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Intrinsic charm and the $D^+ - D^-$ asymmetry produced in proton-proton collisions

G.I. Lykasov,[a,*] **M.N. Sorokovikov**[a] **and S.J. Brodsky**[b]

[a] *Joint Institute for Nuclear Research, 141980, Dubna, Moscow region, Russia*

[b] *SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, United States*

E-mail: gennady.lykasov@cern.ch

We investigate the contribution of the charm-anticharm ($c\bar{c}$) asymmetry of the proton eigenstate obtained from QCD lattice gauge to the asymmetry of D^+, D^- and $D^0, \bar{D}^0$ mesons produced in pp collisions at large Feynman variables x. Predictions for the asymmetry as function of x for different probabilities of intrinsic charm (IC) in proton are presented.

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According to Quantum Chromodynamics (QCD), the heavy quarks in the nucleon sea have both perturbative *extrinsic* and non-perturbative intrinsic heavy quark (*IQ*) components. The extrinsic sea quarks arise from gluon splitting, which is triggered by a probe in the reaction. It can be calculated in QCD within perturbation theory. In contrast, the intrinsic sea quarks are contributions within the non-perturbative wave functions of the nucleon eigenstate which do not depend on the probe. The existence of non-perturbative intrinsic charm *IC* was originally proposed in the BHPS model [1] and developed further in subsequent papers [2–9].

Recently a new prediction for the non-perturbative intrinsic charm-anticharm asymmetry of the proton eigenstate has been obtained from a QCD lattice gauge theory calculation of the proton's $G_E^p(Q^2)$ form factor [10]. This form factor arises from the fact that the non-valence quarks and anti-quarks have different distributions in the proton's eigenstate. This result predicts a significant non-perturbative $c(x,Q) - \bar{c}(x,Q)$ asymmetry in the proton structure function at high x, consistent with the dynamical features predicted by intrinsic charm models.

In this paper we analyze the heavy hadron asymmetry arising from nonperturbative sources of intrinsic charm in detail. For the calculation of the inclusive D-meson spectra and the $D\ \bar{D}$ asymmetry in pp collisions, we use the quark-gluon string model (QGSM),see [11, 12] and references therein. We show why the asymmetry of $D\ \bar{D}$ mesons can be an ideal tool for identifying the *IC* content in the proton in comparison to the inclusive D-meson inclusive spectra.

The inclusive spectrum of hadrons produced in pp collisions as a function of the Feynman variable x within the QGSM is presented in the following form [11, 12]:

$$\rho_h(x) = \int E\frac{d^3\sigma}{d^3p}d^2p_\perp = \sum_{n=0}^{\infty}\sigma_n(s)\varphi_n^h(s,x), \tag{1}$$

where $\sigma_n(s)$ is the cross section of $2n$-strings (chains) production, corresponding to the s-channel discontinuity of the multi-pomeron diagrams. The analysis is performed for pomerons with n cuts and an arbitrary number of external pomerons taking into account elastic re-scattering. Here $\varphi_n^h(s,x)$ is the x-distribution of the hadron h produced in the fission of $2n$ quark-gluon strings: $\varphi_0^h(s,x)$ accounts for the contribution of the diffraction dissociation of colliding hadrons, $n = 1$ corresponds to the strings formed by valence quarks and diquarks; terms with $n > 1$ are related to sea quarks and antiquarks.

The cross sections $\sigma_n(s)$ were calculated in the quasi-eikonal approximation which accounts for the low-mass diffractive excitation of the colliding particles and corresponds to maximum inelastic diffraction consistent with the unitarity condition. Only non-exchanged graphs were considered, neglecting the interactions between pomerons.

We note that the sea quark distributions within the QGSM have the same forms as the valence quarks; however, they contribute to inclusive hadron spectra starting from two-pomeron exchange, i. e., at $n \geq 2$.

