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$D^{\pm}$ and $D^0(\bar{D}^0)$ production asymmetries in πp collisions*

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Abstract. We use a two-component model to describe the production mechanism of D mesons in πp collisions. The model combines the usual QCD processes plus fragmentation and recombination of charm that has been produced by nonperturbative QCD mechanisms. A hard charm component in the pion must be responsible of the particle anti-particle production asymmetries observed.

1 Introduction

Recent measurements of charm meson production in πp collisions [1–5] indicate that there are important nonperturbative QCD phenomena in the production process.

The so called "leading effect" or particle anti-particle production asymmetry is much bigger than predicted by next-to-leading (NLO), QCD predictions.

In this article we study the x_F distribution of $D^{\pm}$ and D^0 mesons in the framework of a two-component model. The production of D mesons in the model is assumed to take place *via* two different processes, namely QCD parton fusion with the subsequent fragmentation of quarks in the final state and conventional recombination of valence and sea quarks present in the initial state.

The asymmetry obtained with the conventional soft charm component does not reproduce the experimental results. We show that with the presence of a hard charm component in the pion, the sum of these two processes gives rise to an enhancement at large values in the x_F distribution of leading mesons.

Unlike the Λ_c [6,7] where the asymmetry is generated by the presence of the ud diquark in the initial hadron, the meson production asymmetry seems to imply the presence of a hard charm component in the pion.

To quantify the difference in the production of leading and non-leading particles, an asymmetry A is defined

$$A(x_F) = \frac{\sigma(leading) - \sigma(nonleading)}{\sigma(leading) + \sigma(nonleading)}. \qquad (1)$$

In the reaction $\pi(d\bar{u})$ - $proton(uud)$ the $D^0(c\bar{u})$ and $D^-(\bar{c}d)$ are leading mesons while $\bar{D}^0$ and D^+ are non-leading.

Several models have been proposed although none fully account for the difference in production between leading and non-leading particles. The intrinsic charm model [8] postulates the existence of quantum fluctuations in the beam particle that bring about Fock states containing $c\bar{c}$ pairs. The $c\bar{c}$ quarks having the same velocity as the original valence quarks are likely to coalesce forming leading particles. Although the shape of the asymmetry as a function of x_F predicted by this model is similar to the experimental measurement, the prediction is to low for the whole x_F interval.

In [9] it is pointed out that the annihilation of the u from the proton and the $\bar{u}$ in the pion would liberate the d of the pion which can then recombine to form a D^- and certainly not a D^+. The D^0 will not be enhanced because it cannot be formed with this simple annihilation diagram. The recent measurement of significant asymmetry in Λ_c production in pp collisions [1] however, shows that there must be other production mechanisms at work that must account for the asymmetry.

In two component models [6,10] the production of charm mesons by parton fusion is the same for $D^{\pm}$ and D^0. In Sect. 2 the formalism to obtain the cross section by parton fusion is shown for charged and neutral charm mesons. The recombination of charm as the second component is discussed in Sect. 3. Recombination, is different for the charged mesons where a parton process favors the formation of D^- enhancing the $D^{\pm}$ asymmetry. This will be discussed in Sect. 4.

2 Parton fusion production of charmed mesons

In the parton fusion mechanism the $D^{\pm}$ $D^0(\bar{D}^0)$ mesons are produced via the $q\bar{q}(gg) \rightarrow c\bar{c}$ with the subsequent

