The Charm of the Proton and the $\Lambda_c^+$ Production

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Abstract. We propose a two component model for charmed baryon production in $pp$ collisions consisting of the conventional parton fusion mechanism and fragmentation plus quarks recombination in which a $ud$ valence diquark from the proton recombines with a $c$-sea quark to produce a $\Lambda_c^+$. Our two-component model is compared with the intrinsic charm two-component model and experimental data.

INTRODUCTION

The production mechanism of hadrons containing heavy quarks is not well understood. Although the fusion reactions $gg \rightarrow Q\bar{Q}$ and $q\bar{q} \rightarrow Q\bar{Q}$ are supposed to be the dominant processes, they fail to explain important features of heavy quark hadro-production like the leading particle effects observed in $D^\pm$ produced in $\pi^-p$ collisions [1], $\Lambda_c^+$ production in $pp$ interactions [2] [3] and in others baryons containing heavy quarks [4], the $J/\Psi$ cross section at large $x_F$ observed in $\pi p$ collisions [5], etc.

The above mentioned effects have been explained using a two-component model [6] consisting of the parton fusion mechanism calculable in perturbative QCD plus the coalescence of intrinsic charm [7].

In hadron-hadron collisions the recombination of valence spectator quarks with $c$-quarks present in the sea of the initial hadron is a possible mechanism for charmed hadron production. Here we explore that possibility for the $\Lambda_c^+$’s production in $pp$ interactions. We will assume that in addition to the usual parton fusion processes, a $ud$ diquark recombines with $c$-sea quark both from the incident proton.
We compare our results with those of the intrinsic charm two-component model and the experimental data available.

Λ⁺ᶜ PRODUCTION VIA PARTON FUSION

In the parton fusion mechanism the Λ⁺ᶜ is produced via the subprocesses $q\bar{q}(gg) \rightarrow c\bar{c}$ with the subsequent fragmentation of the $c$ quark. The inclusive $x_F$ distribution of the Λ⁺ᶜ in $pp$ collisions is given by [8] [9]

$$\frac{d\sigma_{nf}}{dx_F} = \frac{1}{2} \sqrt{s} \int H_{ab}(x_a, x_b, Q^2) \frac{1}{E} \frac{D_{\Lambda_c/c}(z)}{z} dz d\hat{p}_T^2 dy,$$  \hspace{1cm} (1)

where

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

$$+ g_a(x_a, Q^2)g_b(x_b, Q^2) \frac{d\hat{\sigma}}{d\hat{t}} |_{gg}$$  \hspace{1cm} (2)

with $x_a$ and $x_b$ being the parton momentum fractions, $q(x, Q^2)$ and $g(x, Q^2)$ the quark and gluon distribution in the proton, $E$ the energy of the produced $c$-quark and $D_{\Lambda_c/c}(z)$ the fragmentation function. In eq. 1, $p_T^2$ 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 Λ⁺ᶜ. The sum in eq. 2 runs over $a, b = u, \bar{u}, d, \bar{d}, s, \bar{s}$.

We use the LO results for the elementary cross-sections $\frac{d\hat{\sigma}}{d\hat{t}} |_{q\bar{q}}$ and $\frac{d\hat{\sigma}}{d\hat{t}} |_{gg}$ [8].

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

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

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

In order to be consistent with the LO calculation of the elementary cross sections, we use the GRV-LO parton distribution functions [10], allowing by a global factor $K \sim 2 - 3$ in eq. 1 to take into account NLO contributions [6].
We take $m_c = 1.5 \text{ GeV}$ for the $c$-quark mass and fix the scale of the interaction at $Q^2 = 2m^2_c$ [8]. Following [6], we use two fragmentation functions to describe the hadronization of the charm quark:

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

and the Peterson fragmentation function [11]

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

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

$\Lambda_C^+$ PRODUCTION VIA RECOMBINATION

The production of leading mesons at low $p_T$ by recombination of quarks was proposed long time ago [12]. The method introduced by Das and Hwa for mesons was extended by Ranft [13] to describe single particle distributions of leading baryons in $pp$ collisions.

In recombination models one assumes that the outgoing hadron is produced in the beam fragmentation region through the recombination of the maximum number of valence and the minimum number of sea quarks coming from the projectile according to the flavor content of the final hadron. Thus, e.g. $\Lambda_C^+$'s produced in $pp$ collisions are formed by the $ud$ valence diquark and a $c$-quark from the sea of the incident proton. One ignores other type of contributions involving more than one sea flavor recombination.

The invariant inclusive $x_F$ distribution for leading baryons is given by

$$\frac{2E}{\sqrt{S\sigma}} \frac{d\sigma^{rec}}{dx_F} = \int_0^{x_F} dx_1 dx_2 dx_3 \ F_3(x_1,x_2,x_3) \ R_3(x_1,x_2,x_3,x_F)$$

where $x_i, i = 1, 2, 3$, is the momentum fraction of the $i^{th}$ quark, $F_3(x_1,x_2,x_3)$ is the three-quark distribution function in the incident hadron and $R_3(x_1,x_2,x_3,x_F)$ is the three-quark recombination function.