The distribution of the sea charmed quark in the proton has the following form within the QGSM, see [12] and references therein:

$$f_{c\bar{c}}^{(n)} = C_{c\bar{c}}\delta_{c\bar{c}}x^{a_c}(1-x)^{b_c^n}\ , \tag{2}$$

where $a_c = -\alpha_\psi(0)$ and $b_c^n = 2\alpha_R(0) - 2\alpha_N(0) - \alpha_\psi(0) + n - 1$; $\delta_{c\bar{c}}$ is the weight of the sea $c\bar{c}$ in the proton. The coefficient $C_{c\bar{c}}$ is determined from the normalization condition

$$\int_0^1 f_{c\bar{c}}^{(n)}(x)dx \ = \ C_{c\bar{c}} \tag{3}$$

$$C_{c\bar{c}} = \frac{\Gamma(2 + a_c + b_c^n)}{\Gamma(1 + a_c)\Gamma(1 + b_c^n)}. \tag{4}$$

Here $\Gamma(\alpha)$ is the gamma function. The distribution of the sea bottom quark in proton has the following form within QGSM, see [12] and references therein:

$$f_{b(\bar{b})}^{(n)} \ = \ C_{b(\bar{b})}\delta_{b(\bar{b})}x_b^a(1-x)^{b_b^n} \ , \tag{5}$$

where $a_b = -\alpha_Y(0)$ and $b_b^n = 2\alpha_R(0) - 2\alpha_N(0) - \alpha_Y(0) + n - 1$, $\delta_{b(\bar{b})}$ is the weight of the sea $b\bar{b}$ pairs in the proton. The normalization coefficient $C_{b(\bar{b})}$ has the similar form as Eq. (4) by replacing a_c, b_c^n into a_b, b_b^n.

We now include the contribution of IC in the sea charmed quark distributions obtained within the QGSM. We modify Eq. (2) to the form

$$f_{c\bar{c}}^{(n)}(x) \rightarrow (1-w)f_{c\bar{c}}^{(n)}(x) + wf_{c\bar{c}}^{in}(x), \tag{6}$$

where w is the probability of the IC contribution in the proton and $f_{c\bar{c}}^{in}$ is the intrinsic charm contribution to the conventional charm distribution $f_{c\bar{c}}^{(n)}(x)$ at $n \geq 2$ given by Eq. (2). The form of $f_{c\bar{c}}^{in}$ in the case of a symmetric $c\bar{c}$ sea in the proton, calculated within the BHPS model [1] at $Q^2 = m_c^2$, has the following form

$$f_{c\bar{c}}^{in}(x) \ = \ 600x^2\left\{(1-x)(x^2+10x+1) + 6x(x+1)ln(x)\right\} \ , \tag{7}$$

with the normalization condition

$$\int_0^1 f_{c\bar{c}}^{in}(x)dx \ = \ 1. \tag{8}$$

The asymmetric intrinsic $f_{c(\bar{c})}^{in}(x)$ distributions obtained within the meson cloud-model, where the $|uudc\bar{c}\rangle$ Fock state can be identified with the $|\Lambda_{udc}D_{\mathrm{u}\bar{\mathrm{c}}}\rangle$ off-shell excitation of the proton. This distribution is parameterized in the following form (see [12] and references therein):

$$f_c^{in}(x) \ = \ Bx^{1.897}(1-x)^{6.095} \tag{9}$$

and

$$f_{\bar{c}}^{in}(x) \ = \ \bar{B}x^{2.5}(1-x)^{4.929} \ , \tag{10}$$

where $B/\bar{B}$ is determined by the quark number sum rule :

$$\int_0^1 \left\{f_c^{in}(x) - f_{\bar{c}}^{in}(x)\right\}dx \ = 0 \ . \tag{11}$$

Generally the probability of the intrinsic heavy quark-anti quark $Q\bar{Q}$ contribution in the proton is proportional to $1/M_Q^2$. It means that the coefficients B and $\bar{B}$ are proportional to $1/M_Q^2$. The light-front x-distribution $f_{\bar{c}}^{in}(x)$ for the intrinsic $\bar{c}$ quarks is calculated as follows:

$$f_{\bar{c}}^{in}(x) = f_c^{in}(x) - \Delta c(x) \ , \tag{12}$$

where the difference $\Delta c(x) = [c(x) - \bar{c}(x)]$, obtained using lattice QCD, was taken from [10].

In Fig. (1) the inclusive x-spectrum of D^0 mesons produced in pp collisions at the initial energy in the laboratory system E_{lab} = 400 GeV ($\sqrt{s}$ = 27.42 GeV) is presented. One can observe a good description of NA27 data for D^0-mesons. The results are presented at different values of the *IC* probabilities $\omega = 0.01$ (BHPS1) and $\omega = 0.035$ (BHPS2), including both the important interference effect and without it; see Appendix of ref. [12]. One can see that the maximum signal of the *IC* contribution to the spectrum is less than 1%. The NA27 data on $D^\pm$ meson [13] production have large error bars, much larger than the data on $D^0(\bar{D}^0)$; therefore, we compare our calculations with the data for $D^0(\bar{D}^0)$ mesons.

In an important recent development [10], the difference of the nonperturbative charm and anticharm quark distributions in the proton $\Delta c(x) = c(x) - \bar{c}(x)$ has been computed using lattice gauge theory. The predicted $\Delta c(x)$ distribution is non-zero at large $x \geq 0.4$, remarkably consistent with the expectations of intrinsic charm. The $c(x)$ vs. $\bar{c}(x)$ asymmetry can be understood physically by identifying the $|uudc\bar{c}\rangle$ Fock state with the $|\Lambda_{udc} D_{\mathrm{u}\bar{\mathrm{c}}}\rangle$ off-shell excitation of the proton.

Let us calculate the asymmetry $A_{D^0\bar{D}^0}(x)$ and $A_{D^-D^+}(x)$ for D-mesons produced in pp collisions, including the asymmetry between the intrinsic c-quark and $\bar{c}$ quark as a function of x.

$$A_{D^0\bar{D}^0}(x) = \frac{d\sigma_{D^0}/dx - d\sigma_{\bar{D}^0}/dx}{d\sigma_{D^0}/dx + d\sigma_{\bar{D}^0}/dx} \tag{13}$$

$$A_{D^-D^+}(x) = \frac{d\sigma_{D^-}/dx - d\sigma_{D^+}/dx}{d\sigma_{D^-}/dx + d\sigma_{D^+}/dx} \tag{14}$$

The calculation of these asymmetries was done within two sets. The first one *Set 1* corresponds to use Eqs.(9,10) for distributions $f_c^{in}(x)$ and $f_{\bar{c}}^{in}(x)$ respectively obtained in [**?**] within the the meson cloudy bag model. *Set 2* was performed using Eq.9 for $f_c^{in}(x)$ and calculating $f_{\bar{c}}^{in}(x)$ from Eq. (12) because only $\Delta c(x)$ was calculated in [10] within the lattice QCD.

The calculations were done taking into account the interference between different parton contributions, also including the important interference between the contributions of extrinsic and intrinsic quarks, see [12].

The inclusion of the interference effects increases the asymmetry at $0 < x < 0.4$ by a maximum of (25-30)% for both calculations *Set 1* and *Set 2*, as it is seen in Fig. 2. Our calculations have showed very small *IC* contribution for the $D^0\bar{D}^0$ asymmetry [12].

The asymmetry $A_{D^-D^+}(x)$ as a function of x using *Set 1* (left) and *Set 2* (right) is presented in Fig. 2. In the bottom of these plots, the ratios of the asymmetry for non-zero *IC* probability ω_c to the asymmetry at $\omega_c = 0$ are presented. The *Set 1* is more sensitive to the *IC* probability ω_c compared to *Set 2*, if we compare the bottom plots in Fig. 2. The difference between the left and right panels of Fig. (2) is due to the absence of information on the separate distributions $c(x)$ and $\bar{c}(x)$

