Λ_c/Λ_c production asymmetries in pp and π^-p collisions

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Abstract

We study Λ_c/Λ_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.

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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 cannot 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 ¯¯¯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

\[ A_{L/NL}(x_F) = \frac{d\sigma_L/dx_F - d\sigma_{NL}/dx_F}{d\sigma_L/dx_F + d\sigma_{NL}/dx_F} \] (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 Λ_c/Λ_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 $\Lambda_c$ and $\bar{\Lambda}_c$ production in $pp$ and $\pi^-p$ collisions

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

2.1 $\Lambda_c$ and $\bar{\Lambda}_c$ production via parton fusion

The calculation we present here is at Lowest Order (LO) in $\alpha_s$. 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 \cite{12}.

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

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

where

\[
H_{ab}^{AB}(x_a, x_b, Q^2) = \Sigma_{a,b} \left(q_a(x_a, Q^2)\bar{q}_b(x_b, Q^2) \right) \frac{d\hat{\sigma}}{d\hat{t}} \mid_{q\bar{q}} \]

\[
+ \left(\bar{q}_a(x_a, Q^2)q_b(x_b, Q^2) \right) \frac{d\hat{\sigma}}{d\hat{t}} \mid_{\bar{q}q} \]

\[
+ g_a(x_a, Q^2)g_b(x_b, Q^2) \frac{d\hat{\sigma}}{d\hat{t}} \mid_{gg}, \tag{3}
\]

with $x_a$ and $x_b$ the parton momentum fractions in the initial 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 appropriate fragmentation function. In eq. \ref{eq: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 $\Lambda_c (\bar{\Lambda}_c)$. The sum in eq. \ref{eq:3} runs over $a, b = u, \bar{u}, d, \bar{d}, s, \bar{s}$. $d\hat{\sigma}/d\hat{t} \mid_{q\bar{q}}$ and $d\hat{\sigma}/d\hat{t} \mid_{gg}$ are the elementary cross sections for the hard processes $q\bar{q} \rightarrow c\bar{c}$ and $gg \rightarrow c\bar{c}$ at LO given by

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

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

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

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

The use of the delta fragmentation function implies that the $\Lambda_c$ 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 $\Lambda_c$ and the $\bar{\Lambda}_c$ 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 $\bar{\Lambda}_c/\Lambda_c$ asymmetry is present.

### 2.2 $\Lambda_c$ and $\bar{\Lambda}_c$ 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 $\Lambda_c$ and $\bar{\Lambda}_c$ 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 $\Lambda_c$ and $\bar{\Lambda}_c$ 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 $\Lambda_c$ ($\bar{\Lambda}_c$) production in $pp$ interactions in the forward region is given by

$$\frac{2E}{\sigma_{\text{rec}}} \frac{d\sigma_{\text{rec}}}{dx_F} = \int_0^{x_F} \frac{dx_1}{x_1} \frac{dx_2}{x_2} \frac{dx_3}{x_3} F^\Lambda_c(\bar{\Lambda}_c)(x_1, x_2, x_3) R_3(x_1, x_2, x_3, x_F)$$

(8)

where $E$ is the energy of the produced hadron, $\sqrt{s}$ is the center of mass energy, $R_3(x_1, x_2, x_3, x_F)$ is the recombination function and $F^\Lambda_c(\bar{\Lambda}_c)(x_1, x_2, x_3)$ 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 Ref. [18], the three quark distribution function is assumed to be of the form

$$F_3^\Lambda_c(\bar{\Lambda}_c)(x_1, x_2, x_3) = \beta_p F_{q_1}^p(x_1) F_{q_2}^p(x_2) F_{q_3}^p(x_3) (1 - x_1 - x_2 - x_3) \gamma_p$$

(9)

In eq. (9), $F_{q_i} = x_i q_i(x_i)$ is the single quark distribution of the $i$th valence quark in the produced $\Lambda_c$ ($\bar{\Lambda}_c$) inside the proton and the coefficients $\beta_p$ and $\gamma_p$ are fixed using the consistency condition

$$F_q(x_i) = \int_0^{1-x_i} dx_j \int_0^{1-x_i-x_j} dx_k F_3^\Lambda_c(\bar{\Lambda}_c)(x_1, x_2, x_3).$$

(10)

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

In eq. (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 $F_3^\Lambda_c(\bar{\Lambda}_c)(x_1, x_2, x_3)$ also depends on $Q^2$. We use $Q^2 = 4m^2_c$ with $m_c = 1.5$ GeV as in Ref. [14]. 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 $\Lambda_c$ 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 accurate prediction for the $\Lambda_c/\bar{\Lambda}_c$ asymmetry at small $x_F$, VSS and SSS processes must be included in the calculation of the $\Lambda_c$ cross section. $\bar{\Lambda}_c$ production in $pp$ interactions proceeds only through SSS recombination.

For the recombination function we take

$$R_3 (x_1, x_2, x_3) = \alpha \frac{(x_1 x_2)^{n_1} x_3^{n_2}}{x_F^{n_1+n_2-1}} \delta (x_1 + x_2 + x_3 - x_F)$$

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 Ref. [9] in connection with charmed meson production in the valon model.

The constant $\alpha$ in eq. (11) is fixed by the condition

$$\frac{1}{\sigma_{\text{rec}}^{\Lambda_c}} \int_0^1 dx_F \frac{d\sigma_{\text{rec}}^{\Lambda_c}}{dx_F} = 1$$

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

In Fig. 4 we show the $\Lambda_c$ and $\bar{\Lambda}_c$ $x_F$ inclusive distribution for $n_1 = n_2 = 1$ [8] and $n_1 = 1, n_2 = 5$ [4] with $\beta_p = 75$ and $\gamma_p = -0.1$ as given in Ref. [11].

