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Study of quark GTMDs for kaon in light-cone quark model

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We investigate the generalized transverse momentum-dependent quark and anti-quark distributions (GTMDs) for kaon in light-cone quark model. The leading-twist GTMDs are evaluated from the quark-quark correlator by considering the unpolarized, longitudinally polarized and transversely-polarized quark/anti-quark in unpolarized kaon. For the evaluation of GTMDs, the overlap representation of light-cone wavefunctions is used. We observe the variation of GTMDs with longitudinal momentum fraction (x) at different values of quark/anti-quark transverse momentum as well as momentum transfer.

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1. Introduction

In Quantum Chromodynamics (QCD), the formation of hadron in respect of its constituents i.e. quarks, antiquarks and gluons, is an important key to understand. The non-perturbative effects of QCD give knowledge about the internal complex structure of the hadron. To perceive the relation between the hadron and its degrees of freedom, several distributions are present. The generalized parton distributions (GPDs) [1] and transverse momentum-dependent distributions (TMDs) [2] explain three-dimensional picture of hadron, in position and momentum space respectively. The generalized transverse momentum-dependent parton distributions (GTMDs) [3] explain the complete picture of hadron. Due to the ability to reduct the GTMDs in further GPDs and TMDs at certain kinematic limits, the GTMDs are entitled as *mother distributions*. The Fourier transform of GTMDs lead to the quasi-probabilistic Wigner distributions [4], which are the quantum phase-space distributions and can be interpreted in terms of impact-parameter dependent distributions (IPDs) and TMDs.

By taking the kaon, which is a pseudoscalar composite particle, we study the dynamics of valence partons. Being a spin-0 meson system, it is easier to understand the dynamical structure of kaon because of its composition of quark-antiquark pair. The model used to investigate the kaon structure is the light-cone QCD inspired model [5]. In context of relativistic dynamical study of hadron structure, the light-cone framework imparts a suitable environment. The Fock state expansion of meson in light-cone model is described as $|M\rangle = \sum |q\bar{q}\rangle \psi_{q\bar{q}} + \sum |q\bar{q}g\rangle \psi_{q\bar{q}g} + \ldots$ [6]. As we investigate the leading-twist distributions, we choose the quark-antiquark state here, which is the minimal Fock state description.

2. Generalized Transverse Momentum-dependent Distributions (GTMDs)

In case of pseudoscalar mesons, the GTMDs F_1, $\tilde{G}_1$, H_1^k and H_1^Δ are related to the Wigner correlator $\hat{W}^{[\Gamma]}$, depending upon the different polarizations of quark/antiquark, as follows [3],

$$\hat{W}^{[\gamma^+]} = F_1, \tag{2.1}$$

$$\hat{W}^{[\gamma^+\gamma_5]} = \frac{i\varepsilon_\perp^{ij} k_\perp^i \Delta_\perp^j}{M^2} \tilde{G}_1, \tag{2.2}$$

$$\hat{W}^{[i\sigma^{j+}\gamma_5]} = \frac{i\varepsilon_\perp^{ij} k_\perp^i}{M} H_1^k + \frac{i\varepsilon_\perp^{ij} \Delta_\perp^i}{M} H_1^\Delta, \tag{2.3}$$

where the definition of $\hat{W}^{[\Gamma]}$ including Γ-matrices specifically, $\Gamma = \gamma^+, \gamma^+\gamma_5$ and $i\sigma^{j+}\gamma_5$ corresponding to unpolarized, longitudinally polarized and transversely polarized quark/antiquark respectively [7] is given as

$$\hat{W}^{[\Gamma]}(\Delta_\perp, \mathbf{k}_\perp, x) = \frac{1}{2}\int \frac{dz^- d^2 z_\perp}{(2\pi)^3} e^{ik\cdot z} \left\langle M(P'') \middle| \bar{\psi}\left(-\frac{z}{2}\right) \Gamma \mathscr{W}_{[-\frac{z}{2},\frac{z}{2}]} \psi\left(\frac{z}{2}\right) \middle| M(P') \right\rangle \Bigg|_{z^+=0} . \tag{2.4}$$

The two-particle Fock state expansion for kaon in terms of its constituents with λ_1 (helicity of quark) and λ_2 (helicity of antiquark) is expressed as [6]

$$|M(P,S)\rangle = \sum_{\lambda_1,\lambda_2} \int \frac{dx d^2\mathbf{k}_\perp}{\sqrt{x(1-x)}16\pi^3} |x, \mathbf{k}_\perp, \lambda_1, \lambda_2\rangle \psi_{S_z}^{\lambda_1,\lambda_2}(x, \mathbf{k}_\perp). \tag{2.5}$$