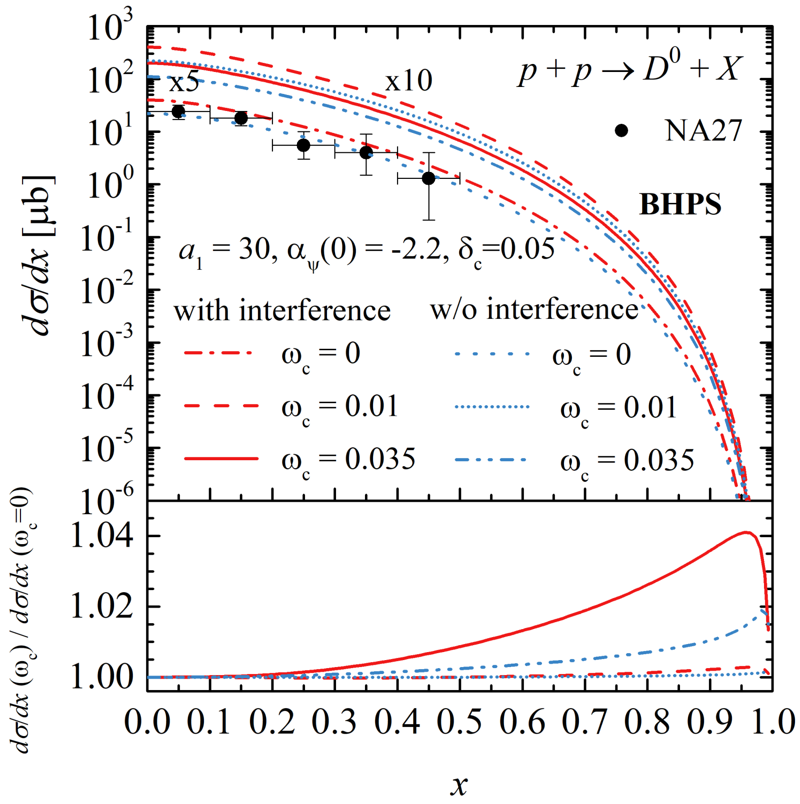

Figure 1: The x-distribution of the inclusive spectrum of D^0-mesons produced in pp collisions at the initial energy E_{lab} = 400 GeV and $0 \le x \le 1$. Top: the inclusive spectrum at different values of ω with and without (w/o) the interference of the quark (diquark) and the sea quark (extrinsic and intrinsic) amplitudes. The interference between the extrinsic and intrinsic quark contributions are also taken into account; see Appendix. The NA27 data were taken from [13]. Bottom: the ratio of the x-spectrum for the nonzero *IC* probability ω_c to the spectrum at $\omega_c = 0$, with interference and without it. With interference: slid red line at $\omega_c = 0.035$, dashed red line at $\omega_c = 0.01$. Without interference (w/o): double dashed blue line at ω_c = 0.035, dotted blue line at $\omega_c = 0.01$. The calculations were done using the *IC* distributions in forms of Eqs.(9,10), labeled as **BHPS**.

obtained within the **Lattice** QCD, in [10] only $\Delta c(x)$ is presented. It is not sufficient to calculate the asymmetry precisely. The maximum value of the D^-D^+ asymmetry could be about 50% at $x \simeq$ 0.9 at $a_1 = 2$ (right bottom in figure). Both bottom panels of Fig. 2 show a sizable sensitivity of the asymmetry to the interference effects at large x. The interference effects for the D^-D^+ asymmetry increase, when x grows, as Fig. 2 shows. Note that the interference between different amplitudes estimated in Appendix is maximal, when the relative phase angle between different amplitudes is approximately zero, i.e., the constructive sum of the amplitudes is calculated. The form of the $A_{D^-D^+}(x)$ enhancement at large x corresponding to the positive difference $d\sigma_{D^-}/dx - d\sigma_{D^+}/dx$ at 0.5< x <1.0 is determined mainly by the FF of quarks and diquarks to D^- or D^+, which are presented in the Appendix of [12].

The experimental data of WA82 [14] and E769 [15] for $D\bar{D}$ production in $\pi^- p$ production at initial momenta 250 GeV/c and 340 GeV/c display an increase of the D^-D^+ asymmetry as a