We use a parametrization containing explicitly the single quark distributions for the three-quark distribution function

$$F_3(x_1,x_2,x_3) = \beta F_{u,\text{val}}(x_1) \ F_{d,\text{val}}(x_2) \ F_{c,\text{sea}}(x_3) \ (1-x_1-x_2-x_3)$$

with $F_q(x_i) = x_i q(x_i)$ and $F_u$ normalized to one valence $u$ quark. The parameters $\beta$ and $\gamma$ are constants fixed by the consistency condition

$$F_q(x_i) = \int_0^{1-x_i} dx_j \int_0^{1-x_i-x_j} dx_k \ F_3(x_1,x_2,x_3), \hspace{1cm} i,j,k = 1, 2, 3$$

(9)
for the valence quarks of the incoming proton as in ref. [13].

We use the GRV-LO parametrization for the single quark distributions in eq. 8. It must be noted that since the GRV-LO distributions are functions of $x$ and $Q^2$, then our $F_3(x_1, x_2, x_3)$ also depends on $Q^2$.

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 there is not clear way to fix the value of the parameter $Q^2$, which in this case is not properly a scale parameter and should be used to give adequately the content of the recombining quarks in the initial hadron.

Since the charm content in the proton sea increases rapidly for $Q^2$ growing from $m_c^2$ to $Q^2$ of the order of some $m_c^2$’s when it become approximately constant, we take $Q^2 = 4m_c^2$, a conservative value, but sufficiently far from the charm threshold in order to avoid a highly depressed charm sea which surely does not represent the real charm content of the proton. At this value of $Q^2$ we found that the condition of eq. 9 is fulfilled approximately with $\gamma = -0.1$ and $\beta = 75$. We have verified that the recombination cross section does not change appreciably at higher values of $Q^2$.

For the three-quark recombination function for $\Lambda_c^+$ production we take the simple form [13]

$$R_3(x_u, x_d, x_c) = \frac{\alpha x_u x_d x_c}{x_F^2} \delta(x_u + x_d + x_c - x_F)$$

(10)

with $\alpha$ fixed by the condition $\int_0^1 dx_F (1/\sigma) d\sigma^{rec}/dxF = 1$, then $\sigma$ is the cross section for $\Lambda_c^+$’s inclusively produced in pp collisions. From eqs 7 and 8, the invariant $x_F$ distribution for $\Lambda_c^+$ is

$$\frac{2E_\sqrt{s} \sigma^{\Lambda_c^+}_{rec}}{\sigma} = 75\alpha \frac{(1 - x_F)^{-0.1}}{x_F^2} \int_0^{x_F} dx_1 F_{u,\text{val}}(x_1)$$

$$\times \int_{x_F - x_1}^{x_F} dx_2 F_{d,\text{val}}(x_2) F_{c,\text{sea}}(x_F - x_1 - x_2)$$

(11)

where we already integrated over $x_3$. The parameter $\sigma$ will be fixed with experimental data.

The inclusive production cross section of the $\Lambda_c^+$ is obtained by adding the contribution of recombination eq. 11 to the QCD processes of eq. 7, then

$$\frac{d\sigma^{\Lambda_c^+}_{rec}}{dx_F} \frac{d\sigma^{pf}}{dx_F} + \frac{d\sigma^{\Lambda_c^+}_{rec}}{dx_F}$$

(12)

The resulting inclusive $\Lambda_c^+$ production cross section $d\sigma^{\Lambda_c^+}/dx_F$ is plotted in fig. 1 using the two fragmentation function of eqs. 5 and 6 and compared
FIGURE 1. $x_F$ distribution predicted by parton fusion plus recombination (full line) and parton fusion plus IC coalescence (dashed line) for Peterson fragmentation (a) and delta fragmentation function (b). Experimental data (black dots) are taken from ref. 3.

with experimental data in $pp$ collisions from the ISR [3]. As we can see, the shape of the experimental data is very well described by our model. We use a factor $\sigma = 0.92(0.72)\mu$bar for Peterson (delta) fragmentation respectively.

In a similar approach R. Vogt et al. [6] calculated the $\Lambda_c^+$ production in $pp$ and $\pi p$ collisions. The two component model used by them consists of a parton fusion mechanism plus coalescence of the intrinsic charm in the proton. Their results are shown in fig.1. The normalization however has been modified to make a proper comparison to our result.

CONCLUSIONS

We have studied the $\Lambda_c^+$ production in $pp$ collisions with a two component model. We show that both the intrinsic charm model and the conventional recombination of quarks can describe the shape of the $x_F$ distribution for $\Lambda_c^+$'s produced in $pp$ collisions. None of them, however, can describe the abnormally high normalization of the ISR data quoted in ref. [3]. This discrepancy between theory and experiment does not exist for charmed meson production, which is well described both in shape and normalization with the parton fusion mechanism plus intrinsic charm coalescence [9] and with the conventional recombination as proposed here [14].

An interesting test to rule out one of the two models would come from a
measurement of the \( \Lambda_c \) polarization as proposed in [15].

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