

# Asymmetry in $\Lambda_b$ and $\bar{\Lambda}_b$ production

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(Received 28 May 2014; published 15 July 2014)

In CMS data at the CERN Large Hadron Collider, the ratio  $\sigma(pp \rightarrow \bar{\Lambda}_b X)/\sigma(pp \rightarrow \Lambda_b X)$  appears to fall as the baryons become more forward. Mechanisms which could give rise to this effect are discussed. It is urged that the same physics be explored in data from the ATLAS and LHCb detectors at CERN and the Fermilab Tevatron proton-antiproton collider. In the latter, if such leading-baryon effects are present, one expects  $\Lambda_b$  to be preferentially produced in the direction of the proton and  $\bar{\Lambda}_b$  to be preferentially produced in the direction of the antiproton.

DOI: 10.1103/PhysRevD.90.014023

PACS numbers: 14.20.Mr, 12.38.Aw, 12.38.Qk, 14.65.Fy

## I. INTRODUCTION

The production of heavy baryons and antibaryons in hadronic collisions has posed a theoretical puzzle for a number of years, ever since the observation at the CERN Intersecting Storage Rings (ISR) of the charmed baryon  $\Lambda_c$  [1,2]. Lowest-order QCD involving the subprocesses  $q\bar{q} \rightarrow c\bar{c}$  and  $gg \rightarrow c\bar{c}$ , where  $q$  is a light quark ( $u, d, s$ ) and  $g$  is a gluon, would predict equal cross sections for  $\Lambda_c$  and  $\bar{\Lambda}_c$  for each value of  $x_F$  and  $p_T$ . However, production of  $\Lambda_c$  in proton-proton collisions at the ISR is favored over that of  $\bar{\Lambda}_c$ , indicating the presence of nonperturbative final-state interactions such as those occurring in a QCD string model like PYTHIA [3,4]. (For an early overview of fragmentation models see [5].)

Asymmetries in the production of bottom quarks at the LHC were investigated some time ago [6] and found to be negligible except in the very forward direction (beyond the reach of LHCb). Methods employed were the Lund string fragmentation model [7] and the intrinsic heavy quark model [8,9].

At  $\sqrt{s} = 7$  TeV the LHCb Collaboration [10] finds a production asymmetry  $A_p = [\sigma(D_s^+) - \sigma(D_s^-)]/[\sigma(D_s^+) + \sigma(D_s^-)] = (-0.33 \pm 0.22 \pm 0.10)\%$  for  $2.0 \leq y \leq 4.5$ , exhibiting no preference for a leading-quark effect. Recently the production of  $\Lambda_b$  and  $\bar{\Lambda}_b$  has been studied by the CMS Collaboration at the CERN LHC. While no significant difference between  $\Lambda_b$  and  $\bar{\Lambda}_b$  production is seen in the central region with  $|y^{\Lambda_b}| \leq 1.5$  [11], the  $\bar{\Lambda}_b$  is produced only about 2/3 as frequently as the  $\Lambda_b$  in the most forward rapidity bin  $1.5 \leq |y^{\Lambda_b}| \leq 2.0$ . The present article calls attention to a simple way of evaluating the string-based fragmentation mechanism leading to an asymmetry, and to urge that this asymmetry be examined in the data of ATLAS and LHCb at the LHC and CDF and D0 at the Fermilab Tevatron.

In Sec. II we review recent data on  $\Lambda_b$  and  $\bar{\Lambda}_b$  production at the LHC. We then recall in Sec. III a “color reconnection” mechanism proposed recently [12] in the context of a

forward-backward asymmetry in top quark production at the Tevatron observed by CDF [13–16] and D0 [17–22]. Effects of this mechanism should be contained in any model which seeks to predict the production of  $\Lambda_b$  and  $\bar{\Lambda}_b$  at hadron colliders. Questions of  $p_T$  and  $y$  dependence, and possible polarization effects, are discussed very briefly in Sec. IV. We close in Sec. V by urging such studies at ATLAS, LHCb, and the Tevatron.