The wavefunctions $\psi_{S_z}^{\lambda_1,\lambda_2}$ having different helicities combinations corresponding to quark and antiquark, are expressed as [6]

$$\begin{aligned}
\psi_0^{\uparrow,\uparrow}(x,\mathbf{k}_\perp) &= -\frac{1}{\sqrt{2}}\frac{k_1-ik_2}{\sqrt{\mathbf{k}_\perp^2+(1-x)m_1^2+xm_2^2-x(1-x)(m_1-m_2)^2}}\varphi(x,\mathbf{k}_\perp),\\
\psi_0^{\uparrow,\downarrow}(x,\mathbf{k}_\perp) &= \frac{1}{\sqrt{2}}\frac{(1-x)m_1+xm_2}{\sqrt{\mathbf{k}_\perp^2+(1-x)m_1^2+xm_2^2-x(1-x)(m_1-m_2)^2}}\varphi(x,\mathbf{k}_\perp),\\
\psi_0^{\downarrow,\uparrow}(x,\mathbf{k}_\perp) &= -\psi_0^{\uparrow,\downarrow}(x,\mathbf{k}_\perp),\quad \psi_0^{\downarrow,\downarrow}(x,\mathbf{k}_\perp)=[\psi_0^{\uparrow,\uparrow}(x,\mathbf{k}_\perp)]^*,
\end{aligned} \tag{2.6}$$

where $\varphi(x,\mathbf{k}_\perp)$ is the momentum-space wavefunction described as [8]

$$\varphi(x,\mathbf{k}_\perp) = A\,\exp\left[-\frac{\frac{\mathbf{k}_\perp^2+m_1^2}{x}+\frac{\mathbf{k}_\perp^2+m_2^2}{1-x}}{8\beta^2}-\frac{(m_1^2-m_2^2)^2}{8\beta^2\left(\frac{\mathbf{k}_\perp^2+m_1^2}{x}+\frac{\mathbf{k}_\perp^2+m_2^2}{1-x}\right)}\right]. \tag{2.7}$$

The explicit expressions for u-quark GTMDs in kaon are calculated as

$$F_1^{(u)} = \frac{1}{16\pi^3}\left[\mathbf{k}_\perp^2-(1-x)^2\frac{\mathbf{\Delta}_\perp^2}{4}+((1-x)m_1+xm_2)^2\right]\frac{\varphi_u^\dagger(x,\mathbf{k}''_\perp)\varphi_u(x,\mathbf{k}'_\perp)}{\sqrt{\mathbf{k}''^2_\perp+l_u^2}\sqrt{\mathbf{k}'^2_\perp+l_u^2}}, \tag{2.8}$$

$$\tilde{G}_1^{(u)} = -\frac{M^2}{16\pi^3}(1-x)\frac{\varphi_u^\dagger(x,\mathbf{k}''_\perp)\varphi_u(x,\mathbf{k}'_\perp)}{\sqrt{\mathbf{k}''^2_\perp+l_u^2}\sqrt{\mathbf{k}'^2_\perp+l_u^2}}, \tag{2.9}$$

$$H_1^{\Delta(u)} = \frac{M}{16\pi^3}(1-x)((1-x)m_1+xm_2)\frac{\varphi_u^\dagger(x,\mathbf{k}''_\perp)\varphi_u(x,\mathbf{k}'_\perp)}{\sqrt{\mathbf{k}''^2_\perp+l_u^2}\sqrt{\mathbf{k}'^2_\perp+l_u^2}}, \tag{2.10}$$

where $l_u^2=(1-x)m_1^2+xm_2^2-x(1-x)(m_1-m_2)^2$, with $\mathbf{k}'_\perp=\mathbf{k}_\perp+(1-x)\frac{\mathbf{\Delta}_\perp}{2}$ and $\mathbf{k}''_\perp=\mathbf{k}_\perp-(1-x)\frac{\mathbf{\Delta}_\perp}{2}$ represent the momenta of u quark initial and final state. The flavor decomposition of u-quark and $\bar{s}$-quark in kaon is related as [1]

$$F^u(x,\mathbf{k}_\perp^2,\mathbf{k}_\perp.\mathbf{\Delta}_\perp,\mathbf{\Delta}_\perp^2,m_1,m_2) = -F^{\bar{s}}(-x,\mathbf{k}_\perp^2,-\mathbf{k}_\perp.\mathbf{\Delta}_\perp,\mathbf{\Delta}_\perp^2,m_2,m_1). \tag{2.11}$$

