >$ 20 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.

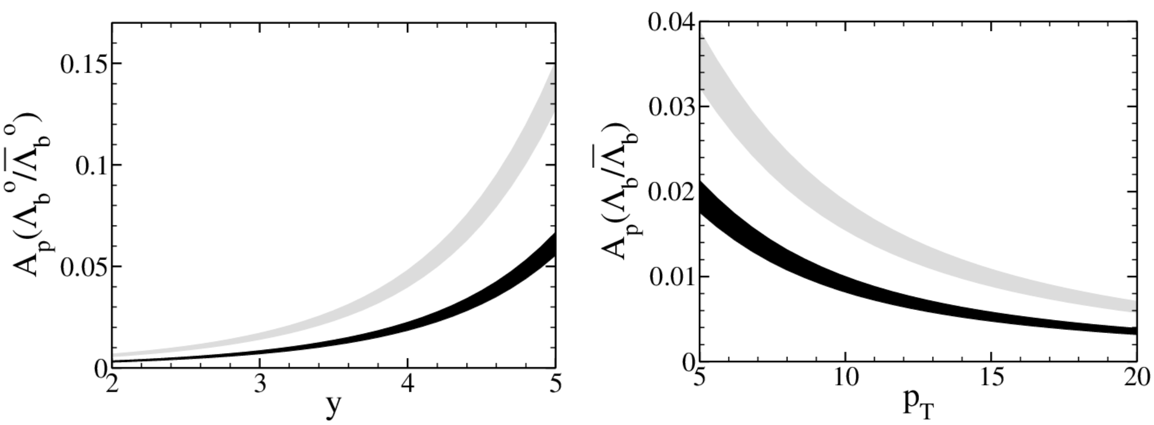
An appealing feature of the heavy quark recombination mechanism is that it has its basis in perturbative QCD and thus is model-independent [18]. However, it should be emphasized that the heavy quark recombination mechanism is not the only possible way to give rise to production asymmtries of heavy hadrons 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



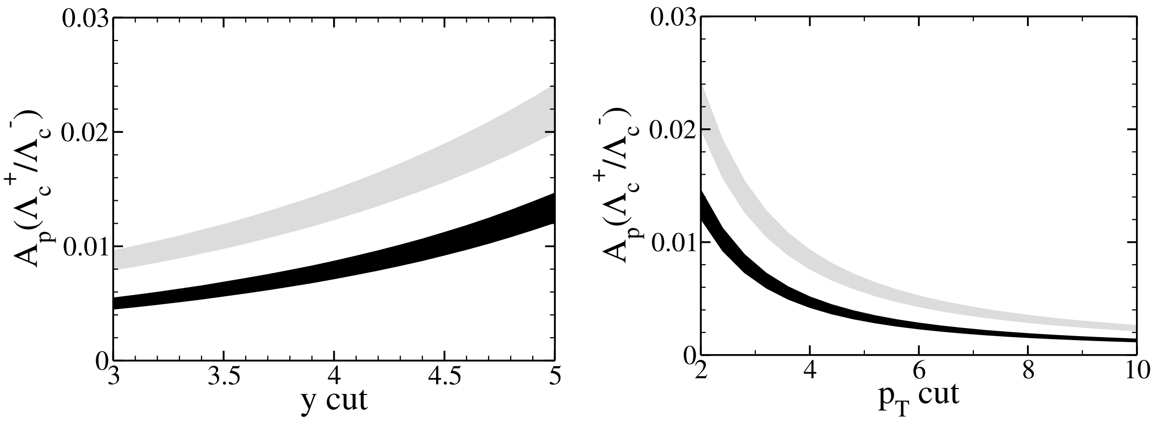
(a) (b)

FIG. 2: Asymmetry in Λ_c^+/Λ_c^- production as a function of (a) rapidity y and (b) transverse momentum p_T in the kinematic region $2 < y < 5$ and 2 GeV $< p_T <$ 20 GeV in 7 TeV (grey band) and 14 TeV (black band) pp collisions.