## II. RECENT DATA

The production of  $\Lambda_b$  and  $\bar{\Lambda}_b$  has been studied at the LHC by the CMS Collaboration [11], based on an integrated luminosity of  $1.96 \text{ fb}^{-1}$  at  $\sqrt{s} = 7$  TeV. The reported ratio of  $\bar{\Lambda}_b$  and  $\Lambda_b$  cross sections is illustrated in Fig. 1 as a function of  $|y(\Lambda_b)|$ , the  $\Lambda_b$  rapidity. Although no significant variation with  $|y(\Lambda_b)|$  is claimed in Ref. [11], one can also see a modest decrease in the ratio in the most forward rapidity bin, as pointed out in Ref. [12].

It was noted in Ref. [12] that the LHCb Collaboration was in an ideal position to extend this measurement to larger  $|y|$ , where a string fragmentation picture would predict a growing predominance of  $\Lambda_b$  over  $\bar{\Lambda}_b$ . If the trend suggested by CMS continues to higher  $y$ , the  $\bar{\Lambda}_b$  cross section at LHCb would be no more than 2/3 that of the  $\Lambda_b$ , suggesting that different production mechanisms were at work in the central and forward directions. Some possibilities for these mechanisms are described in the next section. It is notable that the decreased ratio of cross sections suggested by the CMS data is not reproduced by the POWHEG or PYTHIA Monte Carlo predictions.

We note briefly some other LHC  $\Lambda_b$  data in  $\bar{p}p$  collisions at  $\sqrt{s} = 7$  TeV, to be discussed in more detail in Sec. IV. The CMS Collaboration has studied the polarization of  $\Lambda_b$  and  $\bar{\Lambda}_b$  with a sample corresponding to  $5.1 \text{ fb}^{-1}$  of integrated luminosity [23]. The ATLAS Collaboration [24] has published a study of  $\Lambda_b$  and  $\bar{\Lambda}_b$  polarization with  $4.6 \text{ fb}^{-1}$  of data, but without stating the

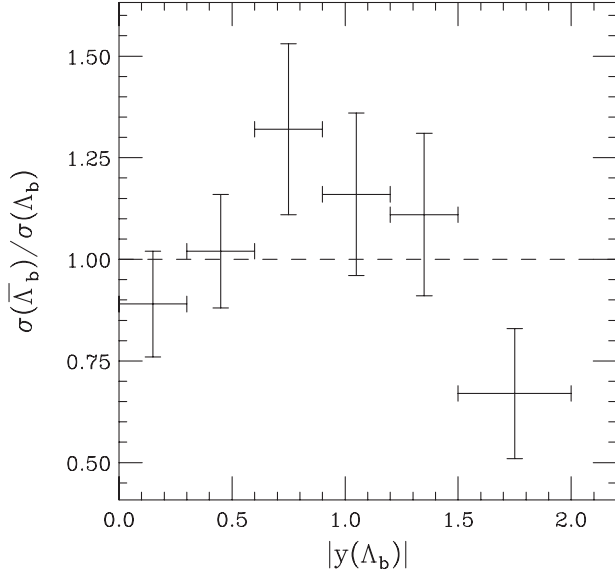


FIG. 1. Ratio of  $\bar{\Lambda}_b$  and  $\Lambda_b$  cross sections reported by the CMS Collaboration [11] as a function of rapidity. Only statistical errors are shown; systematic errors for the points are  $\pm 0.09$ ,  $\pm 0.09$ ,  $\pm 0.13$ ,  $\pm 0.12$ ,  $\pm 0.15$ ,  $\pm 0.16$ , respectively. The dashed line denotes a ratio of 1.

relative production fractions of  $\Lambda_b$  and  $\bar{\Lambda}_b$ . Finally, the LHCb Collaboration [25] has studied  $\Lambda_b$  and  $\bar{\Lambda}_b$  polarization with  $1 \text{ fb}^{-1}$ .