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fragmentation of the $c(\bar{c})$ quark. The inclusive x_F distribution of the charm mesons in πp collisions, is given by [11]

$$\frac{d\sigma^{pf}}{dx_F} = \frac{1}{2}\sqrt{s}\int H_{ab}(x_a, x_b, Q^2)\frac{1}{E}\frac{D_{D/c}(z)}{z}dz dp_T^2 dy, \quad (2)$$

where

$$H_{ab}(x_a, x_b, Q^2) = \Sigma_{a,b}\left(q_a(x_a, Q^2)\bar{q_b}(x_b, Q^2) + \bar{q_a}(x_a, Q^2)q_b(x_b, Q^2)\right)\frac{d\hat{\sigma}}{d\hat{t}}\mid_{q\bar{q}} + g_a(x_a, Q^2)g_b(x_b, Q^2)\frac{d\hat{\sigma}}{d\hat{t}}\mid_{gg}, \quad (3)$$

and x_a and x_b being the parton momentum fractions, $q(x, Q^2)$ and $g(x, Q^2)$ the quark and gluon distribution in colliding hadrons, E the energy of the produced c-quark and $D_{D/c}(z)$ the appropriated fragmentation function. In (2), p_T^2 is the squared transverse momentum of the produced c-quark, y is the rapidity of the $\bar{c}$ quark and $z = x_F/x_c$ is the momentum fraction of the charm quark carried by the D. The sum in (3) runs over $a, b = u, \bar{u}, d, \bar{d}, s, \bar{s}$.

We use the LO results for the elementary cross-sections $\frac{d\hat{\sigma}}{d\hat{t}}\mid_{q\bar{q}}$ and $\frac{d\hat{\sigma}}{d\hat{t}}\mid_{gg}$:

$$\frac{d\hat{\sigma}}{d\hat{t}}\mid_{q\bar{q}} = \frac{\pi\alpha_s^2\left(Q^2\right)}{9\hat{m}_c^4}\frac{cosh\left(\Delta y\right) + m_c^2/\hat{m}_c^2}{\left[1 + cosh\left(\Delta y\right)\right]^3} \quad (4)$$

$$\frac{d\hat{\sigma}}{d\hat{t}}\mid_{gg} = \frac{\pi\alpha_s^2\left(Q^2\right)}{96\hat{m}_c^4}\frac{8cosh\left(\Delta y\right) - 1}{\left[1 + cosh\left(\Delta y\right)\right]^3} \times\left[cosh\left(\Delta y\right) + \frac{2m_c^2}{\hat{m}_c^2} + \frac{2m_c^4}{\hat{m}_c^4}\right], \quad (5)$$

where Δy is the rapidity gap between the produced c and $\bar{c}$ quarks and $\hat{m}_c^2 = m_c^2 + p_T^2$.

In order to be consistent with the LO calculation of the elementary cross sections, we use the GRV-LO parton distribution functions [12], and apply a global factor $K \sim 2 - 3$ in (2) to take into account NLO contributions [13].

We take $m_c = 1.5GeV$ for the c-quark mass and fix the scale of the interaction at $Q^2 = 2m_c^2$ [11]. Following [10], we use a delta fragmentation function $D_{D/c}(z) = \delta(1-z)$, which seems to describe experimental data better than the Peterson fragmentation function.

3 Charmed meson production by recombination

Sometime ago V. Barger et al. [14] explained the spectrum enhancement at high x_F in Λ_c production assuming a hard momentum distribution of charm in the proton. According with them charm anti-charm pairs which give rise to the flavor excitation diagrams (see Fig. 1) are not intrinsic but generated by QCD evolution of the structure functions.

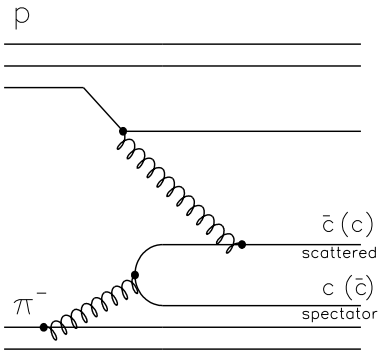

Fig. 1. Heavy flavor excitation diagram. This and similar diagrams are included in a NLO QCD calculation. However, in oder to reproduce particle anti-particle asymetries a hard charm component in the pion is needed

In this framework, following the gluon scattering process of Fig. 1 the charm quarks will fragment into charm hadrons. When the $\bar{c}$ is scattered, the spectator quark could recombine with the $\bar{u}$ valence quark of the pion to form a $D^0(c\bar{u})$ or less frequently with an antiquark from the pion's sea. On the other hand, when the c quark is scattered, the spectator quark $\bar{c}$ could recombine with d valence quark from the pion to form a $D^-(\bar{c}d)$ meson.