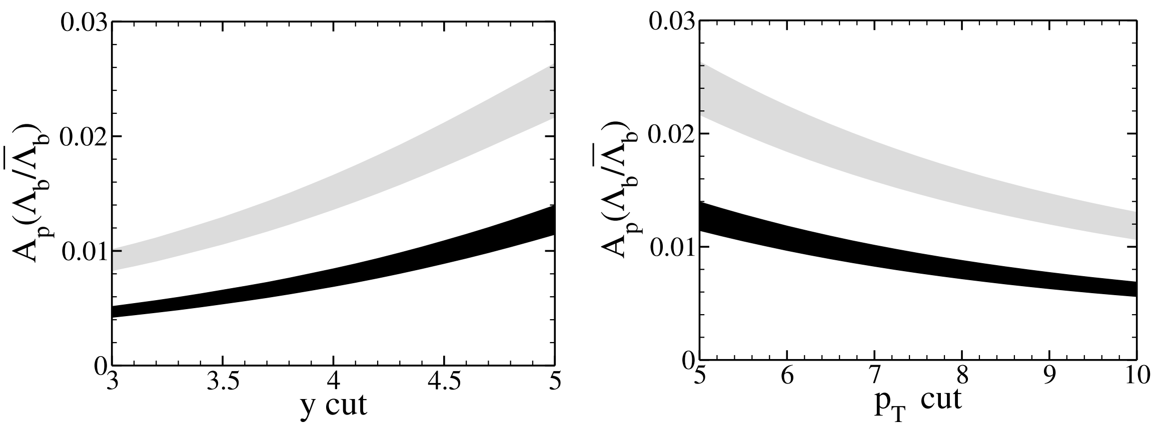
(a) (b)

FIG. 3: Asymmetry in $\Lambda_b^0/\overline{\Lambda}_b^0$ production as a function of (a) rapidity y and (b) transverse momentum p_T in the kinematic region $2 < y < 5$ and 5 GeV $< p_T <$ 20 GeV in 7 TeV (grey band) and 14 TeV (black band) pp collisions.



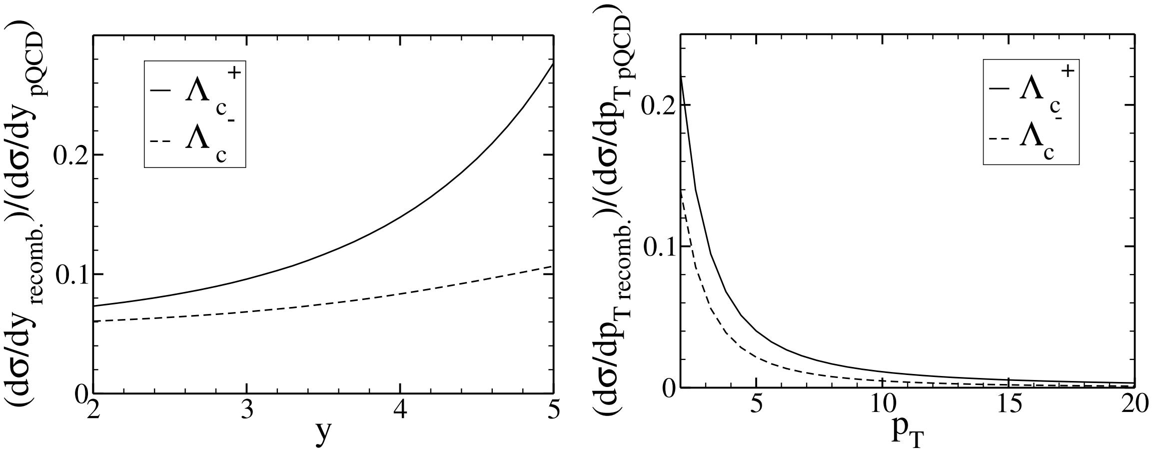
(a) (b)

FIG. 4: Integrated asymmetry in Λ_c^+/Λ_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 GeV $< p_T <$ 20 GeV in 7 TeV (grey band) and 14 TeV (black band) pp collisions.



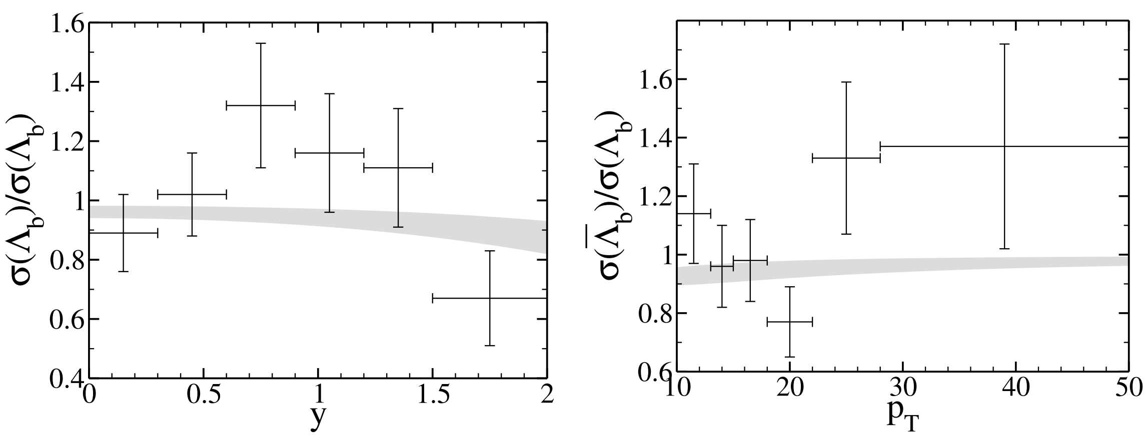
(a) (b)

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



(a) (b)

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



(a) (b)

FIG. 7: $\sigma(\overline{\Lambda}_b^0)/\sigma(\Lambda_b^0)$ as a function of (a) rapidity y and (b) transverse momentum p_T in the kinematic region $0 < y < 2$ and 10 GeV $< p_T <$ 50 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 η_{inc}s set equal to each other, the range being $0.2 < \eta_{inc} < 1$. The ranges of ρs are as those used in Fig. 3.

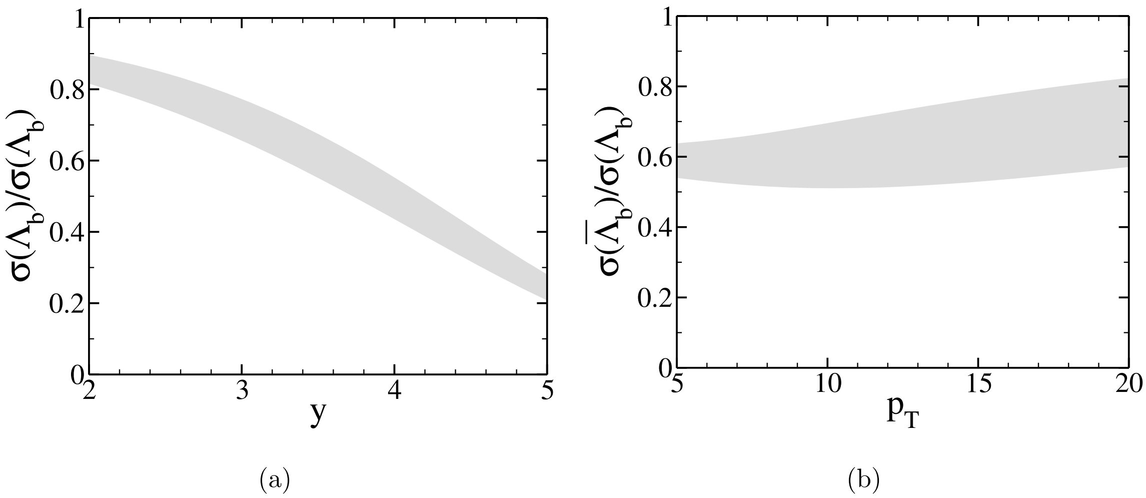


FIG. 8: $\sigma(\overline{\Lambda}_b^0)/\sigma(\Lambda_b^0)$ as a function of (a) rapidity y and (b) transverse momentum p_T in the kinematic region $2 < y < 5$ and 5 GeV $< p_T <$ 20 GeV for 7 TeV pp collisions. The grey band is our prediction from the heavy quark recombination mechanism with all η_{inc}s set equal to each other, the range being $0.2 < \eta_{inc} < 1$. The ranges of ρs 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 Λ over $\overline{\Lambda}$ in pp collisions since the light valence quarks of the Λ or $\overline{\Lambda}$ 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 $|uud\dots\rangle$, where "$\dots$" denotes an arbitrary number of quark-antiquark pairs and gluons. The heavy quark Q in $|uudQ\overline{Q}\rangle$ can combine with the valence quarks ud to form a Λ_Q. The probability for fock state $|uudQ\overline{Q}\rangle$ with a given momentum fraction distribution among the quarks is assumed a simple form proportional to $\alpha_s^4(m_{Q\overline{Q}})$. The produced Λ_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 α_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 Λ over $\overline{\Lambda}$ 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 Λ_c^+/Λ_c^- and $\Lambda_b^0/\overline{\Lambda}_b^0$ at the LHCb experiment. The heavy quark recombination mechanism is a correction of order $\Lambda_{\rm QCD} m_Q/p_T^2$ 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.

---

[1] W. S. Lockman, T. Meyer, J. Rander, P. Schlein, R. Webb, S. Erhan and J. Zsembery, Phys. Lett. B **85**, 443 (1979).

[2] P. Chauvat *et al.* [R608 Collaboration], Phys. Lett. B **199**, 304 (1987).

[3] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **714**, 136 (2012) [arXiv:1205.0594 [hep-ex]].

[4] R. C. Hwa Phys. Rev. D **51**, 85 (1995)

[5] S. J. Brodsky, P. Hoyer, C. Peterson and N. Sakai, Phys. Lett. B **93**, 451 (1980).

[6] S. J. Brodsky, C. Peterson and N. Sakai, Phys. Rev. D **23**, 2745 (1981).

[7] R. Vogt and S. J. Brodsky, Nucl. Phys. B **438**, 261 (1995) [hep-ph/9405236].

[8] J. L. Rosner, Phys. Rev. D **90**, 014023 (2014) [arXiv:1405.2885 [hep-ph]].

[9] J. L. Rosner, Phys. Rev. D **86**, 014011 (2012) [arXiv:1205.1529 [hep-ph]].

[10] E. Braaten, Y. Jia and T. Mehen, Phys. Rev. D **66**, 034003 (2002) [hep-ph/0108201].

[11] E. Braaten, Y. Jia and T. Mehen, Phys. Rev. D **66**, 014003 (2002) [hep-ph/0111296].

[12] E. Braaten, Y. Jia and T. Mehen, Phys. Rev. Lett. **89**, 122002 (2002) [hep-ph/0205149].

[13] E. Braaten, M. Kusunoki, Y. Jia and T. Mehen, Phys. Rev. D **70**, 054021 (2004) [hep-ph/0304280].

[14] R. Aaij *et al.* [LHCb Collaboration], Phys. Lett. B **718**, 902 (2013) [arXiv:1210.4112 [hep-ex]].

[15] W. K. Lai, A. K. Leibovich and A. A. Petrov, Phys. Rev. D **90**, 054022 (2014) [arXiv:1408.2843 [hep-ph]].

[16] E. M. Aitala *et al.* [E791 Collaboration], Phys. Lett. B **371**, 157 (1996) ; *ibid.* **411**, 230 (1997); G. A. Alves *et al.* [E769 Collaboration], Phys. Rev. Lett. **72**, 812 (1994); *ibid.* **77**, 2392 (1996); M. Adamovich *et al.* [BEATRICE Collaboration], Nucl. Phys. B **495**, 3 (1997); M. Adamovich *et al.* [WA82 Collaboration], Phys. Lett. B **305**, 402 (1993); F. G. Garcia *et al.* [SELEX Collaboration], Phys. Lett. B **528**, 49 (2002); E. M. Aitala *et al.* [E791 Collaboration], Phys. Lett. B **495**, 42 (2000); M. I. Adamovich *et al.* [WA89 Collaboration], Eur. Phys. J. C **8**, 593 (1999).

[17] J. C. Collins, D. E. Soper and G. F. Sterman, Nucl. Phys. B **263**, 37 (1986).

[18] C. H. Chang, J. P. Ma and Z. G. Si, Phys. Rev. D **68**, 014018 (2003) [hep-ph/0301253].

[19] H. Abramowicz *et al.* [ZEUS Collaboration], JHEP **1309**, 058 (2013) [arXiv:1306.4862 [hep-ex]].

[20] T. Affolder *et al.* [CDF Collaboration], Phys. Rev. Lett. **84**, 1663 (2000) [hep-ex/9909011].