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**POLARIZATION PROPERTIES
OF DIFFRACTIVELY PRODUCED Λ_c^+**

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Abstract

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The Pomeron-gluon-gluon interaction is considered in the QCD-based model for the charmed baryon production in the process Pomeron + $p \rightarrow \Lambda_c^+ + X$. The polarization of the produced heavy quark is induced effectively through the non-perturbative long-range interaction with the gluon field of the type $[\vec{\sigma} \cdot \text{rot}\mathcal{A}]$. The x_F -dependence of Λ_c^+ polarization, $P_{\Lambda_c^+}(x_F, p_T)$, has been studied. Its absolute value depends on the model parameter a and it appears to be sizeable in the wide range of a values: when a ranges from 0.1 to 1.0, the polarization $P_{\Lambda_c^+}(x_F, p_T)$ varies from -0.2 to -0.5 at $x_F \sim 0.5$ and p_T in the interval $1 \div 2 \text{ GeV}/c$.

Аннотация

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Рассматривается померон-глюон-глюонное взаимодействие в модели КХД для образования чармованного бариона в процессе Pomeron + $p \rightarrow \Lambda_c^+ + X$. Поляризация рожденного тяжелого кварка вводится эффективно через непертурбативное взаимодействие с глюонным полем на больших расстояниях вида $[\vec{\sigma} \cdot \text{rot}\mathcal{A}]$. Изучена x_F -зависимость поляризации $P_{\Lambda_c^+}(x_F, p_T)$. Ее абсолютное значение зависит от параметра модели a и оказывается значительным в широком интервале значений a : когда a меняется от 0.1 до 1.0 поляризация $P_{\Lambda_c^+}(x_F, p_T)$ меняется с -0.2 до -0.5 при $x_F \sim 0.5$ и p_T в интервале $1 \div 2 \text{ ГэВ}/c$.

Introduction. Polarization properties of heavy quarks have been studied for a long period, both experimentally and theoretically. A major piece of knowledge came from the experimental study of strange Λ baryons. The polarization of the final-state Λ 's at large x_F is negative and it reaches 20-30%. The most recent and full review on the polarization of the strange baryons can be found in K. Heller's report at SPIN96 [1].

So far, the experimental data on the charmed Λ_c^+ polarization have been restricted to the output of only one experiment performed in IHEP, Protvino at the neutron beam in the reaction $n + C_{12} \rightarrow \Lambda_c^+ + X$ [2]. The measured upper limit of the absolute value of Λ_c^+ polarization was equal to 0.5 ± 0.2 . The momentum of the neutron beam ranged from 40 to 70 GeV/c.

Perhaps soon new data on the Λ_c^+ polarization will come from the E-831 experiment at Fermilab (FOCUS) in which the polarization measurements can be performed in the reaction $\gamma + p \rightarrow \Lambda_c^+ + X$ at 300 GeV/c.

The forthcoming collider experiments at RHIC and LHC will make it possible to study the Λ_c^+ production and its spin properties in various kinematic regions, in particular, in the diffraction region. Theoretically the spin phenomena in diffractive processes are under intensive study. Three refs. in [3] represent different aspects of the spin dependence of diffractive interactions.

Unlike the strange Λ , the theory predictions for the Λ_c^+ polarization P are not numerous. The large values up to 100% were predicted for the absolute value of $P_{\Lambda_c^+}$ in an early paper [4]. The recent estimates were made in ref. [5] for the intrinsic charmed sea contribution to the Λ_c^+ production. Under various model assumptions, $P_{\Lambda_c^+}$ ranges from -0.02 to -0.11 at large x_F in the recombination approach.

Note also that the spin of $\Lambda_c^+(2285)$ has not firmly been established so far. In the following we shall assume that the spin is equal to 1/2 as it is accepted by the PDG [6].