As pointed out in [14] the charm hadrons resulting from the scattered charm quark, populate the low x_F region of the cross section, while those originating from the spectator quark dominate at high x_F.

Here we assume a QCD evolved charm distribution, of the form proposed by V. Barger et al. [14]

$$xc(x, \langle Q^2\rangle) = Nx^l(1-x)^k, \quad (6)$$

with a normalization N fixed to

$$\int dx \cdot xc(x) = 0.005 \quad (7)$$

and $l = k = 1$. With this values for l and k one tries to resemble the distribution of valence quarks. In contrast with the parton fusion calculation, in which the scale Q^2 of the interaction is fixed at the vertices of the appropriated Feynman diagrams, in recombination the value of the parameter Q^2 should be used to give adequately the content of the recombining quarks in the initial hadron. We used $Q^2 = 4m_c^2$ and therefore, the integrated charm quark distribution would take the value given in (7).

The production of leading mesons at low p_T was described by recombination of quarks long time ago [15].

In recombination models it is assumed that the outgoing hadron is produced in the beam fragmentation region through the recombination of the maximum number of valence quarks and the minimum number of sea quarks of the incoming hadron. The invariant inclusive x_F distribution for leading mesons is given by

$$\frac{2E}{\sqrt{s}\sigma}\frac{d\sigma^{rec}}{dx_F} = \int_0^{x_F}\frac{dx_1}{x_1}\frac{dx_2}{x_2} \times F_2\left(x_1, x_2\right)R_2\left(x_1, x_2, x_F\right) \quad (8)$$

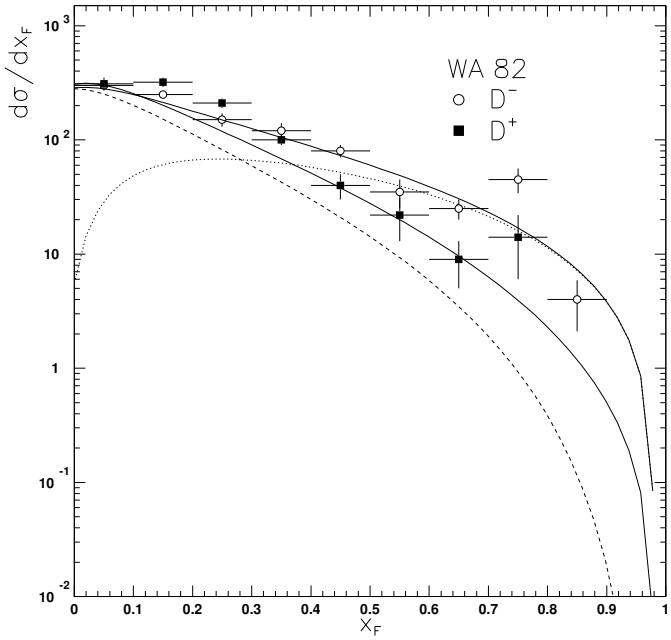

Fig. 2. Production cross section for D^- and D^+ mesons in $\pi^- p$ collisions. The *dashed line* represents the parton fusion contribution with a delta fragmentation function. The *dotted line* gives the contribution from recombination for D^-. The *solid line* is the sum of the two contributions

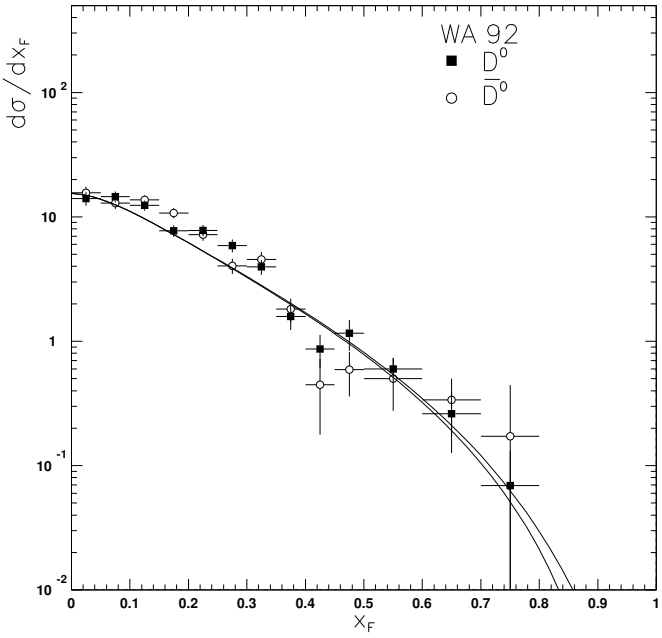

Fig. 4. Production cross section for D^0 and $\bar{D}^0$ mesons produced in $\pi^- p$ collisions. Experimental points [5] and two component model prediction (*solid line*)

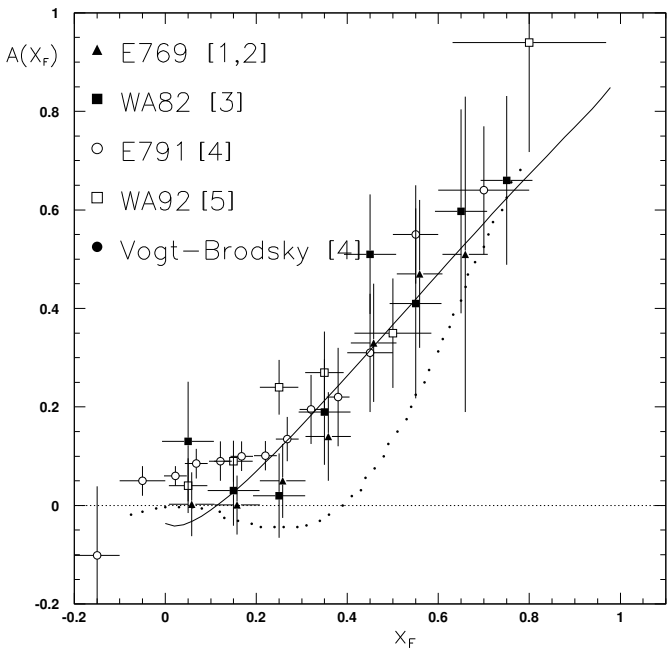

Fig. 3. Measured production asymmetry for D^- and D^+ and the model incorporating a hard charm component in the pion (*solid line*). The *dotted line* shows the intrinsic charm model prediction

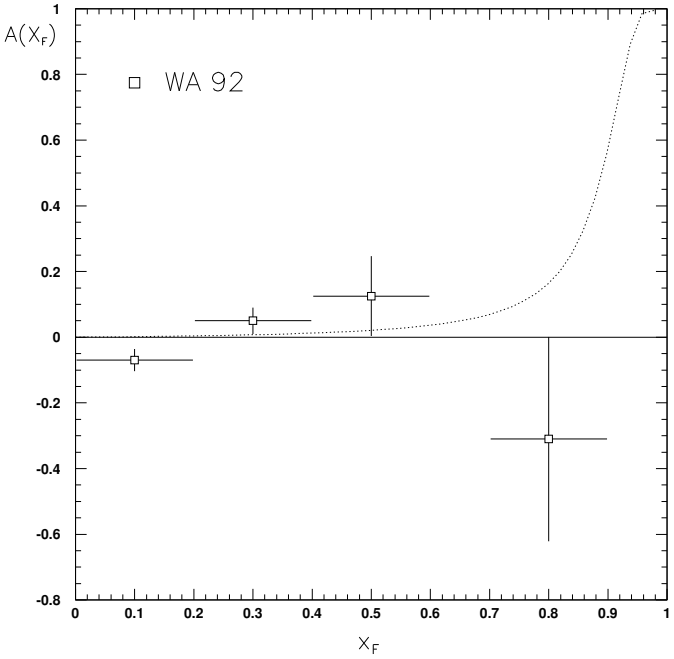

Fig. 5. Measured production asymmetry for D^0 and $\bar{D}^0$ and the model incorporating a hard charm component in the pion. The *horizontal line* at $A(x_F) = 0$ is for reference only

where x_1, x_2 are the momentum fractions and $F_2\,(x_1, x_2,)$ is the two-quark distribution function of the incident hadron. $R_2(x_1, x_2, x_F)$ is the two-quark recombination function.

The two-quark distribution function is parametrized in terms of the single quark distributions

$$F_2\,(x_1, x_2,) = \beta F_{d,val}\,(x_1)\,F_{c,sea}\,(x_2)\,(1 - x_1 - x_2)\,, \quad (9)$$

with $F_q\,(x_i) = x_i q\,(x_i)$. We use the GRV-LO parametrization for the single quark distributions in (9). The charm contribution however, is parametrized with the distribution of (6). It must be noted that since the GRV-LO distributions are functions of x and Q^2, then our $F_2\,(x_1, x_2)$ also depends on Q^2. The recombination function is given by

$$R_2\,(x_d, x_c) = \alpha \frac{x_d x_c}{x_F^2} \delta\,(x_d + x_c - x_F)\ , \qquad (10)$$

with α fixed by the condition $\int_0^1 dx_F (1/\sigma) d\sigma^{rec}/dx_F = 1$.

4 $D^{\pm}$ and $D^0(\bar{D}^0)$ total production

The inclusive production cross section of the D is obtained by adding the contribution of recombination (8) to the QCD processes of (2),

$$\frac{d\sigma^{tot}}{dx_F} = \frac{d\sigma^{pf}}{dx_F} + \frac{d\sigma^{rec}}{dx_F}. \qquad (11)$$

The resulting inclusive D production cross section $d\sigma^{tot}/dx_F$ is used then to construct the asymmetry defined in (1).

In the πp reaction however, the recombination of a $D^-(d\bar{c})$ gets a higher probability than the recombination of a D^0 $\bar{u}c$ [9].

The process that releases a d quark from the incident π to form a $D^-(d\bar{c})$ (after recombination with a c-quark from the sea) is also present in the formation of a D^0. In this case the released quark should be $\bar{u}$. In the D^- case however, there is an additional mechanism that releases the d quark from the pion, namely the fusion of a u-quark from the proton with the u from the pion. This is correctly incorporated by the fact that a higher contribution from the recombination is needed to describe the D^- asymmetry while $D^0(\bar{D}^0)$ production and its production asymmetry requires a small contribution from the recombination process.

Figure 2 shows the model prediction for the D^- and D^+ cross section and experimental results from the WA82 Collaboration [3]. The corresponding production asymmetry is shown in Fig. 3 together with all the experimental measurements available. Figure 4 shows the cross section for D^0 and $\bar{D}^0$ mesons produced in $\pi^- p$ collisions and the experimental points from the WA92 Experiment [5]. The corresponding production asymmetry for D^0 and $\bar{D}^0$ is shown in Fig. 5. By looking at the fit of the cross section in Fig. 4 one can see that the asymmetry obtained for $D^0(\bar{D}^0)$ could actually change drastically by slightly changing the curves. More statistics is needed to improve the confidence of the predicted asymmetry.

5 Conclusions

In an earlier work [6] the production asymmetry of Λ_c was described using the same recombination scheme used here. The presence of a diquark in the initial state, plays an important role in Λ_c production. However, it is not possible to describe the asymmetry in charm mesons using the GRV structure functions for the charm in the pion. A hard charm component must be present. This fact has been pointed out before [8,14] but the asymmetry in the intrinsic charm model [8] does not seem to fit experimental results very well. The hard charm component proposed in [14] and a recombination scheme, give a good description of particle anti-particle production asymmetries for mesons.

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