

Charm production asymmetry at the LHC

E.R. Cazaroto¹, V.P. Goncalves², F.S. Navarra¹ and M. Nielsen¹

¹ Instituto de Física, Universidade de São Paulo, C.P. 66318, 05315-970, São Paulo, SP, Brazil

² Instituto de Física e Matemática, Universidade Federal de Pelotas, C.P. 354, CEP 96010-900, Pelotas, RS, Brazil.

E-mail: navarra@if.usp.br

Abstract. In this work we use the meson cloud model to study the energy dependence of the asymmetry in D meson production in $p-p$ collisions. We find a good agreement with the recent data from LHCb on D^-/D^+ asymmetry. Although small, this asymmetry may shed light on the role played by the charm meson cloud of the proton.

1. Introduction

It is well known from experiments [1, 2, 3, 4, 5, 6] that the production of D^+/D^- in hadronic collisions is not exactly symmetric. For large x_F (Feynman momentum) it is clearly observed that there are more D^- 's than D^+ 's produced in pp , Σ^-p and π^-p collisions. The recent data from COMPASS collaboration [7] have confirmed that charm production asymmetry is also observed in γp collisions, and the very recent data from LHCb collaboration [8] on pp collisions at 7 TeV show a very small (but different of zero) asymmetry. The origin of the observed asymmetries is still an open question and cannot be explained with usual perturbative QCD (pQCD) or with the string fragmentation model contained in PYTHIA. This fact motivated the construction of alternative models [9, 10, 11] that were able to obtain a reasonable description of the low energy data and make predictions for higher energies. Now we can, for the first time, compare the predictions of these models with the high energy data from LHCb and study the energy dependency of the production asymmetry.

2. Charm production asymmetry

The production asymmetry is quantified as:

$$A = \frac{N_{D^-} - N_{D^+}}{N_{D^-} + N_{D^+}} \quad (1)$$

where N_i represents the number of mesons i produced as a function of, e.g., the Feynman x_F variable. In pQCD the most relevant elementary processes of charm production are $q + \bar{q} \rightarrow c + \bar{c}$ and $g + g \rightarrow c + \bar{c}$. At high energies the distribution of gluons is much larger than the one of any other parton and the second process dominates. After being produced the c and \bar{c} quarks fragment independently and the resulting D^+ and D^- (also D^0 and \bar{D}^0) mesons will have the same rapidity y , p_T and x_F distributions. Consequently, in calculations using pQCD there is no production asymmetry ($A = 0$). This is indeed true for the bulk of charm production. Experimental results on hadronic collisions show that differences between the D^+ and D^- x_F



distributions appear at large x_F , with D^- being harder. Given the valence quark content of the proton $p(ud)$ and of the $D^-(d\bar{c})$, a natural explanation of the observed effect is that the \bar{c} is “dragged” by the projectile valence d quark, forming the, somewhat harder, $d\bar{c}$ bound state. This process, that has been called “recombination” (or coalescence), is a non-perturbative process. Recombination models have been first proposed long time ago [12, 13, 14] and then used more recently [15, 16] to study the accumulated experimental data and to make predictions for the RHIC collisions.

A possible way to implement the idea of recombination is to use models in which the proton is a fluctuating object. In this approach, before colliding with the target the proton projectile fluctuates into a “charm baryon - charm meson” virtual pair. The charmed meson can be liberated during the interaction, being present in the final state of the collision. This type of fluctuation happens all the time. Sometimes the proton fluctuates into a virtual pair “pion - neutron” and then the virtual pair recombines back to its original form, the proton. It was shown [17] that this type of fluctuation is quite relevant to the understanding of hadron structure. This mechanism, in which the “meson cloud” plays a major role (see [18] for light mesons) is usually called the Meson Cloud Model (MCM). A simple and accurate description of charm asymmetry production at lower energies ($\sqrt{s} \simeq 10 - 40$ GeV) within the framework of the MCM can be found in [19].

In Fig. 1 we show an illustration of D^+/D^- production in the meson cloud approach. Before the collision, the proton projectile fluctuates into a virtual meson-baryon (MB) pair. Fig. 1 and 1 b show the situation in which the meson (the baryon) scatters with the target producing a system X of particles. The system X contains all sorts of particles, including the mesons D^+ and D^- , however there is no asymmetry since the D^+ and the D^- are identically distributed. In what follows we shall call it “indirect production” (I) of D^\pm . The production asymmetry happens when the proton fluctuates into a pair $\Sigma_c^{++}D^-$ and the D^- is liberated by the interaction with the target, as shown in Fig. 1c. We shall call it “direct production” (D) of D^- . This last mechanism is, of course, very much suppressed but it is the responsible for the asymmetry because only D^- is produced in this process. This happens because the valence quark content of the proton (uud) only allows its fluctuation into a baryon-meson pair where the meson is always $D^- (d\bar{c})$ and never $D^+ (\bar{d}c)$. The meson and the baryon in the cloud have fractional momentum y_M and y_B , with distributions called $f_{M/MB}(y_M)$ and $f_{B/MB}(y_B)$ respectively (we shall use for them the short notation f_M and f_B). Of course, by momentum conservation, $y_M + y_B = 1$ and these distributions are related by [17, 20]:

$$f_M(y) = f_B(1 - y) \quad (2)$$

The “splitting function” $f_M(y)$ represents the probability density to find a meson with momentum fraction y of the total cloud state MB . With f_M and f_B we can compute the differential cross section of D production. In the reaction $pp \rightarrow D^- X$ the differential cross section of D^- production is given by:

$$\frac{d\sigma^{pp \rightarrow DX}}{dx_F} = \Phi_0 + \Phi_I + \Phi_D \quad (3)$$

where Φ_0 and Φ_I refer respectively to “bare” and indirect contributions to D meson production and x_F is the fractional longitudinal momentum of the outgoing meson. By “bare” contribution we mean the process in which the hadron projectile does not fluctuate into any cloud state. The bare contribution is responsible for most of the production and does not generate any asymmetry. The term Φ_D represents the direct process depicted in Fig. 1c and is given by [21, 20]:

$$\Phi_D = \frac{\pi}{x_F} f_D(x_F) \sigma^{\Sigma p} \quad (4)$$

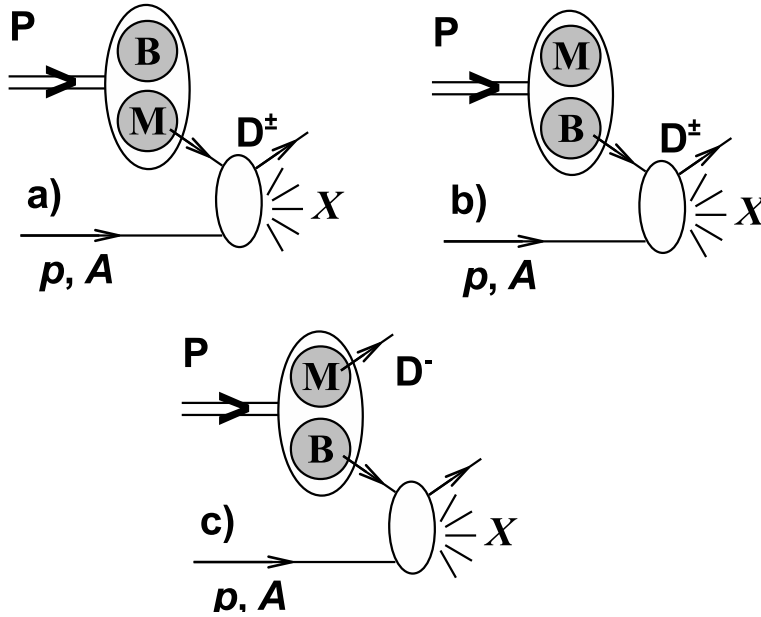


Figure 1. pp collision in which the projectile is in a MB state. Figs. a) and b) show the “indirect” D^\pm production and c) the “direct” D^- production.

where $f_D \equiv f_{D^-/\Sigma_c^{++}D^-}$ and $\sigma^{\Sigma p}$ is the total $p\Sigma_c^{++}$ cross section. The term Φ_I in Eq. (3) can generate some asymmetry, however we can neglect its contribution when compared with the asymmetry generated by the term Φ_D . Thus the D^+/D^- production asymmetry is given by [22]:

$$A^D(x_F) = \frac{\frac{d\sigma^{D^-}(x_F)}{dx_F} - \frac{d\sigma^{D^+}(x_F)}{dx_F}}{\frac{d\sigma^{D^-}(x_F)}{dx_F} + \frac{d\sigma^{D^+}(x_F)}{dx_F}} \simeq \frac{\Phi_D}{\Phi_T^D} \quad (5)$$

where Φ_T^D is the total $D^+ + D^-$ x_F distribution. The denominator of this expression can be replaced by a parametrization of the experimental data [1, 2, 3, 4, 5, 6], being given by [22]:

$$\Phi_T^D = \frac{d\sigma^{D^-}(x_F)}{dx_F} + \frac{d\sigma^{D^+}(x_F)}{dx_F} \simeq 2\sigma_0^D (1 - x_F)^{n_D} \quad (6)$$

where $n_D = 5$ for D mesons [22]. Integrating the above expression we obtain the total cross section for charged charm meson production $\sigma^{D^\pm} = 1/3 \sigma_0^D$. Assuming isospin symmetry the charged and neutral (σ^{D^0}) production cross sections are equal. Neglecting the contribution of other (heavier) charm states we can relate the D meson production cross section to the total $c - \bar{c}$ production cross section, $\sigma_{c\bar{c}}$, in the following way:

$$\sigma^{D^\pm} = \sigma^{D^0} = \frac{1}{3}\sigma_0^D = \frac{1}{2}\sigma_{c\bar{c}}. \quad (7)$$

From the above relation we can extract the parameter σ_0^D from the experimentally measured $\sigma_{c\bar{c}}$:

$$\sigma_0^D = 1.5 \sigma_{c\bar{c}}. \quad (8)$$

Inserting (4) and (6) into (5) the asymmetry becomes:

$$A^D(x_F) = \frac{\pi \sigma^{\Sigma p}}{2 \sigma_0^D} \frac{f_D(x_F)}{x_F (1 - x_F)^{n_D}}. \quad (9)$$

The behavior of the asymmetry, Eq. (9), is controlled by the splitting function $f_D(x_F)$. For the splitting function we will use the Sullivan approach [17, 20]. The fractional momentum distribution of a pseudoscalar meson M in the Fock state $|MB'\rangle$ (of a baryon $|B\rangle$) is given by [17, 20]:

$$f_M(y) = \frac{g_{MBB'}^2}{16\pi^2} y \int_{-\infty}^{t_{max}} dt \frac{[-t + (m_{B'} - m_B)^2]}{[t - m_M^2]^2} F_{MBB'}^2(t) \quad (10)$$

where t and m_M are the four momentum square and the mass of the meson in the cloud state and

$$t_{max} = m_B^2 y - m_{B'}^2 \frac{y}{1-y}$$

is the maximum t , with m_B and $m_{B'}$ being the B and B' masses respectively. Following a phenomenological approach, we use for the baryon-meson-baryon form factor $F_{MBB'}$ the exponential form:

$$F_{MBB'}(t) = \exp\left(\frac{t - m_M^2}{\Lambda_{MBB'}^2}\right) \quad (11)$$

where $\Lambda_{MBB'}$ is the form factor cut-off parameter. Considering the particular case where $B = p$, $B' = \Sigma_c^{++}$ and $M = D^-$, we insert (10) into (9) to obtain the final expression for the asymmetry in our approach:

$$A^D(x_F) = \frac{N^D}{(1-x_F)^{n_D}} \int_{-\infty}^{t_{max}} dt \frac{[-t + (m_\Sigma - m_p)^2]}{[t - m_D^2]^2} F_{pD\Sigma}^2 \quad (12)$$

where

$$N^D = \frac{g_{pD\Sigma_c}^2 \sigma^{\Sigma_c p}}{32 \pi \sigma_0^D} \quad (13)$$

Noticing that $y = x_F$ in the above equations, we can see that in the limit $x_F \rightarrow 1$, $t_{max} \rightarrow -\infty$, and the integral in (12) goes to zero. In fact, it vanishes faster than the denominator and therefore $A \rightarrow 0$. This behavior does not depend on the cut-off parameter but it depends on the choice of the form factor. For a monopole form factor we may obtain asymmetries which grow even at very large x_F . Before presenting the results we emphasize that they depend only on two parameters: Λ and N . Whereas Λ affects the width and position of the maximum of the momentum distribution of the leading meson in the cloud (and consequently of the asymmetry), N is a multiplicative factor which determines the strength of the asymmetry.

3. Results and discussion

Although the recent data [8] are given in terms of the pseudo-rapidity η , in order to study the energy dependence it is more convenient to use the Feynman x_F variable, which for $\eta > 1$ is given by $x_F \simeq 2m_T e^\eta / \sqrt{s}$. If the transverse momentum of the final D meson is zero or very small we have $m_T \simeq m_D$.

In order to study the energy dependence of the asymmetry we shall consider the two energies where we have experimental data: $\sqrt{s_1} = 33$ GeV and $\sqrt{s_2} = 7000$ GeV (see Table 1). Let us consider the asymmetry ratio $R_A = A(\sqrt{s_2})/A(\sqrt{s_1})$. Using the definitions of the splitting function (10) in (4) and then in (5), many energy independent factors cancel out and we find:

$$R_A = \frac{A(s_2)}{A(s_1)} = \left(\frac{\sigma^\Sigma(s_2)}{\sigma^\Sigma(s_1)}\right) / \left(\frac{\sigma_0^D(s_2)}{\sigma_0^D(s_1)}\right) = \left(\frac{\sigma^{pp}(s_2)}{\sigma^{pp}(s_1)}\right) / \left(\frac{\sigma_{c\bar{c}}(s_2)}{\sigma_{c\bar{c}}(s_1)}\right) \quad (14)$$

where in the last step we have used (8) and assumed that $\sigma^\Sigma = \sigma^{\Sigma_c^{++} p} = \text{const.} \sigma^{pp}$. Moreover, we have neglected the energy dependence of n_D . The above ratios can be estimated with the

Table 1. Total pp cross section from [23] and total $c\bar{c}$ production cross section from [24] as a function of the energy. The first two lines refer to measurements and the last one show model calculations described in the corresponding references.

Energy (GeV)	σ_{pp} (mb)	$\sigma_{c\bar{c}}$ (mb)
33	40	0.04
7000	97	8
14000	110	11

recently obtained experimental data listed in Table 1. For $\sqrt{s_1} = 33$ GeV and $\sqrt{s_2} = 7000$ GeV we obtain $R_A = 1/75$. Therefore there is a strong decrease in the asymmetry when we increase the energy. This happens because the responsible for the asymmetry is meson emission, a non-perturbative process, which has a slowly growing cross section. In contrast, the symmetric processes are driven by the perturbative partonic interactions, which have strongly growing cross sections. With the data presented in Table 1 we can make the prediction for the order of magnitude of the D^+/D^- asymmetry in the forthcoming 14 TeV pp collisions. Using the last line of Table 1, setting $\sqrt{s_2} = 14$ TeV and substituting the numbers in (14) we find $R_A = 1/100$ showing the decreasing trend of the asymmetry.

Due to the lack of experimental data a direct comparison of D^+/D^- asymmetries in the same reaction, e.g. proton-proton, at different energies is difficult. However, we can relate and compare similar reactions. In [22] we related the two sets of data on asymmetries in proton-proton collisions: the low energy one taken by the SELEX collaboration [6] and the high energy one obtained by the LHCb collaboration [8]. In Ref. [22], using the definition (13) we made an estimate for N^D ($N^D \simeq 32$).

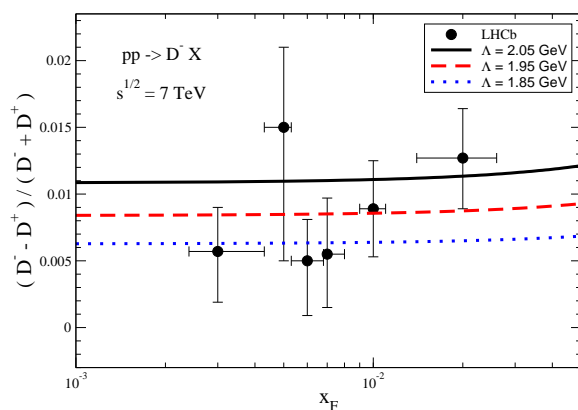


Figure 2. Comparison of the MCM asymmetry with experimental data [8] for D^-/D^+ .

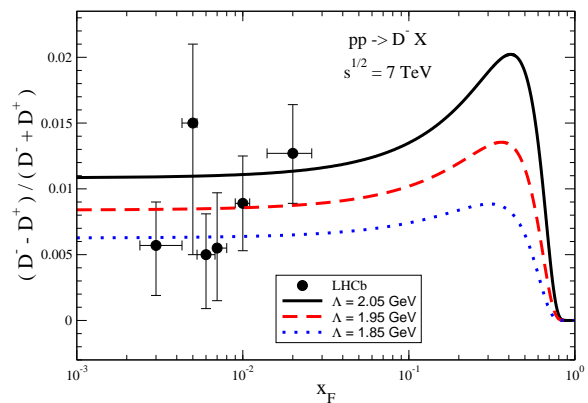


Figure 3. Comparison of the MCM asymmetry with experimental data [8] for D^-/D^+ . Extension of Fig. 2 to the large x_F region.

Since we do not have data on D meson asymmetry at $\sqrt{s} = 33$ GeV we fixed the values of the cut off parameter by fitting the data of LHCb at $\sqrt{s} = 7$ TeV. In Fig. 2 we show the curves corresponding to the different cut off parameters. The values of Λ used to draw the curves are quite reasonable. It is interesting to amplify the region of higher x_F in Fig. 2, where we do not have experimental data. The amplified curves are shown in Fig. 3. Having fixed all the

parameters at the LHC energy, we can go back to the energy $\sqrt{s} = 33$ GeV and compute the asymmetry. This is shown in Fig. 4. Comparing Figs. 3 and 4 we draw the most important conclusion of this work: the asymmetry definitely decreases at increasing energies, reaching at most 2 % at $x_F \simeq 0.4$.

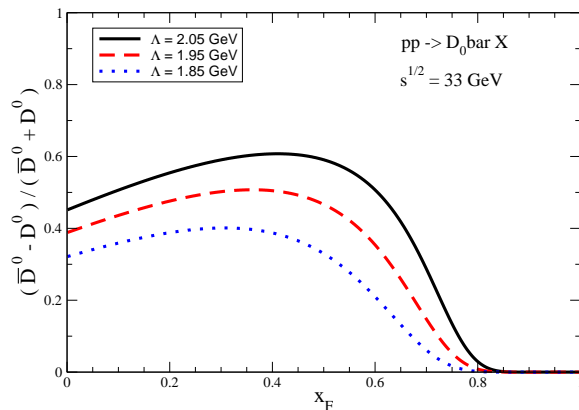


Figure 4. MCM prediction of the \bar{D}^0/D^0 asymmetry for $\sqrt{s} = 33$ GeV.

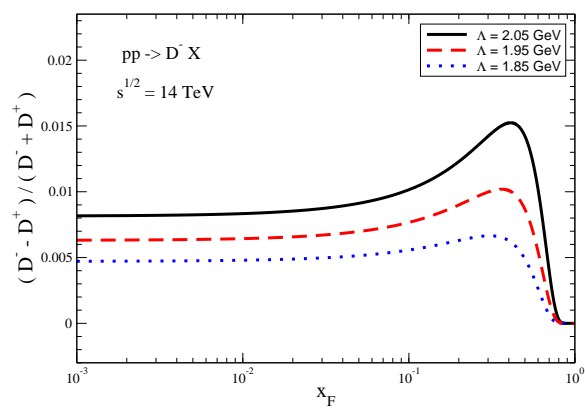


Figure 5. Prediction of the D^-/D^+ asymmetry for $\sqrt{s} = 14$ TeV.

Finally, in Fig. 5 we show our prediction for the D^-/D^+ asymmetry to be measured at $\sqrt{s} = 14$ TeV.

Acknowledgments

This work has been partially supported by the brazilian funding agencies CNPq and FAPESP.