In this paper we are interested in the Λ_c^+ polarization in the diffractive production process

$$p + p \rightarrow \Lambda_c^+ + X \tag{1}$$

at high energies (fig. 1). In the upper block the $c\bar{c}$ pair is produced and c quark is polarized in the final state. The model for the heavy quark polarization depends on the kinematics in the upper block and does not promptly depend on the diffractive production of the

upper block. The advantage of the diffractive $c\bar{c}$ production in (1) displayed in fig. 1 is the simplicity of the lowest-order model with the dominance of the Pomeron-gluon-gluon coupling. The more general consideration would require an additional determination of, at least, the ratio of the coupling constants Pomeron-gluon-gluon/Pomeron-quark-quark.

Formulation of the model. We study the inclusive production of $c\bar{c}$ pair by the initial Pomeron in the process

$$p + \text{Pomeron} \rightarrow \Lambda_c^+ + X \quad (2)$$

(fig. 2) which is relevant to the inclusive reaction (1). In this reaction the incoming proton energy $\sqrt{s}/2$ and the Pomeron 4-momentum q are those of reaction (1). q is fixed at an arbitrary small value. The results of the calculations of the polarization $P_{\Lambda_c^+}(x_F, p_T)$ do not depend essentially on q in the diffractive region.

The underlying parton subprocess is shown in fig. 2 as the lowest-order heavy quark pair production by the gluon-Pomeron coupling:

$$g + \text{Pomeron} \rightarrow c + \bar{c}. \quad (3)$$

We neglect the charmed sea, so the leading order process $c + \text{Pomeron} \rightarrow c + g$ does not contribute to the Λ_c^+ polarization. Also we neglect parton transverse momenta. The Λ_c^+ transverse momenta in (2) are taken in the region $p_T = 1 \div 2$ GeV/c.

Another assumption is the dominance of the Pomeron-gluon-gluon coupling constant g_{Pgg} compared to the Pomeron-quark-quark coupling g_{Pqq} , so that $g_{Pqq}/g_{Pgg} \ll 1$. Hence, at this level we exclude from the consideration the next-order subprocess $q + \text{Pomeron} \rightarrow q + c\bar{c}$ in which a valence quark q is excited by the Pomeron and it emits the $c\bar{c}$ pair.

The produced c quark recombines inclusively with the spectator ud diquark system thus forming the final Λ_c^+ .

The Λ_c^+ polarization originates from the polarization of the produced c quark and is expressed in terms of the quark spin density matrix $\rho_Q^{\lambda\lambda'}$ by the following formula for the charmed baryon spin density matrix in process (2):

$$\rho^{\lambda\lambda'} E \frac{d^3\sigma}{dp^3} = \int dx_{ud} dx_g dz f_g(x_g, Q^2) f_{ud}(x_{ud}, Q^2) \varepsilon_Q \frac{d^3\hat{\sigma}}{dp_Q^3} \rho_Q^{\lambda\lambda'}(\vec{p}_Q, \mathcal{A}) R(x_F, p_T, x_Q, x_{ud}; z). \quad (4)$$

Here f_g and f_{ud} are gluon and diquark distribution functions with x_g and x_{ud} standing for the momentum fractions of the gluon and diquark, respectively. Q^2 is the QCD scale chosen in the form $Q^2 = m_Q^2 + p_T^2$. The quantities $\hat{\sigma}$, p_Q , ε_Q refer to the underlying subprocess (3). The hadronization process in (4) is described by the inclusive recombination function R depending on the c quark, diquark and Λ_c^+ momenta with z being the energy fraction of (ud, c) system carried away by Λ_c^+ . Using (4) the Λ_c^+ polarization is written as $P_{\Lambda_c^+} = \text{Tr}(\sigma\rho)/\text{Tr}(\rho)$.

A model for the final-state quark polarization expressed in terms of $\rho_Q^{\lambda\lambda'}(\vec{p}_Q, \mathcal{A})$ was initially formulated in [7]. In this paper we explore a corrected version of that model applied to the charmed baryon production. In the model the produced heavy quark scatters off the external gluon field \mathcal{A} and the quark spin \vec{s}_Q may couple to the field, so that the correlation $\vec{s}_Q \cdot \text{rot}\mathcal{A}$ occurs.