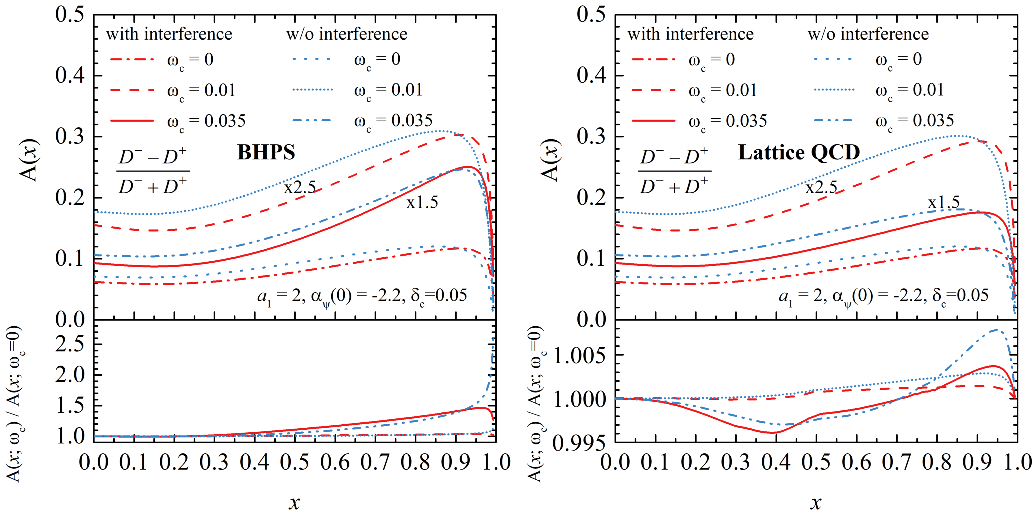

Figure 2: The plots for asymmetry $A_{D^-D^+}(x)$ with the same notations as in Fig.1.

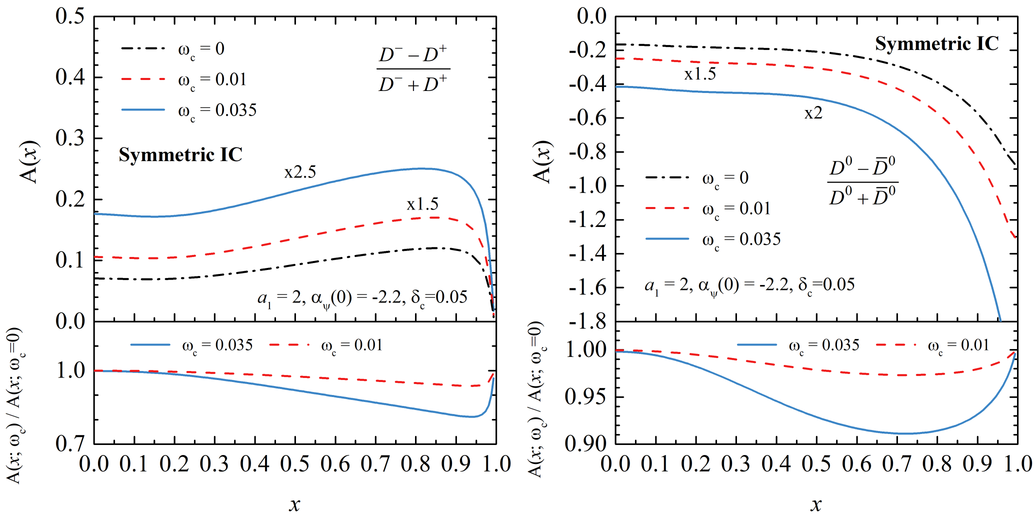

Figure 3: The plots of the asymmetries $A_{D^-D^+}(x)$ (left) and $A_{D^0\bar{D}^0}(x)$ (right) using the symmetric *IC* distribution, according to Eq. (6) with the same notations as in Fig. 1.

function of x, consistent with the calculation of $A_{D^-D^+}(x)$ presented in Fig. 2.

In Fig.(3) the asymmetries D^+D^- (left) and $D^0\bar{D}^0$ (right) are presented for the symmetric *IC* distribution given by Eq. (6). Comparing Fig.(2) and Fig.(3) one can see that both asymmetries change sign if the asymmetric *IC* distributions are included. This is a very important signal for identifying the *IC* contribution in the proton.

We have shown that the inclusion of the asymmetric *IC* components in the proton as calculated within the meson cloudy-bag model leads to the enhancement of the D^-D^+ asymmetry at x >0.7. The *IC* signal of this asymmetry depends on the intrinsic charm probability w_c. The maximal deviation of the D^-D^+ asymmetry compared to the prediction for zero *IC* is about 50% at $x \simeq 0.9$ and w_{IC} =3.5%. In principle, such a deviation in the range of 15%-20% can be experimentally observed.

As for the $D^0\bar{D}^0$ asymmetry in pp collisions, the *IC* signal is too small, less than 1% even at large *IC* probability w_c =3.5%.

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