In $\pi^- p$ interactions in the beam fragmentation region both $\Lambda_c$ and $\bar{\Lambda}_c$ inclusive $x_F$ distributions are given by formulas formally identical to that of eq. (8). As the $\pi^-$ has an $\bar{u}$ and a $d$ valence quarks, the recombination processes involved in $\Lambda_c$ as well as in $\bar{\Lambda}_c$ production are VSS and 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 $\Lambda_c$ and $\bar{\Lambda}_c$ inclusive $x_F$ distributions are the same. Notice that $\Lambda_c$ production in $\pi^- p$ interactions in the proton fragmentation region is double leading and $\bar{\Lambda}_c$ is non-leading whereas in the beam fragmentation region both particle and anti-particle production are leading, so in this case a $\Lambda_c/\bar{\Lambda}_c$ asymmetry is expected for $x_F < 0$. 

6
3 \( \Lambda_c/\bar{\Lambda}_c \) 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 eqs. 2 and 8 respectively. Its general form is

\[
\frac{d\sigma^{\text{tot}}}{dx_F} \bigg|_{\Lambda_c(\bar{\Lambda}_c)} = \frac{d\sigma^{\text{pf}}}{dx_F} + \sigma^{\text{rec}}_{\Lambda_c} \frac{d\sigma^{\text{rec}}}{dx_F} \bigg|_{\Lambda_c(\bar{\Lambda}_c)}
\]

(13)

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

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

\[
A_{\Lambda_c/\bar{\Lambda}_c} (x_F) = \frac{d\sigma^{\text{rec}}/dx_F}{2d\sigma^{\text{pf}}/dx_F + \sigma^{\text{rec}}_{\Lambda_c}} \left[ \frac{d\sigma^{\text{rec}}/dx_F}{\Lambda_c} - d\sigma^{\text{rec}}/dx_F \bigg|_{\bar{\Lambda}_c} \right] \frac{d\sigma^{\text{rec}}/dx_F}{\Lambda_c} + d\sigma^{\text{rec}}/dx_F \bigg|_{\bar{\Lambda}_c}
\]

(14)

for the asymmetry as a function of \( x_F \).

It should be noted that pQCD at NLO predicts a bigger \( \bar{\Lambda}_c \) than \( \Lambda_c \) 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 \( \Lambda_c \) and the \( \bar{\Lambda}_c \) 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 \( N(\Lambda_c)/N(\bar{\Lambda}_c) = 0.99 \pm 0.16 \) measured by the ACCMOR collaboration [9] which indicates no asymmetry \((A = -0.002 \pm 0.16)\). Also a preliminary analysis in 500 GeV/c \( \pi^- \)-nucleus interactions from the E791 collaboration [1] 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 [3]. The ratio \( N(\Lambda_c)/N(\bar{\Lambda}_c) = 1.17 \pm 0.08 \) \((A = 0.078 \pm 0.034)\) measured by the E791 collaboration [3] is described by our model with a recombination cross section \( \sigma^{\text{rec}}_{\Lambda_c} \approx 1.1\sigma^{\text{pf}} \) and \( n_1 = 1, n_2 = 5 \) in the recombination function of eq. 11 in the Peterson fragmentation scheme. Here \( \sigma^{\text{pf}} = \int_0^1 dx_F d\sigma^{\text{pf}}/dx_F \).

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 $\pi^-$, $K$ and $p$ beam on a multifold target of Be, Cu, Al and W. However, although this experiment presents an evidence of $\Lambda_c/\bar{\Lambda}_c$ asymmetry, the value quoted in Ref. [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 $\Lambda_c/\bar{\Lambda}_c$ 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 needed not only on $\Lambda_c/\bar{\Lambda}_c$ asymmetries as well as on $\Lambda_c$ and $\bar{\Lambda}_c$ $x_F$ distributions in order to do a meaningful comparison.

Using the preliminary analysis of the E791 collaboration [4], 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.

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 $\Lambda_c$ than for $\bar{\Lambda}_c$ 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 $\Lambda_c$ 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 $\Lambda_c$ 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 $\Lambda_c/\bar{\Lambda}_c$ production asymmetry is the intrinsic charm two component model \[1,0\]. In this model the enhancement in the $\Lambda_c$ over the $\bar{\Lambda}_c$ 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 asymmetries 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 $\Lambda_c$ $x_F$ distribution peaked close to zero whereas the intrinsic charm model gives a $\Lambda_c$ $x_F$ 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 $\Lambda_c$ inclusive $x_F$ distribution (see Refs. \[10, 11\]) but both models predict very different forms for the $\Lambda_c/\bar{\Lambda}_c$ 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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**Figure Captions**

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

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.

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 $\Lambda_c$ distributions. The $\Lambda_c$ distribution is normalized to unity and the $\bar{\Lambda}_c$ distribution is normalized relative to the first one.

Fig. 5: $\Lambda_c/\bar{\Lambda}_c$ 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 (Ref. [4]) experiment is shown.

Fig. 6: Same as in Fig. 1 for $\pi^- p$ interactions. Experimental points are calculated from the $N(\Lambda_c)/N(\bar{\Lambda}_c)$ ratios measured in Refs. [5] and [19].
Figure 1:
Figure 2:
Figure 3:
Figure 4:
Figure 5:
Figure 6: