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$\Lambda_c/\overline{\Lambda}_c$ production asymmetries in pp and π^-p collisions

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Abstract. We study $\Lambda_c/\overline{\Lambda}_c$ production asymmetries in pp and π^-p collisions using a recently proposed two component model. The model includes heavy baryon production by the usual mechanism of parton fusion and fragmentation plus recombination of valence and sea quarks from the beam and target hadrons. We compare our results with experimental data on asymmetries measured recently.

1 Introduction

Recent experimental data on charmed meson hadroproduction shows a strong correlation between the flavor content of the incident hadron and the produced meson [1, 2]. This effect, known as leading particle effect, has been observed also in Λ_c production in pp [3,4] and π^-p [5] interactions, in Λ_b production in pp collisions [6] and Ξ_c production in hyperon-nucleus interactions [7].

The leading particle effect can not be explained within the usual framework based in the factorization theorem. In fact, although perturbative QCD (pQCD) at Next to Leading Order (NLO) predicts a small enhancement of the $\bar{c}$ over the c-quark cross section [8], the effect of this asymmetry is very small to account for the observed D^-/D^+ asymmetry measured in π^--nucleus interactions [2]. On the other hand, the evidence of leading particle effects in Λ_c production at large x_F clearly shows that non-perturbative mechanisms play a fundamental role in hadroproduction.

Leading particle effects in charmed hadron production has been studied from two different points of view: the soft scattering - low virtuality approach [9], in which charmed meson anti-meson production is reviewed within the valon recombination model, and two component models, in which charmed hadron production takes place by two different mechanisms, namely perturbative QCD (pQCD) followed by fragmentation plus coalescence of intrinsic charm [10] or recombination of the valence quarks with the charmed sea quarks of the initial hadrons liberated in the collision [11]. In the two component models, the intrinsic charm coalescence or the valence and sea quark recombination gives the non-perturbative contribution which takes into account the observed flavor correlation.

Leading particle correlations can be quantified by studies of the production asymmetries between leading and non-leading particles. The production asymmetry is defined by

$$A_{L/NL}(x_F) = \frac{d\sigma_L/dx_F - d\sigma_{NL}/dx_F}{d\sigma_L/dx_F + d\sigma_{NL}/dx_F} \quad (1)$$

in which L stands for Leading and NL for Non-Leading particles. In this paper we give the predictions of the recombination two component model for $\Lambda_c/\overline{\Lambda}_c$ production asymmetries in pp and π^-p interactions. We also compare the predictions of the model with recent experimental data in pp [4] and π^-p [5] interactions.

2 Λ_c and $\overline{\Lambda}_c$ production in pp and π^-p collisions

In this section we review $\Lambda_c/\overline{\Lambda}_c$ production in the recombination two component model [11]. In Sect. 2.1 we present the calculation of the parton fusion contribution and in Sect. 2.2 the recombination picture is studied for both pp and π^-p interactions.

2.1 Λ_c and $\overline{\Lambda}_c$ production via parton fusion

The calculation we present here is at Lowest Order (LO) in α_s. A constant factor $K \sim 2-3$ is included in the parton fusion cross section to take into account Next to Leading Order (NLO) contributions [12].

The inclusive x_F $(= 2p_L/\sqrt{s})$ distribution for Λ_c $(\overline{\Lambda}_c)$ production in hadron-hadron interactions, assuming factorization, has the form [13]

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

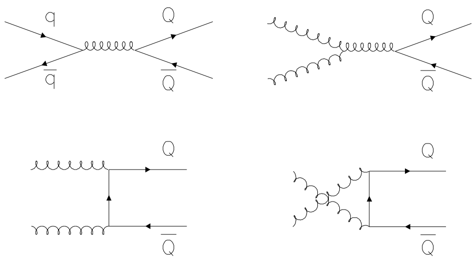

Fig. 1. Feynman diagrams involved in the LO calculation of the parton fusion cross section

where

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

with x_a and x_b the parton momentum fractions in the inital hadrons A and B, $q(x,Q^2)$ and $g(x,Q^2)$ the quark and gluon distribution in the corresponding colliding hadrons, E the energy of the produced $c\,(\bar{c})$-quark and $D_{\Lambda_c/c}\,(z)$ the appropriated fragmentation function. In (2), p_T^2 is the squared transverse momentum of the produced $c\,(\bar{c})$-quark, y is the rapidity of the $\bar{c}\,(c)$ quark and $z = x_F/x_c$ is the momentum fraction of the charm quark carried by the $\Lambda_c\,(\overline{\Lambda}_c)$. The sum in 3 runs over $a,b = u,\bar{u},d,\bar{d},s,\bar{s}$. $d\hat{\sigma}/d\hat{t}\,|_{q\bar{q}}$ and $d\hat{\sigma}/d\hat{t}\,|_{gg}$ are the elementary cross sections for the hard processes $q\bar{q} \to c\bar{c}$ and $gg \to c\bar{c}$ at LO given by

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

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

where Δy is the rapidity gap between the produced c and $\bar{c}$ quarks and $\hat{m}_c^2 = m_c^2 + p_T^2$. The Feynman diagrams involved in the calculation of (4) and (5) are shown in Fig. 1.

For consistency with the LO calculation, we use the GRV-LO parton distributions for both the proton [14] and the pion [15]. The hard momentum scale is fixed at $Q^2 = 2m_c^2$.

The fragmentation is modeled by two different functions; the Peterson fragmentation function extracted from data in e^+e^- interactions [16]

$$D_{\Lambda_c/c}(z) = \frac{N}{z\left[1 - 1/z - \epsilon_c/(1-z)\right]^2} \tag{6}$$

with $\epsilon_c = 0.06$ and the normalization defined by $\sum_H \int D_{H/c}(z)dz = 1$ and the delta fragmentation function

$$D_{\Lambda_c/c}(z) = \delta(1-z). \tag{7}$$

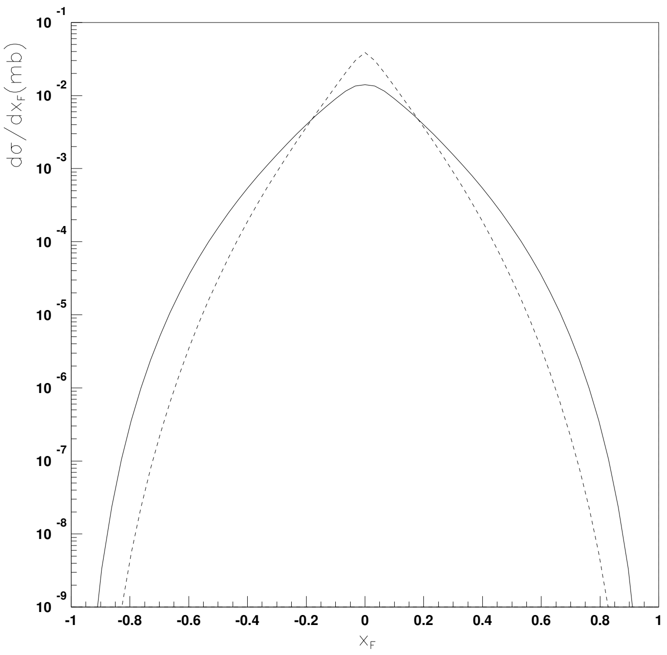

Fig. 2. Parton fusion cross section for pp at 500 GeV/c energy beam. Peterson (*dashed line*) and Delta (*full line*) fragmentation are shown

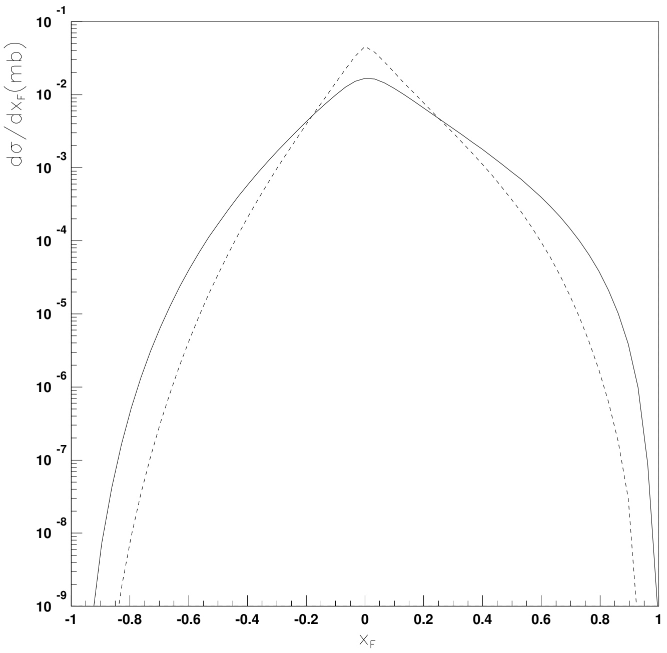

Fig. 3. Parton fusion cross section for $\pi^- p$ at 500 GeV/c energy beam. Peterson (*dashed line*) and Delta (*full line*) fragmentation are shown

The use of the delta fragmentation function implies that the Λ_c is produced with the same momentum carried by the fragmenting c-quark. This mechanism for fragmentation has been used to simulate the coalescence of the c-quark, produced in a hard interaction, with light valence quarks coming from the initial hadrons [10].

In Figs. 2 and 3 we show the parton fusion distributions obtained for the two fragmentation functions in pp and $\pi^- p$ interactions respectively. Notice that the Λ_c and the $\overline{\Lambda}_c$ parton fusion distributions are equal at LO. However, at NLO there is an small $\bar{c}/c$ asymmetry due to the fact that to this order in perturbative theory the cross section for the production of a quark differs from the cross section for the production of an anti-quark [8] and consequently a small $\overline{\Lambda}_c/\Lambda_c$ asymmetry is present.

2.2 Λ_c and $\overline{\Lambda}_c$ production *via* recombination in pp and $\pi^- p$ interactions

The method introduced by K.P. Das and R.C. Hwa for meson recombination [17] was extended by J. Ranft [18] to describe single particle distributions of baryons in pp collisions. In a recent work R.C. Hwa [9] studied $D^\pm$ inclusive production using the valon recombination model.

In recombination, all products of the reaction appearing in the forward region ($x_F > 0$) are thought as coming from the beam particle fragmentation while hadrons produced in the backward region ($x_F < 0$) come from the target fragmentation. Since the two reactions we are considering here have the same target particles, then the recombination Λ_c and $\overline{\Lambda}_c$ inclusive x_F distributions are the same for both reactions in the backward region. In the forward region, however, they must be different since the outgoing hadron is produced from the debris of different initial particles. Hence it is sufficient to study Λ_c and $\overline{\Lambda}_c$ production by recombination in the forward region for pp and $\pi^- p$ collisions, being the backward x_F distributions symmetrical with respect to the forward x_F distribution in pp interactions in both reactions under study.

The invariant x_F inclusive distribution for Λ_c $\left(\overline{\Lambda}_c\right)$ production in pp interactions in the forward region is given by

$$\frac{2E}{\sigma^{rec}\sqrt{s}}\frac{d\sigma^{rec}}{dx_F} = \int_0^{x_F}\frac{dx_1}{x_1}\frac{dx_2}{x_2}\frac{dx_3}{x_3}F_3^{\Lambda_c\,(\overline{\Lambda}_c)} \times \left(x_1,x_2,x_3\right) R_3\left(x_1,x_2,x_3,x_F\right) \qquad (8)$$

where E is the energy of the produced hadron, $\sqrt{s}$ is the center of mass energy, $R_3\left(x_1,x_2,x_3,x_F\right)$ is the recombination function and $F_3^{\Lambda_c\,(\overline{\Lambda}_c)}\left(x_1,x_2,x_3\right)$ is the three quark distribution function. x_i, i=1, 2, 3 is the momentum fraction of the i^{th} quark with respect to the proton.