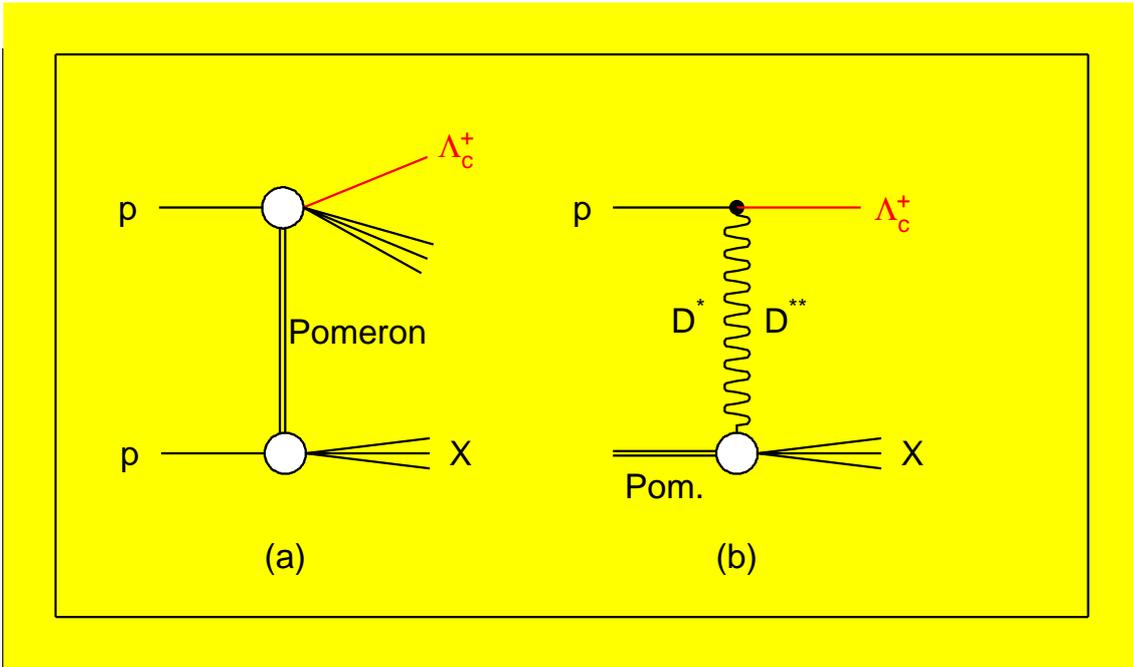


Fig. 1. (a) – Diffractive production of Λ_c^+ with $c\bar{c}$ pair in the upper block in reaction (1); (b) – Regge exchanges in the upper block.

