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$D^{\pm}$ production asymmetry at the LHC from heavy quark recombination

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The asymmetry in the forward region production cross section of $D^{\pm}$ is calculated using the heavy quark recombination mechanism for pp collisions at 7 TeV. By suitable choices of four nonperturbative parameters, our calculated results can reproduce those obtained at LHCb. We find $A_p \sim -1\%$ when integrated over 2.0 GeV $< p_T <$ 18 GeV and $2.2 < \eta < 4.75$, which agrees with $A_p = -0.96 \pm 0.26 \pm 0.18\%$ as measured by LHCb. Furthermore, the calculated distributions in η and p_T agree reasonably well with those obtained at LHCb.

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Observation and proper interpretation of CP violation in the charm system could provide an outstanding opportunity for indirect searches for physics beyond the standard model. Even already available bounds on CP-violating interactions provide rather stringent constraints on the models of new physics because of availability of large statistical samples of charm data from the LHCb, Belle, and BaBar experiments. Larger samples will be available soon from both pp and e^+e^- machines [1].

One of the simplest signals for CP violation in charm is obtained by comparing partial decay widths of charm mesons to those of anticharm mesons. While CPT symmetry requires the total widths of D and $\overline{D}$ to be the same, the partial decay widths $\Gamma(D \to f)$ and $\Gamma(\overline{D} \to \overline{f})$ are different in the presence of CP violation, which is signaled by a nonzero value of the asymmetry

$$a^f_{CP} = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})}. \tag{1}$$

This signal is reasonably robust for D^+/D^- mesons, provided that the number of decaying particles and antiparticles is the same. However, at the Large Hadron Collider (LHC), the number of produced D^+ and D^- mesons might not be the same due to the fact that the initial state contains two protons. With CP-violating asymmetries expected to be at the per mille levels [2], it is important to examine the production asymmetry of D mesons both experimentally and theoretically.

Indeed, fixed-target experiments have already observed large asymmetries of charmed mesons and baryons in the forward region. In hadroproduction, the charmed hadrons are preferentially produced with a light valence quark of the same type as what appears in the hadronic beam, for example [3]. This has been termed the "leading particle effect." More recently, a similar asymmetry in $D^{\pm}$ production, defined as

$$A_p = \frac{\sigma(D^+) - \sigma(D^-)}{\sigma(D^+) + \sigma(D^-)}, \tag{2}$$

has been measured in the forward region to be $\sim -1\%$ by the LHCb Collaboration [4]. What are the theoretical expectations for this asymmetry?

Factorization theorems of perturbative QCD [5] state that the heavy hadron production cross section can be written in a factorized form. At the LHC, the cross section for producing a D ($c\bar{q}$) meson in a pp collision, at leading order in a $1/p_T$ expansion, is given by

$$d\sigma[pp \to D + X] = \sum_{i,j} f_{i/p} \otimes f_{j/p} \otimes d\hat{\sigma}[ij \to c\bar{c} + X] \otimes D_{c\to D}, \tag{3}$$

where $f_{i/p}$ is the parton distribution function for parton i in the proton, $d\hat{\sigma}(ij \to c\bar{c} + X)$ is the partonic cross section and $D_{c\to D}$ is the fragmentation function describing hadronization of a c quark into a D meson. The corresponding equation for $\overline{D}$ is obtained by replacing $D_{c\to D}$ by $D_{\bar{c}\to\overline{D}}$. Charge conjugation C is expected to be a good symmetry in QCD, so $D_{c\to D} = D_{\bar{c}\to\overline{D}}$. Thus, perturbative QCD predicts that $A_p = 0$, which is at least true at leading order in the $1/p_T$ expansion.

This conclusion led theorists to examine other mechanisms for generating production asymmetry of Eq. (2), including attempts to describe the effect phenomenologically. The main idea of those approaches is to identify phenomenological mechanisms that can lead to enhanced production asymmetries, such as "meson cloud" effects.