In this work, the relations of quark(antiquark) GTMDs with the respective longitudinal momentum fraction x(-x) are presented. Specifically, we have shown the results of u and $\bar{s}$ GTMDs $F_1,\tilde{G}_1$ and H_1^Δ in kaon w.r.t. x in Fig. 1. Despite of the support interval $-1<x<1$ for the study of distributions, we chose the DGLAP regions for antiquark and quark i.e. $-1<x<0$ and $0<x<1$. We have fixed the values of $\mathbf{\Delta}_\perp$ and observed the effect of GTMDs w.r.t. x at different values of $\mathbf{k}_\perp$ in first case and vice versa in other. In first case, we observe the shift in the distribution peaks towards the lower values of x and with the growing quark transverse momentum, magnitude goes lower. We see that the effects are opposite in case of $\bar{s}$ quark in all distributions. In other case, the distribution effect converses w.r.t. quark(antiquark) longitudinal momentum fraction. The peak moves towards the higher values of x with the increase in the values of total momentum transferred to the kaon. When the momentum transfered to the kaon is more, the distribution magnitude decreases with x. Depending upon the on-shell masses of active quark or antiquark, the difference between the peaks of distributions occur. The GTMDs are related to Wigner distributions by the effect of Fourier

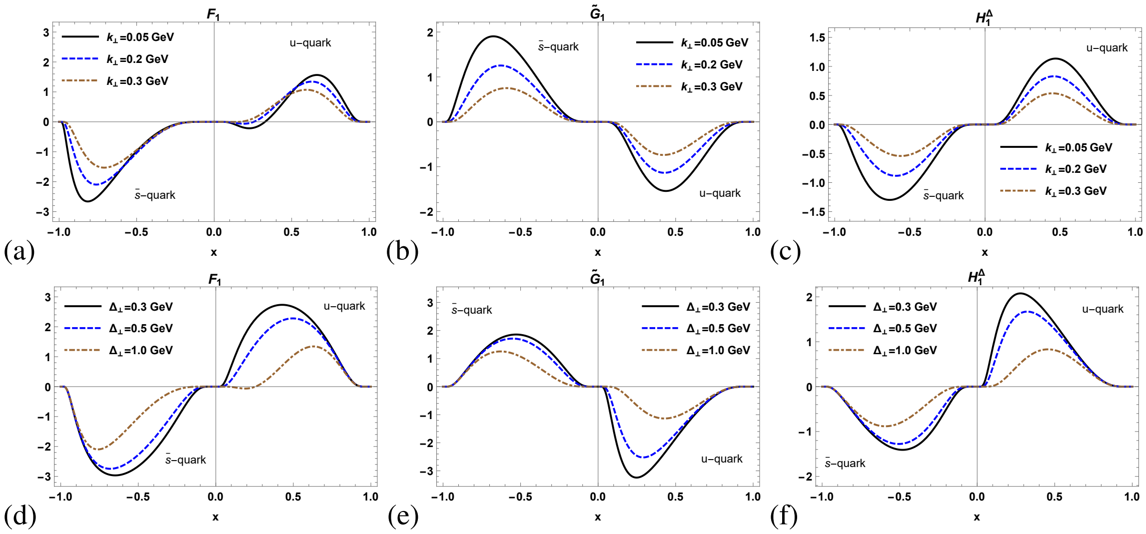

Figure 1: The GTMDs F_1, $\tilde{G}_1$ and H_1^Δ w.r.t x (i) at different values of $\mathbf{k}_\perp$ with fixed $\mathbf{\Delta}_\perp = 1$ GeV (upper panel), and (ii) at different values of $\mathbf{\Delta}_\perp$ with fixed $\mathbf{k}_\perp = 0.2$ GeV (lower panel) for $\bar{s}$ and u quarks.

transformation. The distribution F_1 is related to the unpolarized Wigner distribution ρ_{UU}. Further, being the *mother distributions*, the GTMDs can give the probabilistic distributions i.e. GPDs and TMDs after applying certain limits. The distribution F_1 relates the unpolarized GPD H and TMD f_1. There is no three-dimensional distribution i.e. GPD or TMD across $\tilde{G}_1$ and leads to the effect of spin and orbital angular momentum correlation. Furthermore, corresponding to H_1^Δ, T-odd Boer-Mulder TMD $h_1^\perp$ and T-odd GPD E_T come into picture. Because we are not dealing with any gluon contribution in this work, we are not able to extract any TMD or GPD here corresponding to H_1^Δ.

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