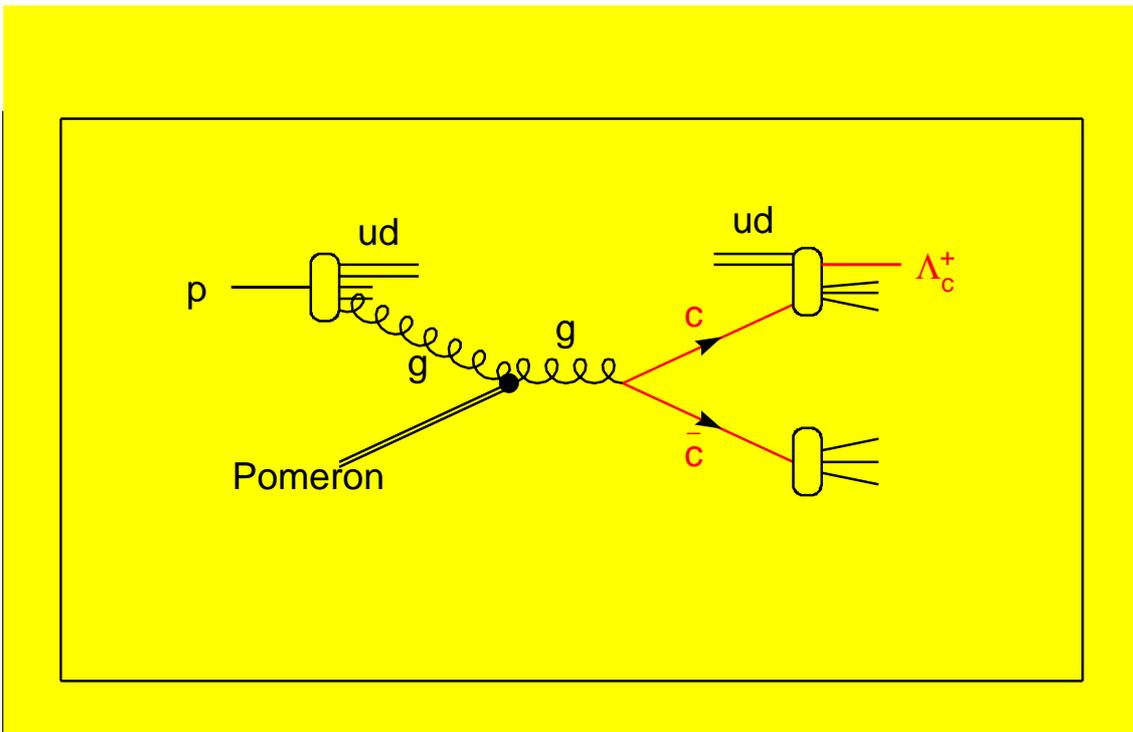


Fig. 2. The leading-order parton subprocess in reaction $p + \text{Pomeron} \rightarrow \Lambda_c^+ + X$.

To estimate this correlation, a non-trivial model for the external gluon field \mathcal{A} itself is needed. In case of the simplest color field, the spin flip properties and polarization of a scattered massive quark were considered, for example, in the early paper [8] by J. Szwed, where the external gluon field $\Phi^a(q) = 4\pi g I^a / \bar{q}^2$ was used in the perturbative second-order calculations. Note that the massive quark polarization obtained in [8] was negative.

An alternative way is to parametrize the heavy quark spin density matrix ρ_Q^{+-} globally rather than to introduce an explicit model for \mathcal{A} and for the quark interaction with this field.

The parametrization of ρ_Q is based on the following considerations. By definition $\rho_Q^{\lambda\lambda'} = \sum L^{\lambda\mu} \bar{L}^{\lambda'\mu}$ where $L^{\lambda\mu}$ is the quark transition amplitude in the gluon field \mathcal{A} . The following traces relate to the basic formula (4): $\text{Tr}(\sigma\rho_Q) = -2\text{Im}\rho_Q^{+-} = 4\text{Im}(L^{++} \bar{L}^{+-})$ and $\text{Tr}(\rho_Q) = 2(|L^{++}|^2 + |L^{+-}|^2)$. Under the space parity conservation the relations $L^{++} = L^{--}$ and $L^{+-} = -L^{-+}$ hold.

For the parametrization it is convenient to include $\text{Tr}(\rho_Q)$ into the recombination (hadronization) function R in (4). Then the trace of the convolution of (4) with the Pauli matrix $\vec{\sigma}$ will contain in the integrand the expression $P_Q = \text{Tr}(\sigma\rho_Q)/\text{Tr}(\rho_Q)$ which is exactly the heavy quark polarization (see below).

After these generalities the time has come to parametrize the ratio P_Q . The normalized spin-flip transition amplitude squared $|L^{+-}|^2$ has the sense of probability to make quark spin-flip in the external field. It seems natural to think that it increases with the quark mean range. Henceforth, it grows with increasing quark energy, ε_Q , since at hadronization the mean range of a fast quark is proportional to ε_Q/M^2 where M^{-1} is of order of the confinement radius. Thus, we accept the equality $|L^{+-}|^2/(|L^{++}|^2 + |L^{+-}|^2) = a\varepsilon_Q/\varepsilon_Q^{max}$ with the suppression parameter $0 < a < 1$. The normalization ε_Q^{max} depends, of course, on the kinematics, however, for the simplicity we take it equal to $\sqrt{s}/2$.