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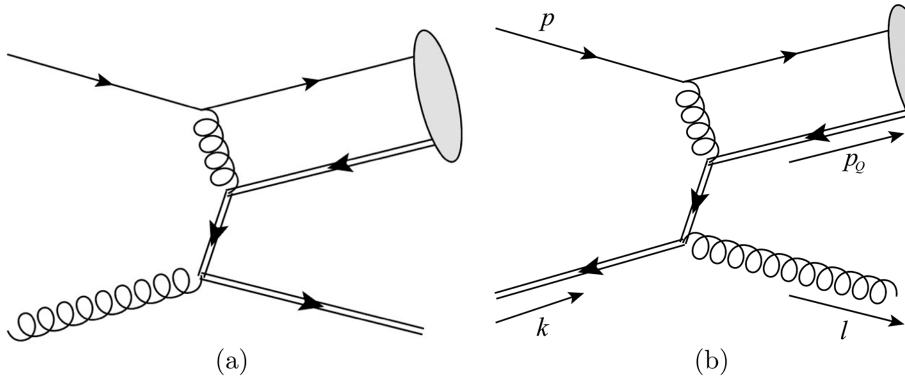

FIG. 1. Diagrams for production of a $\bar{D}$ meson by the heavy quark recombination mechanism for (a) $qg \to (\bar{c}q)^n + c$ and (b) $q\bar{c} \to (\bar{c}q)^n + g$. Each process has five diagrams. Single lines represent light quarks, double lines heavy quarks, and the shaded blob the $\bar{D}$ meson.

The results of these model-dependent calculations can be found in Refs. [6,7]. We note that it might be challenging to interpret some of those mechanisms in QCD.

To reconcile the experimental observations with QCD, we note that there are corrections to Eq. (3) that scale as powers of $\Lambda_{\mathrm{QCD}}/m_c$ and $\Lambda_{\mathrm{QCD}}/p_T$. In principle, one can expect nonvanishing power-suppressed contributions to A_p at low p_T. A QCD-based model for these power corrections is the heavy quark recombination mechanism [8–11]. In this scenario, a light quark involved in the hard scattering process combines with the heavy quark produced in that interaction to form the final state meson, leading to corrections of order $\Lambda_{\mathrm{QCD}} m_c/p_T^2$. In what follows, after a quick review of the heavy quark recombination mechanism,[1] we calculate A_p due to heavy quark recombination.

Imagine production of a heavy meson with the light quark of the same flavor as that appears in the beam. For instance, for a proton beam we could have D^- or $\overline{D}^0$ states, which we shall generically call $\overline{D}$. The recombination process, shown in Fig. 1(a), comes in as a power-suppressed correction to Eq. (3). As mentioned, the light quark in the production of $\overline{D}$ comes from the incident proton. The contribution to the cross section is given by

$$d\hat{\sigma}[\overline{D}] = d\hat{\sigma}[qg \to (\bar{c}q)^n + c]\rho[(\bar{c}q)^n \to \overline{D}], \qquad (4)$$

where $(\bar{c}q)^n$ indicates that the light quark of flavor q with momentum Λ_{QCD} in the $\bar{c}$ 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 $d\hat{\sigma}[qg \to (\bar{c}q)^n + c]$ and the nonperturbative factor $\rho[(\bar{c}q)^n \to \overline{D}]$ encoding the probability for the quark pair with quantum number n to hadronize into the final state including the $\overline{D}$. The perturbative piece was calculated to lowest order in [8]. Equation (4) must then be convoluted with the proton parton distribution functions to get the final hadronic cross section.

Besides the $qg \to (\bar{c}q)^n + c$ process, there are also contributions from $q\bar{c} \to (\bar{c}q)^n + g$, as shown in Fig. 1(b). Using the method introduced in [8], the partonic cross sections from initial state charm are calculated to be

$$\begin{aligned}
\frac{d\hat{\sigma}}{d\hat{t}}[\bar{Q}q({}^1S_0^{(1)})] &= \frac{2\pi^2\alpha_s^3}{243}\frac{m_Q^2}{S^3}\left[\frac{64S^2}{T^2} - \frac{m_Q^2 S}{UT}\left(79 - \frac{112S}{U} - \frac{64S^2}{U^2}\right) + \frac{16m_Q^4}{U^2}\left(1 - \frac{8S}{U}\right)\right],\\
\frac{d\hat{\sigma}}{d\hat{t}}[\bar{Q}q({}^3S_1^{(1)})] &= \frac{2\pi^2\alpha_s^3}{243}\frac{m_Q^2}{S^3}\left[\frac{64S^2}{T^2}\left(1 + \frac{2S^2}{U^2}\right) - \frac{m_Q^2}{T}\left(28 - \frac{4U}{S} - \frac{19S}{U} - \frac{368S^2}{U^2} + \frac{64S^3}{U^3}\right) + \frac{48m_Q^4}{U^2}\left(1 - \frac{8S}{U}\right)\right],\\
\frac{d\hat{\sigma}}{d\hat{t}}[\bar{Q}q({}^1S_0^{(8)})] &= \frac{4\pi^2\alpha_s^3}{243}\frac{m_Q^2}{S^3}\left[\left(9 + \frac{9S}{T} + \frac{4S^2}{T^2}\right) - \frac{m_Q^2}{T}\left(\frac{9U}{S} - \frac{79S}{2U} - \frac{7S^2}{U^2} - \frac{4S^3}{U^3}\right) - \frac{m_Q^4}{U^2}\left(8 + \frac{8S}{U} + \frac{9U}{S}\right)\right],\\
\frac{d\hat{\sigma}}{d\hat{t}}[\bar{Q}q({}^3S_1^{(8)})] &= \frac{4\pi^2\alpha_s^3}{243}\frac{m_Q^2}{S^3}\left[\left(16 + \frac{13U}{T} + \frac{14T}{U} + \frac{12U^2}{T^2} + \frac{8T^2}{U^2}\right) + \frac{m_Q^2}{T}\left(158 + \frac{133U}{S} + \frac{233S}{2U} + \frac{5S^2}{U^2} - \frac{4S^3}{U^3}\right)\right.\\
&\quad\left. - \frac{3m_Q^4}{U^2}\left(8 + \frac{8S}{U} + \frac{9U}{S}\right)\right],
\end{aligned} \qquad (5)$$

[1] For a full review, please see Refs. [8–11].

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 c quark in Eq. (4) could fragment into a D meson, this time of opposite flavor, i.e., a D^+ or D^0, generically labeled D. Thus, to get the full rate due to recombination for producing $\overline{D}$ mesons, we also need to account for the contribution where a light antiquark comes from the proton, while the $\bar{c}$ fragments into a $\overline{D}$. We thus have three contributions,

$$(a)\ d\hat{\sigma}[\overline{D}] = d\hat{\sigma}[qg \to (\bar{c}q)^n + c]\rho[(\bar{c}q)^n \to \overline{D}], \qquad \text{(6a)}$$

$$(b)\ d\hat{\sigma}[\overline{D}] = d\hat{\sigma}[q\bar{c} \to (\bar{c}q)^n + g]\rho[(\bar{c}q)^n \to \overline{D}], \qquad \text{(6b)}$$

$$(c)\ d\hat{\sigma}[\overline{D}] = d\hat{\sigma}[\bar{q}g \to (c\bar{q})^n + \bar{c}]\rho[(c\bar{q})^n \to H] \otimes D_{\bar{c}\to\overline{D}}, \qquad \text{(6c)}$$

where H can be any hadron. The recombination cross section for producing a D is obtained by taking the charge conjugate of the above equations. Below, we will neglect C violation and take $\rho[(\bar{c}q)^n \to \overline{D}] = \rho[(c\bar{q})^n \to D]$. For simplicity, in process (c) we will restrict H to be D or D^* only and sum over $\bar{q} = \bar{u}, \bar{d}$ and $\bar{s}$ with $SU(3)$ flavor symmetry assumed.

As discussed in [10], the nonperturbative parameters $\rho[(\bar{c}q)^n \to \overline{D}]$ with the same flavor and orbital angular momentum quantum numbers as the $\overline{D}$ scale as $\Lambda_{\rm QCD}/m_c$. However, the amplitudes for $(\bar{c}q)^n$ production with $L > 0$ are suppressed relative to the S-wave states. On the other hand, ${}^3S_1 \to D$ transition is achieved via emission of magnetic-type gluons, which, contrary to the heavy quarkonia case, is not suppressed for D mesons. Similarly, unlike the quarkonia case, the soft gluons can radiate color, so the color-octet parameters are not suppressed relative to the color singlet. Thus, the leading contributions to productions of $D^{\pm}$ mesons by heavy quark recombination consists of four possible options of n:

$$\rho_1^{sm} = \rho[c\bar{d}({}^1S_0^{(1)}) \to D^+], \qquad \rho_1^{sf} = \rho[c\bar{d}({}^3S_1^{(1)}) \to D^+],$$
$$\rho_8^{sm} = \rho[c\bar{d}({}^1S_0^{(8)}) \to D^+], \qquad \rho_8^{sf} = \rho[c\bar{d}({}^3S_1^{(8)}) \to D^+]. \qquad (7)$$

These nonperturbative parameters must be extracted from data. Neglecting ρ_1^{sf} and ρ_8^{sf}, the combination $\rho_1^{sm} + \rho_8^{sm}/8$ was determined to be 0.15 by fitting to the E687 and E691 fixed-target photoproduction data [9]. Neglecting ρ_8^{sm}, ρ_1^{sf} and ρ_8^{sf}, the parameter ρ_1^{sm} was determined to be 0.06 by fitting to data from the E791 experiment [10]. In this paper, we take $\rho_1^{sm} \sim 0.06$ and $\rho_8^{sm} \sim 0.7$. It turns out that these two contributions only account for ~10% of the measured asymmetry $A_p = (-0.96 \pm 0.26 \pm 0.18)\%$ at LHCb in Ref. [4]. Therefore, we include ρ_1^{sf} and ρ_8^{sf} and, given the arguments above, choose values of similar size as the spin-matched parameters. We also include feed down from $D^{*\pm}$. From heavy quark spin symmetry, we have

$$\rho[c\bar{d}({}^1S_0^{(c)}) \to D^+] = \rho[c\bar{d}({}^3S_1^{(c)}) \to D^{*+}],$$
$$\rho[c\bar{d}({}^3S_1^{(c)}) \to D^+] = \rho[c\bar{d}({}^1S_0^{(c)}) \to D^{*+}]. \qquad (8)$$

We use MSTW 2008 LO PDFs with $m_c = 1.275$ GeV and the Peterson parametrization for the fragmentation function [12] is used for $D_{c\to H}$:

$$D_{c\to H}(z) = \frac{N_H}{z(1 - \frac{1}{z} - \frac{\epsilon_c}{1-z})^2}. \qquad (9)$$

$\epsilon_c \sim (m_q/m_c)^2$ was measured to be 0.062 ± 0.007 for the D^{*+} meson [13]. Charge conjugation symmetry and approximate heavy quark symmetry implies that ϵ_c is approximately the same for $D^{\pm}$ and $D^{*\pm}$. We will take $\epsilon_c = 0.06$ for both $D^{\pm}$ and $D^{*\pm}$. N_H are determined by the

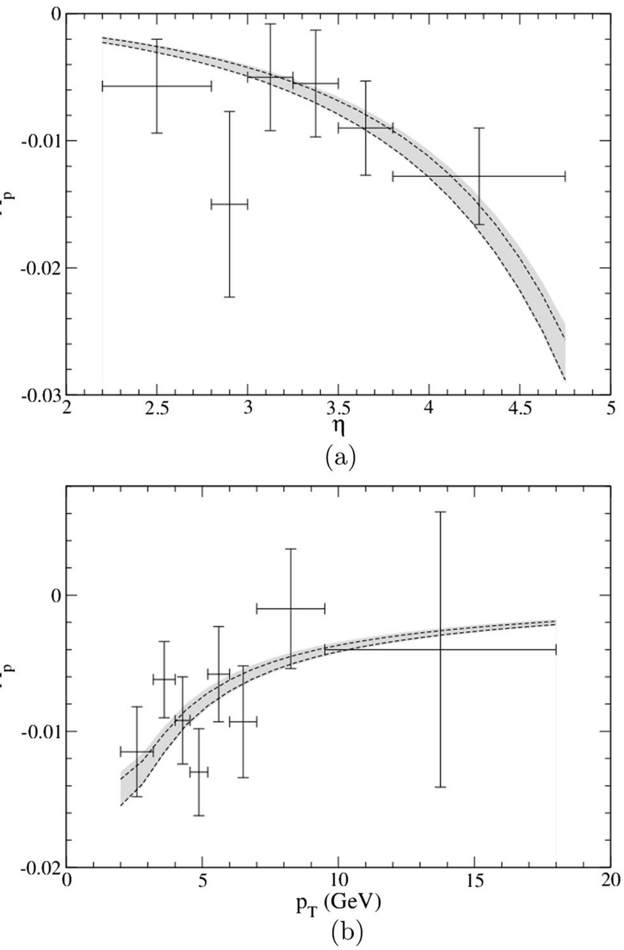

FIG. 2. Asymmetry in $D^{\pm}$ production A_p as a function of (a) pseudorapidity η and (b) transverse momentum p_T in 7 TeV pp collisions. The data points are from LHCb [4]. The grey band is obtained by varying the ρs in the intervals $0.055 < \rho_1^{sm} < 0.065$, $0.65 < \rho_8^{sm} < 0.8$, $0.46 < \rho_1^{sf} < 0.56$ and $0.46 < \rho_8^{sf} < 0.56$ respectively. The dashed lines are from varying $0.055 < \epsilon_c < 0.069$.

averages of the measured fragmentation probabilities listed in [14]. For the perturbative QCD rate, Eq. (3), which has no asymmetry if we ignore C violation but enters into the denominator of Eq. (2), we use the LO cross section. The factorization scale is set to be $\mu_f = \sqrt{p_T^2 + m_c^2}$.

When integrated over $2\ \mathrm{GeV} < p_T < 18\ \mathrm{GeV}$ and $2.2 < \eta < 4.75$, excluding the region with $2\ \mathrm{GeV} < p_T < 3.2\ \mathrm{GeV}$, $2.2 < \eta < 2.8$, the asymmetry A_p for $D^\pm$ is found to be $-0.88\% < A_p < -1.05\%$ with $0.055 < \rho_1^{sm} < 0.065$, $0.65 < \rho_8^{sm} < 0.8$, $0.46 < \rho_1^{sf} < 0.56$ and $0.46 < \rho_8^{sf} < 0.56$. Figure 2 shows A_p as a function of pseudorapidity η and transverse momentum p_T of the $D^\pm$ mesons as predicted by the heavy quark recombination mechanism. Data from Ref. [4] are shown as well. The grey band is from varying the ρ parameters within the ranges above. The dashed line is obtained using the central value of the ρ parameters and varying ϵ_c within its error bars. The calculated distributions are reasonably consistent with the data.

In summary, we have calculated the $D^\pm$ asymmetry using the heavy quark recombination mechanism for production at the LHCb experiment. The measured asymmetry of $A_p = -0.96 \pm 0.26 \pm 0.18\%$ in the kinematic range $2.0\ \mathrm{GeV} < p_T < 18\ \mathrm{GeV}$ and $2.2 < \eta < 4.75$ [4] can be reproduced using reasonably sized nonperturbative parameters $\rho_{1,8}^{sm,sf}$. Further, the p_T and η distributions are simultaneously reproduced by the heavy quark recombination mechanism.

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