References

- [1] Adamovich M I *et al* (WA82 Collab.) 1993 *Phys. Lett. B* **306** 402
- [2] Alves G A *et al* (E769 Collab.) 1996 *Phys. Rev. Lett.* **77** 2392
- [3] Aitala E M *et al* (E791 Collab.) 1997 *Phys. Lett. B* **411** 230
- [4] Adamovich M I *et al* (WA92 Collab.) 1997 *Nucl. Phys. B* **495** 3
- [5] Adamovich M I *et al* (WA89 Collab.) 1999 *Eur. Phys. J. C* **8** 593
Adamovich M I *et al* (WA89 Collab.) 2000 *Eur. Phys. J. C* **13** 247
- [6] Garcia F G *et al* (SELEX Collab.) 2002 *Phys. Lett. B* **528** 49
Iori M *et al* (SELEX Collab.) 1999 *Nucl. Phys. B Proc. Suppl.* **75** 16 (*Preprint hep-ex/0009049*)
Anjos J C and Cuautle E 2000 *Preprint hep-ph/0005057*
- [7] Adolph C *et al* (COMPASS Collaboration) 2012 *Preprint hep-ex/1211.1575*
- [8] Aaij R *et al* (LHCb Collaboration) 2013 *Phys. Lett. B* **718** 902 (*Preprint hep-ex/1210.4112*)
- [9] Navarra F S, Nielsen M, Nunes C A A and Teixeira M 1996 *Phys. Rev. D* **54** 842
Paiva S, Nielsen M, Navarra F S, Durães F O and Barz L L 1998 *Mod. Phys. Lett. A* **13** 2715
Melnitchouk W and Thomas A W 1997 *Phys. Lett. B* **414** 134
- [10] Brodsky S J, Hoyer P, Peterson C and Sakai N 1980 *Phys. Lett. B* **93** 451
- [11] Vogt R, Brodsky S J and Hoyer P 1991 *Nucl. Phys. B* **360** 67
Vogt R and Brodsky S J 1995 *Nucl. Phys. B* **438** 261
Vogt R and Brodsky S J 1996 *Nucl. Phys. B* **478** 311
Gutierrez T and Vogt R 1999 *Nucl. Phys. B* **539** 189
- [12] Das K P *et al* 1977 *Phys. Lett. B* **68** 459 (*Erratum* 1978 *Phys. Lett. B* **73** 504)
Chiu C B *et al* 1979 *Phys. Rev. D* **20** 211
- [13] Hwa R 1980 *Phys. Rev. D* **22** 1593
Hwa R 1995 *Phys. Rev. D* **51** 85
- [14] Kartvelishvili V G *et al* 1981 *Sov. J. Nucl. Phys.* **33** 434 (*Yad. Fiz.* 1981 **33** 832)
Likhoded A K *et al* 1983 *Sov. J. Nucl. Phys.* **38** 433 (*Yad. Fiz.* 1983 **38** 727)
- [15] Cuautle E *et al* 1998 *Eur. Phys. J. C* **2** 473

- Braaten E *et al* 2002 *Phys. Rev. Lett.* **89** 122002
Mehen T 2004 *Acta Phys. Polon. B* **35** 121
Mehen T 2004 *AIP Conf. Proc.* **698** 508
Mehen T 2004 *J. Phys. G* **30** S295
Avila C, Magnin J and Mendoza-Navas L M 2003 *Preprint* hep-ph/0307358
[16] Rapp R and Shuryak E V 2003 *Phys. Rev. D* **67** 074036
[17] For a review see:
Speth J and Thomas A W 1998 *Adv. Nucl. Phys.* **24** 83
Kumano S 1998 *Phys. Rep.* **303** 183
Thomas A W 1983 *Phys. Lett. B* **126** 97
[18] Burkardt M, Hendricks K S, Ji C-R, Melnitchouk W and Thomas A W 2012 *Preprint* hep-ph/1211.5853 and references therein
[19] Carvalho F, Duraes F O, Navarra F S and Nielsen M 2001 *Phys. Rev. Lett.* **86** 5434
[20] Carvalho F, Durães F O, Navarra F S and Nielsen M 1999 *Phys. Rev. D* **60** 094015
Navarra F S, Nielsen M and Paiva S 1997 *Phys. Rev. D* **56** 3041
[21] Holtmann H, Szczurek A and Speth J 1996 *Nucl. Phys. A* **569** 631
Nikolaev N N, Schaefer W, Szczurek A and Speth J 1999 *Phys. Rev. D* **60** 014004
[22] Cazaroto E R, Goncalves V P, Navarra F S and Nielsen M 2013 *Preprint* hep-ph/1302.0035
[23] Fagundes D A, Menon M J and Silva P V R G 2012 *Preprint* hep-ph/1208.3456
[24] Nelson R E, Vogt R and Frawley A D 2013 *Phys. Rev. C* **87** 014908