Following the approach of [18], the three quark distribution function is assumed to be of the form

$$F_3^{\Lambda_c(\overline{\Lambda}_c)}\left(x_1,x_2,x_3\right) = \beta_p F^p_{q_1}\left(x_1\right)F^p_{q_2}\left(x_2\right)F^p_{q_3}\left(x_3\right) \times \left(1-x_1-x_2-x_3\right)^{\gamma_p} \qquad (9)$$

In (9), $F_{q_i} = x_i q_i(x_i)$ is the single quark distribution of the i^{th} valence quark in the produced Λ_c $(\overline{\Lambda}_c)$ inside the proton and the coefficients β_p and γ_p are fixed using the consistency condition

$$F_q\left(x_i\right) = \int_0^{1-x_i} dx_j \int_0^{1-x_i-x_j} dx_k\, F_3^{\Lambda_c(\overline{\Lambda}_c)}\left(x_1,x_2,x_3\right) . \quad i,j,k = 1,2,3 \qquad (10)$$

which must be valid for the valence quarks in the proton.

In (9) we use the single quark GRV-LO distributions [14]. Since the GRV-LO distributions are functions of the momentum fraction x and the momentum scale Q^2, then our $F_3^{\Lambda_c/\overline{\Lambda}_c}\left(x_1,x_2,x_3\right)$ also depends on Q^2. We use $Q^2 = 4m_c^2$ with $m_c = 1.5$ GeV as in [11]. Notice that the scale in the recombination is fixed at a different value than in parton fusion. In fact, in parton fusion the scale Q^2 is fixed at the vertices of the Feynman diagrams involved in the perturbative part of the calculation while in recombination this parameter must be chosen in such a way that small variations in its value does not change appreciably the charmed sea of the initial hadron.

Concerning the single-quark contributions to the three quark distribution function, some comments are in order. In pp interactions, contributions to the Λ_c inclusive x_F distribution in the large x_F region come mainly from Valence-Valence-Sea (VVS) recombination processes, being other processes involving more than one sea-flavor in the recombination completely negligible due to the fast fall of the sea-quark distributions. Conversely, in the small x_F region, contributions of Valence-Sea-Sea (VSS) and Sea-Sea-Sea (SSS) recombination processes are important since sea-quark distributions are peaked at x_F about zero. In this region, the later processes dominate largely over VVS recombination. Hence, in order to have a more acurate prediction for the $\Lambda_c/\overline{\Lambda}_c$ asymetry at small x_F, VSS and SSS processes must be included in the calculation of the Λ_c cross section. $\overline{\Lambda}_c$ production in pp interactions proceeds only through SSS recombination.

For the recombination function we take

$$R_3\left(x_1,x_2,x_3\right) = \alpha\frac{\left(x_1x_2\right)^{n_1}x_3^{n_2}}{x_F^{n_1+n_2-1}} \times\delta\left(x_1+x_2+x_3-x_F\right) \qquad (11)$$

allowing in this way for a different weight for the heavy c $(\bar{c})$ quark (marked with index 3) than for the light u $(\bar{u})$ and d $(\bar{d})$ quarks (indexed 1 and 2 respectively), as suggested in [9] in connection with charmed meson production in the valon model.

The constant α in (11) is fixed by the condition [11]

$$\alpha = \frac{1}{\sigma^{rec}}\int_0^1 dx_F\frac{d\sigma^{rec}}{dx_F} = 1 \qquad (12)$$

for Λ_c inclusive production. Using the same value for the parameter α obtained in (12) to normalize the $\overline{\Lambda}_c$ x_F distribution, the anti-particle cross section is given relative to the particle cross section. In this way $\sigma^{rec}_{\Lambda_c}$ has the physical interpretation of the Λ_c total recombination cross section and it should be fixed by experimental data.

In Fig. 4 we show the Λ_c and $\overline{\Lambda}_c$ x_F inclusive distribution for $n_1 = n_2 = 1$ [18] and $n_1 = 1$, $n_2 = 5$ [9] with $\beta_p = 75$ and $\gamma_p = -0.1$ as given in [11].

In $\pi^- p$ interactions in the beam fragmentation region both Λ_c and $\overline{\Lambda}_c$ inclusive x_F distributions are given by formulas formally identical to that of (8). As the π^- has an $\bar{u}$ and a d valence quarks, the recombination processes involved in Λ_c as well as in $\overline{\Lambda}_c$ production are VSS and

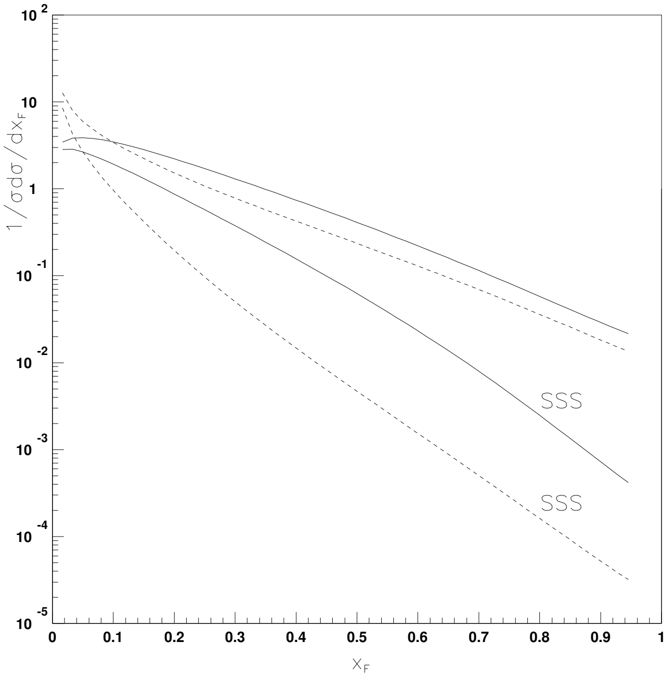

Fig. 4. Recombination cross section in pp collisions for $n_1 = 1$, $n_2 = 5$ (*full line*) and $n_1 = n_2 = 1$ (*dashed line*). *Curves* marked "SSS" are the corresponding $\overline{\Lambda}_c$ distributions. The Λ_c distribution is normalized to unity and the $\overline{\Lambda}_c$ distribution is normalized relative to the first one

SSS. On the other hand, since the GRV-LO [15] valence distributions and quark and anti-quark sea distributions in the pion are equal, then the Λ_c and $\overline{\Lambda}_c$ inclusive x_F distributions are the same. Notice that Λ_c production in $\pi^- p$ interactions in the proton fragmentation region is double leading and $\overline{\Lambda}_c$ is non-leading whereas in the beam fragmentation region both particle and anti-particle production are leading, so in this case a $\Lambda_c/\overline{\Lambda}_c$ asymmetry is expected for $x_F < 0$.

3 $\Lambda_c/\overline{\Lambda}_c$ production asymmetry in the recombination two component model

The total inclusive x_F distributions are obtained by adding the parton fusion and recombination contributions given by (2) and (8) respectively. Its general form is

$$\frac{d\sigma^{tot}}{dx_F}\Big|_{\Lambda_c(\overline{\Lambda}_c)} = \frac{d\sigma^{pf}}{dx_F} + \sigma^{rec}_{\Lambda_c}\frac{d\sigma^{rec}}{dx_F}\Big|_{\Lambda_c(\overline{\Lambda}_c)} \qquad (13)$$

where we have uncovered the parameter $\sigma^{rec}_{\Lambda_c}$ hidden in the $d\sigma^{rec}/dx_F$ definition of (8). Let us stress that $\sigma^{rec}_{\Lambda_c}$ is the only free parameter in the model.

The $\Lambda_c/\overline{\Lambda}_c$ production asymmetry is obtained by replacing the corresponding total inclusive distribution given by (13) in (1). In this way we obtain

$$\begin{aligned} &A_{\Lambda_c/\overline{\Lambda}_c}(x_F) \qquad (14)\\ &= \sigma^{rec}_{\Lambda_c}\frac{d\sigma^{rec}/dx_F\mid_{\Lambda_c} - d\sigma^{rec}/dx_F\mid_{\overline{\Lambda}_c}}{2d\sigma^{pf}/dx_F + \sigma^{rec}_{\Lambda_c}\left[d\sigma^{rec}/dx_F\mid_{\Lambda_c} + d\sigma^{rec}/dx_F\mid_{\overline{\Lambda}_c}\right]} \end{aligned}$$

for the asymmetry as a function of x_F.

It should be noted that pQCD at NLO predicts a bigger $\overline{\Lambda}_c$ than Λ_c production at large values of x_F. Since the asymmetry coming from pQCD is of the order of 10 % at $x_F \approx 1$ and in the large x_F region the recombination component is several orders of magnitude bigger than the perturbative part, this contribution to the asymmetry is completely negligible.

In $\pi^- p$ interactions in the forward region ($x_F > 0$), the Λ_c and the $\overline{\Lambda}_c$ recombination cross sections are equal, then our model predicts zero or a small negative asymmetry due to NLO pQCD effects. This prediction is consistent with the ratio $N(\Lambda_c)/N(\overline{\Lambda}_c) = 0.99 \pm 0.16$ measured by the ACCMOR collaboration [19] which indicates no asymmetry ($A = -0.002 \pm 0.16$). Also a preliminary analysis in 500 GeV/c π^--nucleus interactions from the E791 collaboration [5] is consistent with zero asymmetry in the region $0 \leq x_F \leq 0.55$.

In the backward region, the same E791 preliminary analysis shows a large asymmetry, reaching a value of $A \approx 0.4$ at $x_F \approx -0.13$ but with large error bars [5]. The ratio $N(\Lambda_c)/N(\overline{\Lambda}_c) = 1.17 \pm 0.08$ ($A = 0.078 \pm 0.034$) measured by the E791 collaboration [5] is described by our model with a recombination cross section $\sigma^{rec}_{\Lambda_c} \approx 1.1\sigma^{pf}$ and $n_1 = 1$, $n_2 = 5$ in the recombination function of (11) in the Peterson fragmentation scheme. Here $\sigma^{pf} = \int_0^1 dx_F d\sigma^{pf}/dx_F$. Both Peterson and Delta fragmentation in combination with $n_1 = n_2 = 1$ in the recombination function tend to give a more slowly growing asymmetry with x_F.

The E769 experiment [4] found a lower limit of $A = 0.6$ in the forward region with a 250 GeV/c incident π^-, K and p beam on a multifold target of Be, Cu, Al and W. However, altough this experiment presents an evidence of $\Lambda_c/\overline{\Lambda}_c$ asymmetry, the value quoted in [4] for the asymmetry is not significative due to its very low statistic.

In Figs. 5 and 6 we show the asymmetry as a function of x_F predicted by the recombination two component model in pp and $\pi^- p$ interactions respectively with the recombination normalization suggested by the preliminary analysis from the E791 collaboration.

4 Conclusions

In this work we have presented the predictions of the recombination two component model for the $\Lambda_c/\overline{\Lambda}_c$ production asymmetry in pp and $\pi^- p$ interactions.

The model seems to describe adequately the scarce data available on the subject but, of course, more experimental data are nedeed not only on $\Lambda_c/\overline{\Lambda}_c$ asymmetries as well as on Λ_c and $\overline{\Lambda}_c$ x_F distributions in order to do a meaningful comparison.

Using the preliminary analysis of the E791 collaboration [5], the model predicts that the recombination cross section is as big as the parton fusion cross section, giving a clear idea about the extent to which non-perturbative contributions are important in charm hadroproduction.

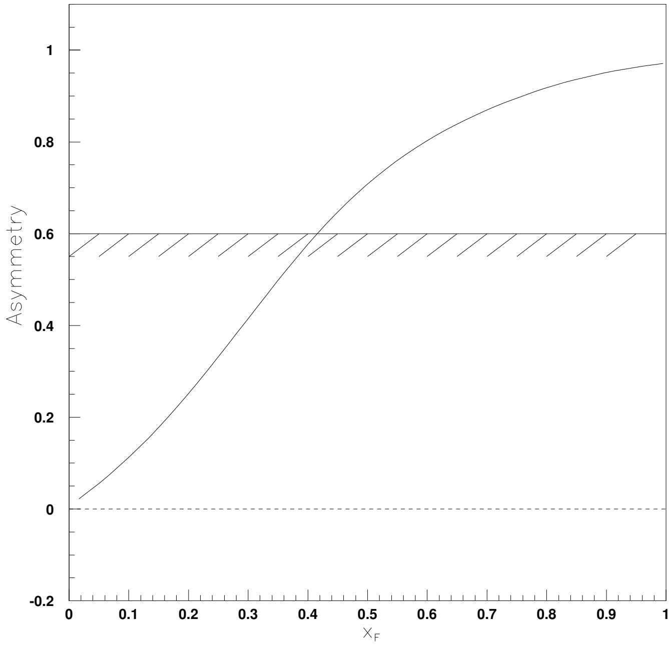

Fig. 5. $\Lambda_c/\overline{\Lambda}_c$ asymmetries in pp interactions for Peterson fragmentation and $n_1 = 1$, $n_2 = 5$ in the recombination function calculated for the recombination cross section suggested by the E791 preliminary data. The lower limit obtained by the E769 ([4]) experiment is shown

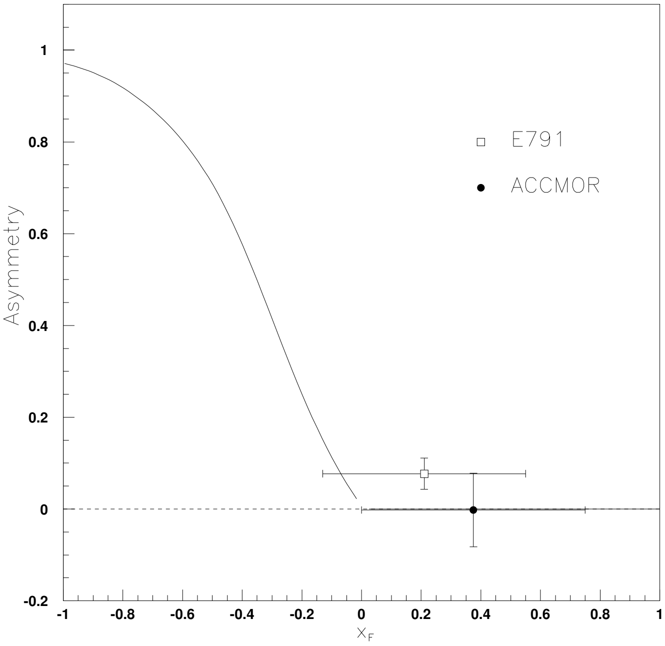

Fig. 6. Same as in Fig. 5 for π^-p interactions. Experimental points are calculated from the $N(\Lambda_c)/N(\overline{\Lambda}_c)$ ratios measured in [5] and [19]

It should be noted that if the production asymmetry is independent of the energy, as indicated by measurements of charmed meson/ anti-meson asymmetries, the model predicts that the ratio of the recombination to the parton fusion cross section does not depend on the energy and could bring about important information about the non-perturbative processes in heavy hadron production.

In the recombination two component model, the part responsible for the asymmetry is recombination. It involves different kinds of processes for Λ_c than for $\overline{\Lambda}_c$ production, giving x_F inclusive distributions which are different in shape for the particle than for the anti-particle.

Notice that strong diquark effects are present in the model for Λ_c production in the proton fragmentation region in the two reactions considered in this paper. In fact, since the u and d are valence quarks in the proton, the ud diquark carries a large amount of the proton momentum when it is liberated in the collision. This large momentum is then transferred to the Λ_c when the ud diquark recombines with a sea c-quark to form the outgoing particle.

Another model which has been used to make predictions on the $\Lambda_c/\overline{\Lambda}_c$ production asymmetry is the intrinsic charm two component model [10]. In this model the enhancement in the Λ_c over the $\overline{\Lambda}_c$ cross section is due to the coalescence of u, d and c quarks coming from the $|uudc\bar{c}\rangle$ Fock state of the proton.

However there are important differences between predictions obtained with one or another model.

In fact, one of the possibly most interesting features which distinguish the recombination from the intrinsic charm two component model is the ability of the first to produce large asymetries in the small x_F region. This difference between the two models is due to the fact that recombination of sea and valence quark produces a Λ_c x_F distribution peaked close to zero whereas the intrinsic charm model gives a Λ_c x_F distribution slowly growing from zero at $x_F = 0$ to its maximum at x_F about 0.6.

Finally, it should be noted that the two models seem to describe adequately the shape of the Λ_c inclusive x_F distribution (see [10,11]) but both models predict very different forms for the $\Lambda_c/\overline{\Lambda}_c$ asymmetry, so a meaningful comparison between models and experimental data should be done with data on asymmetries as well as on x_F distributions.

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