### III. PRODUCTION MECHANISMS

#### A. Mechanisms without asymmetry

The subprocesses  $q\bar{q} \rightarrow b\bar{b}$  and  $gg \rightarrow b\bar{b}$ , followed by fragmentation of a  $b$  quark into  $\Lambda_b$  or a  $\bar{b}$  quark into  $\bar{\Lambda}_b$ , do not lead to an asymmetry between baryon and antibaryon production. One might expect these processes to dominate in production of heavy baryons with small  $|y|$  and large  $p_T$ . Some additional processes are contributing to  $\Lambda_b$  production at small  $p_T$ ; its cross section falls off more rapidly with increasing  $p_T$  than the cross sections for  $B$ -flavored mesons [11].

#### B. Quasidiffractive excitation

In Fig. 2 we illustrate a mechanism which may be expected to contribute to forward heavy baryon production and will favor production of  $\Lambda_b$  by protons and  $\bar{\Lambda}_b$  by antiprotons. The figure suggests that a forward  $\Lambda_b$  often will be accompanied by a forward  $B^+$  or the decay products of an excited  $B^+$ . This mechanism has some features in common with the intrinsic heavy quark model [8,9], in the sense that a heavy forward baryon is more likely to contain a  $b$  quark rather than a  $\bar{b}$ .

#### C. Interaction with spectator quark

The final-state interaction of the heavy quark with the proton remnants [6,7] was noted in the case of  $t\bar{t}$  production

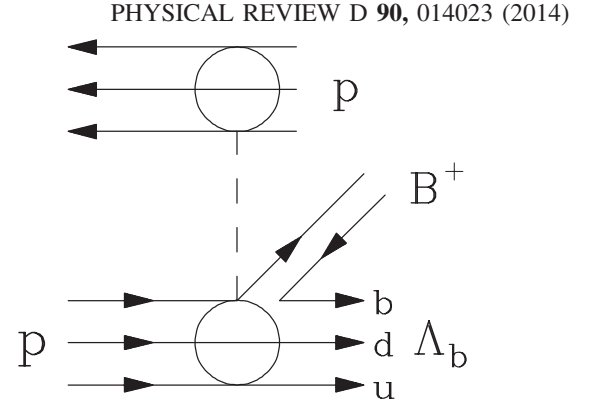


FIG. 2. Quasidiffractive production of  $\Lambda_b$  along the direction of a proton beam. The circles denote vertices for exchange of a pomeron, denoted by the dashed line.

in Ref. [12]. (See also [26].) This mechanism is illustrated in Fig. 3. The effect of this process on the apparent asymmetry in  $t\bar{t}$  production at the Tevatron was seen to be too small to account for the asymmetry claimed initially by both collider collaborations, but in a recent report by D0 the asymmetry no longer conflicts with the standard model [22].

We retrace the argument presented in Ref. [12] for the “drag” exerted by a QCD string on a heavy quark produced through the process illustrated in Fig. 3. We first calculate in the frame where the longitudinal momentum of the heavy quark is zero. A result expressed in terms of rapidity then is invariant under boosts along the  $z$  axis.

A QCD string breaks when it reaches a length of about  $1.5 \text{ fm}$  [27]. If its end attached to the remnant travels with respect to the other end at the speed of light, it acts for a time

$$t = \frac{1.5 \times 10^{-15} \text{ m}}{3 \times 10^8 \text{ (m/s)}} = 5 \times 10^{-24} \text{ s.} \quad (1)$$