Taking these straightforward considerations into account the parametrization has been made as follows:

$$P_Q = \frac{2\text{Im}(L^{++} \bar{L}^{+-})}{|L^{++}|^2 + |L^{+-}|^2} = 2\sqrt{ax_\varepsilon(1 - ax_\varepsilon)} \sin \Delta\phi, \quad (5)$$

where $x_\varepsilon = \varepsilon_Q/\varepsilon_Q^{max}$, and $\Delta\phi$ is the phase difference of the amplitude L^{++} and L^{+-} .

Phase difference. In principle the phase difference $\Delta\phi$ depends on arguments of the amplitudes $L^{\lambda\lambda'}$, i.e. on ε_Q . The simple linear dependence $\Delta\phi = r_1\varepsilon_Q + r_2$ was used in [9] to describe the experimental data on the one-spin asymmetry in the reactions $p_\uparrow + p \rightarrow \pi^\pm + X$ at 13 and 18 GeV/c and in the reaction $\pi^- + p_\uparrow \rightarrow \pi^0 + X$ at 40 GeV/c. Three sets of experimental data were enough to determine the parameters r_1 and r_2 .

In this paper we prefer to imply $\Delta\phi$ value based on the Regge-type considerations. The Regge properties of the reaction (2) are determined by D^* and D^{**} exchange trajectories (see insertion in fig. 1). And in the Regge approach the Λ_c^+ polarization in reaction (2) is due to the interference of the exchange diagrams with these trajectories [4]. Thus the difference of the Regge phases, $\Delta\phi = \phi_{D^*} - \phi_{D^{**}}$ occurs naturally. It depends on t , the

squared momentum transfer from the initial proton to the final charmed baryon. Since we consider Λ_c^+ production at large x_F and relatively small p_T , we neglect the small t contribution in $\Delta\phi$ (in [4] the t -dependence dropped down due to the hypothesis of the weak exchange degeneration). So, we obtain $\Delta\phi = \pm(j_* - j_{**})\pi/2 = \pm\pi/2$. Here the starred j 's correspond to the spins of the exchange trajectories. The sign \pm reflects the non-uniqueness of this procedure and it can be chosen by comparing the results with the strange Λ polarization at large x_F .

Parton distributions. We used two sets of the leading-order parton distribution functions (pdf's): CTEQ4L and GRVLO [10]. In the kinematic region of interest, the gluon pdf's $f_g(x, Q^2)$ from these sets are close at $x < 0.3 \div 0.4$ and they differ at larger x , whereas the pdf's of the light quarks u and d are similar.

For our purpose, the 'diquark' pdf has been constructed of u and d quarks very simply:

$$f_{ud}(x, Q^2) = \int^x \frac{f_u(y, Q^2)}{y} \frac{f_d(x-y, Q^2)}{x-y} dy.$$

The arguments in the denominators means that the pdf's output from the packages in [10] are of the conventional type x times pdf. The diquark distribution is shown in fig. 3.

Inclusive recombination. The hadronization of the produced charmed quark is assumed via the inclusive recombination with the spectator valence ud system. This subprocess is described by the inclusive recombination function

$$R(x_F, p_T, x_Q, x_{ud}; z) = const \cdot \frac{x_{\varepsilon_Q} x_{ud}}{x_{\varepsilon_Q} + x_{ud}} \cdot \frac{1}{z} \delta(z-1)$$

where x_E is the reduced Λ_c^+ energy: $x_E = 2E/\sqrt{s}$, and $z = x_E/(x_{\varepsilon_Q} + x_{ud})$. This expression incorporating the transverse momentum is a generalization of the conventionally used recombination functions. The normalization parameter *const* has not been specified since it drops down in the formula for polarization $P_{\Lambda_c^+}$.

Partonic subprocess. The differential cross section $\varepsilon_Q d^3\hat{\sigma}/dp_Q^3$ has been calculated using the matrix element

$$M = g_{Pgg} g_s \frac{1}{\hat{s}} \phi_P T_{ij}^a \epsilon_\mu^a \bar{u}_Q^i \gamma_\mu v_Q^j.$$

Here g_{Pgg} and g_s are the Pomeron-gluon-gluon and the strong coupling constants, respectively, ϵ_μ^a is the gluon polarization 4-vector, u_Q and v_Q are the quark and antiquark spinors, respectively, T_{ij}^a is the color factor and \hat{s} is the incoming energy squared. ϕ_P is the Pomeron wave function which is normalized as $\phi_P \phi_P^* = 1$.

Kinematics. We are interested in x_F dependence of the Λ_c^+ polarization $P_{\Lambda_c^+}(x_F, p_T)$ in the process (2) with given p_T and at a fixed value of q . The kinematic region $0.2 < x_F < 0.9$ and $1 < p_T < 2 \text{ GeV}/c$ was studied. No visible p_T dependence of $P_{\Lambda_c^+}(x_F, p_T)$ was obtained.

The basic relations for the longitudinal and transverse momenta are the following: $x_F = x_{ud} + x_Q$, $\vec{p}_T = \vec{p}_{TQ}$. This should be added by the 4-momentum conservation in the partonic subprocess. Thus, the integration limits in x_{ud} and x_g can be formally determined. However the lower limit in x_{ud} , the momentum fraction of the spectator valence diquark would be too small from the physical point of view. So the lower limit

of x_{ud} was chosen to be not less than 0.15. Variations around this value do not cause the strong change of the resulting polarization.

The lower limit in integrating over x_g , the gluon momentum fraction, is defined by $x_g^{min} = (2/\sqrt{s})(\sqrt{p_T^2 + m_Q^2} + \varepsilon_Q - q_0)$. The value of the upper limit has been chosen as $x_g^{max} = 0.95$.

An important note. Here is an appropriate place to make a note on the seemingly numerous assumptions before starting to calculate the polarization integrals. The final-state baryon polarization at large x_F is due entirely to the QCD twist-3 contributions. For the twist-3 studies in hadron interactions, there is no commonly used model. At first glance, there is too much freedom in the above considerations of the quark polarization P_Q and/or the inclusive recombination function R . It seems to be a disadvantage of the approach. However the hadron (Λ_c^+ in this paper) polarization is a *ratio* of two integrals which include the same functions in the nominator and denominator, except P_Q presented in the nominator only. And all the functions are rather smooth. From this it follows that the ratio of the integrals depends weakly on the reasonable variations of the separate functions in the integrands. It means, for example, that our results must not change strongly if we use the second order diagrams in $\varepsilon_Q d\hat{\sigma}/dp^3$ instead of the leading order calculations. The same is true for different forms of the inclusive recombination function R . The shape and size of the Λ_c^+ polarization are mostly determined by the parametrization of P_Q in (5).

Results of calculations. As is seen from (4), the sign of the Λ_c^+ polarization is determined by the sign of $\text{Tr}(\sigma\rho_Q)$, that is the sign of the heavy quark polarization P_Q . The presented model for P_Q (5) has the sign ambiguity mentioned above in the paragraph *Phase difference*. Since the model makes no difference between the flavors of the massive quarks, we resolve the sign ambiguity in favor of the strange s quark in order to obtain the negative Λ polarization at large x_F in similar calculations. So the phase difference $\Delta\phi$ in (5) has been chosen equal to $-\pi/2$. It is worth to note that this choice supported by the experimental data for the strange Λ polarization coincides with the sign of P_Q in [8] obtained in perturbative calculations.

The only undetermined quantity is still the suppression factor a in formula (5). The numerical calculations were made for two far-distant values $a=0.1$ (small polarization) and $a=1$ (largest polarization) using two sets of the leading-order parton distributions CTEQ4L and GRVLO [10]. The results for x_F dependence of the Λ_c^+ polarization $P_{\Lambda_c^+}(x_F, p_T)$ at $p_T=1.5$ GeV/c are shown in fig. 4. At $x_F=0.5$ the small and the largest polarizations differ in magnitude by a factor of ~ 2.5 . With growing x_F from 0.2 to 0.9, both the small and the largest polarizations increase by a factor of 2.

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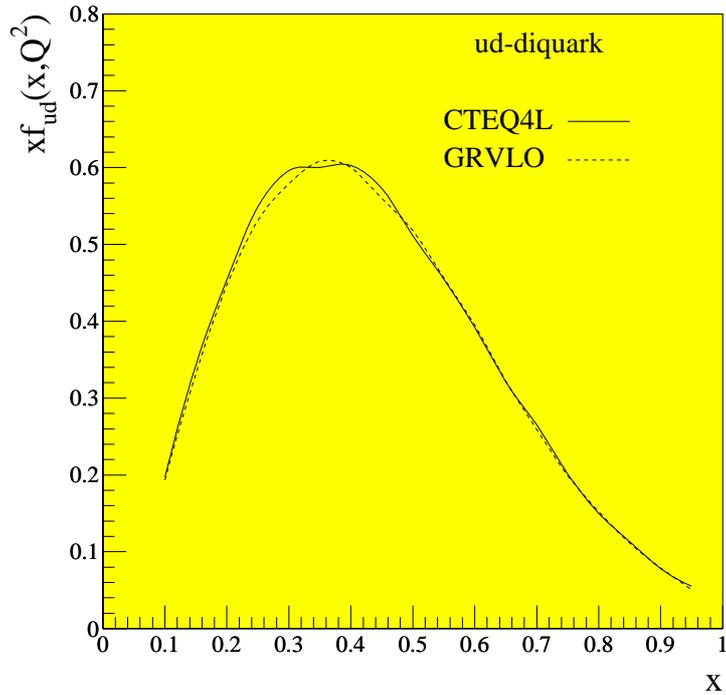


Fig. 3. Diquark distribution function $xf_{ud}(x, Q^2)$ at $Q^2 = m_Q^2 + p_T^2$ with $m_Q = 1.5 \text{ GeV}/c$ and $p_T = 2 \text{ GeV}/c$. The solid (dashed) line corresponds to CTEQ4L(GRVLO) parton distribution functions.

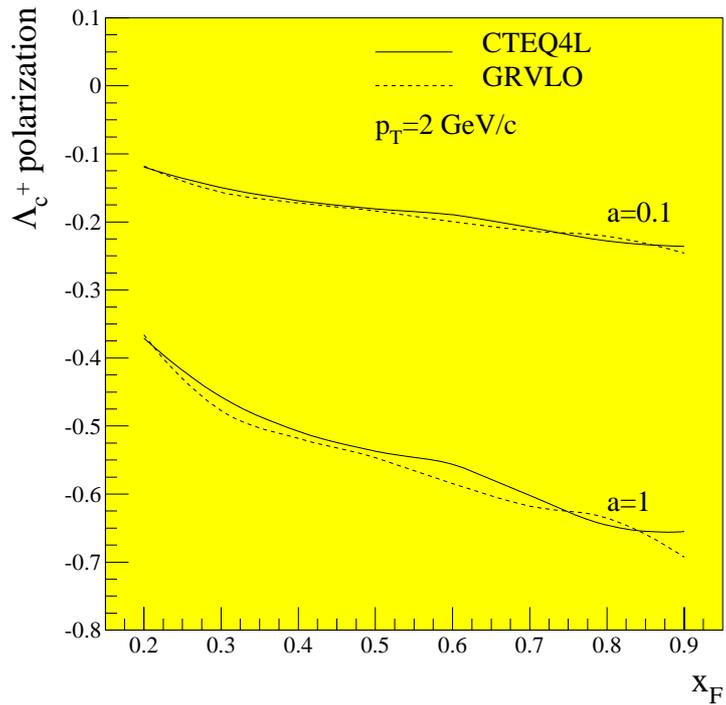


Fig. 4. x_F dependence of the Λ_c^+ polarization in the process $p + \text{Pomeron} \rightarrow \Lambda_c^+ + X$ at $p_T = 2 \text{ GeV}/c$. The solid (dashed) line corresponds to CTEQ4L(GRVLO) parton distribution functions.

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