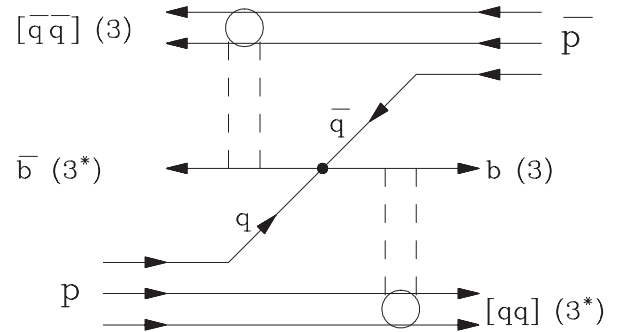


FIG. 3. Interaction of final-state heavy quark with spectator system, as proposed in Ref. [12]. The pairs of dashed lines denote QCD strings connecting the final-state heavy quarks to the spectator systems.

During this time it exerts a force due to the string tension  $k = 0.18 \text{ GeV}^2$  and hence imparts a momentum

$$\Delta p_z = kt = \frac{(0.18 \text{ GeV}^2)(5 \times 10^{-24} \text{ s})}{6.582 \times 10^{-25} \text{ GeV} \cdot \text{s}} \simeq 1.4 \text{ GeV} \quad (2)$$

to the  $b$  quark, pulling it forward in the direction of the proton. Since the average  $p_T$  of the  $\Lambda_b$  in the CMS result is  $\mathcal{O}(m_b) \simeq 5 \text{ GeV}$  (see Fig. 4), this should be a non-negligible effect. Such “string-drag” phenomena are taken into account in recent Monte Carlo approaches [28].

To compare with a result of Ref. [6], we note that with  $y \equiv -\ln \tan(\theta/2)$ ,  $dy/d\theta = -\cosh y$  which is  $-1$  at  $y = 0$ . Here  $\theta$  denotes the polar angle of the  $b$  quark. If  $p_T$  is its transverse momentum, we have  $\Delta\theta \simeq -\Delta p_z/p_T$  or, at  $y = 0$ ,  $\Delta y = -\Delta\theta \simeq 1.4 \text{ GeV}/p_T$ . This is approximately of the form found in Ref. [6], but about three times as large. As the result is expressed in terms of boost-invariant quantities, it is now valid for any  $y$ .

#### IV. OTHER DISTINGUISHING MEASUREMENTS

##### A. Transverse momentum and $|y|$

We have mentioned that the string-drag mechanism leads to an effect  $\Delta y = -1.4 \text{ GeV}/p_T$ . It is harder to separate the  $|y|$  and  $p_T$  dependences of the quasidiffractive excitation model. One may think of the mechanism of Fig. 2 as the effect of diffractive excitation of many  $B^+\Lambda_b$  resonances, in which case there are too many

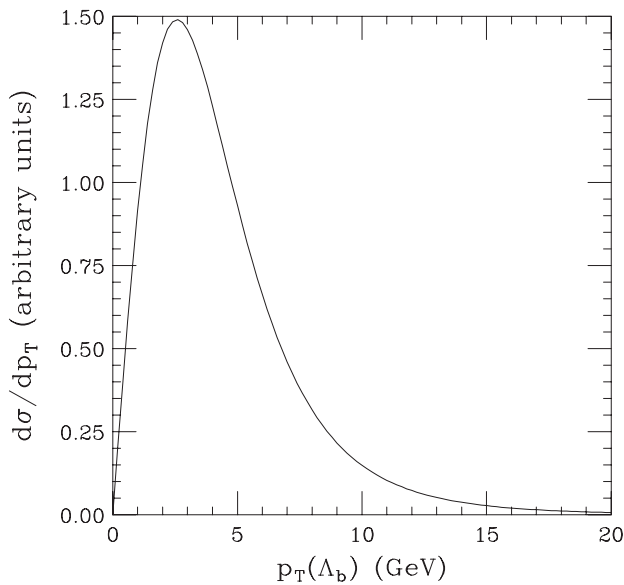


FIG. 4. Distribution (“Tsallis function” [29]) fitting  $p_T$  dependence of  $\Lambda_b$  production reported by the CMS Collaboration [11] at  $\sqrt{s} = 7 \text{ TeV}$ .

unknown variables to permit quantitative estimates. The difficulty of the problem is not unlike that encountered in interpreting fixed-target hyperon production (e.g., [30] and references therein). Nonetheless, one can anticipate that the importance of quasidiffractive excitation should increase with decreasing  $p_T$  and increasing  $|y|$ . One may be able to gauge its importance by looking for  $B^+\Lambda_b$  correlations, as suggested by the picture of Fig. 2.

##### B. $\Lambda_b$ polarization

The fixed-target study of hyperons mentioned above [30] and in earlier investigations turned up unexpectedly large transverse polarizations without a clearly understood pattern. In 500 GeV/ $c$   $\pi^-N$  collisions,  $\Lambda_c$  polarization is found to become increasingly negative with increasing  $p_T$  [31]. A hybrid perturbative QCD model with polarization transfer from  $c$  to  $\Lambda_c$  can account for this effect [32]. In contrast, no  $\Lambda_b$  polarization has been seen by any of the three LHC experiments. CMS [23] finds  $P(\Lambda_b) = 0.03 \pm 0.09 \pm 0.03$  and  $P(\bar{\Lambda}_b) = 0.02 \pm 0.08 \pm 0.05$ ; ATLAS [24] finds both  $P(\Lambda_b)$  and  $P(\bar{\Lambda}_b)$  consistent with zero; and LHCb [25] finds the polarizations of  $\Lambda_b$  and  $\bar{\Lambda}_b$  consistent with each other, giving an average of  $0.06 \pm 0.07 \pm 0.02$ .

One feature of  $\Lambda_b$  polarization is that in the constituent-quark picture, the spin of the  $\Lambda_b$  is carried entirely by the  $b$  quark, as the  $u$  and  $d$  quarks are coupled up to spin zero. This correlation is largely borne out by explicit QCD calculations [33,34]. Standard estimates of  $\Lambda_b$  polarization at the LHC fall in the 10–20% range [35,36].

A relatively recent discussion of the induction of spin-spin forces by exchange of a QCD string has been given in Ref. [37]. An interesting feature, which unfortunately prevents a quantitative conclusion, is that the effect behaves as the fourth power of the string thickness, an unknown quantity.

#### V. CONCLUSIONS

Mechanisms have been described which favor forward production of heavy baryons in  $b$  quark fragmentation. These include quasidiffractive processes, in which a proton dissociates into a heavy baryon and a meson containing a  $\bar{b}$ , and a string-drag effect [6,7] investigated in the context of top quark production [12]. While found to be unimportant in generating any forward-backward asymmetry at the Tevatron for top production, the latter mechanism is seen to have greater effect in generating an asymmetry in  $\Lambda_b$  and  $\bar{\Lambda}_b$  production. Such an asymmetry is suggested in the highest- $y$  bin studied by the CMS Collaboration [11], where the cross section for  $\bar{\Lambda}_b$  production is about 2/3 that for  $\Lambda_b$  production.

It would be extremely interesting to study these effects at ATLAS, LHCb, and the Fermilab Tevatron, comparing them with available Monte Carlo predictions. At the

Tevatron, the quasidiffractive and string-drag processes should generate a leading-baryon effect, in which the  $\Lambda_b$  and  $\bar{\Lambda}_b$  tend to follow the direction of the proton and antiproton, respectively. Such an asymmetry is immune to systematic differences in detection efficiencies for particles and antiparticles [38], lending unique urgency to such studies at the Tevatron.

## ACKNOWLEDGMENTS

I thank Samim Erhan, Jonathan Lewis, Patrick Koppenburg, Patrick Lukens, Brian Meadows, and Sheldon Stone for helpful advice. This work was supported in part by the U. S. Department of Energy under Award No. DE-FG02-13ER41958.

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