Few-Body Systems Suppl. 0, 1–?? (2018)

Few-Body Systems

Single Meson Photoproduction via Higher Twist Mechanism and IR Renormalons

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Abstract. Single pseudoscalar and vector mesons hard semi-inclusive photoproduction $\gamma h \to MX$ via higher twist (HT) mechanism is calculated using the QCD running coupling constant method. The structure of infrared renormalon singularities of the HT subprocess cross section and the Borel sum for it are found. The problem of normalization of HT process cross section in terms of the meson elm form factor is discussed.

One of the fundamental achievements of QCD is the prediction of asymptotic scaling laws for large-angle exclusive processes and their calculation in the framework of pQCD [1-3]. In the context of the factorized QCD an expression for an amplitude of an exclusive process can be written as integral over $\mathbf{x}, \mathbf{y}$ of hadron wave functions (w.f.)[1] $\Phi_i(\mathbf{x}, Q^2)$ (an initial hadron), $\Phi_f^*(\mathbf{y}, Q^2)$ (a final hadron) and amplitude $T_H(\mathbf{x}, \mathbf{y}; \alpha_S(\hat{Q}^2), Q^2)$ of the hard-scattering subprocess [2]. This approach can be also applied for calculation of HT corrections to inclusive processes. The HT corrections to a single meson photoproduction was studied in [4], where for computation of integrals over $\mathbf{x}, \mathbf{y}$, the frozen coupling approximation was used. In our work we consider the hard semi-inclusive photoproduction of single pseudoscalar and vector mesons $\gamma h \to MX$ using the running coupling constant method.

The two HT subprocesses, namely $\gamma q_1 \to M q_2$ and $\gamma \overline{q}_2 \to M \overline{q}_1$ contribute to the photoproduction of the single meson M in the reaction $\gamma h \to MX$. The amplitude for the subprocess $\gamma q_1 \to M q_2$ can be found by means of the Brodsky-Lepage method [2],

$$M = \int_0^1 \int_0^1 dx_1 dx_2 \delta(1 - x_1 - x_2) T_H(x_1, x_2; \alpha_S(\hat{Q}^2),\ \hat{s},\ \hat{u},\ \hat{t}) \Phi_M(x_1, x_2; Q^2) \tag{1}$$

[1] Strictly speaking, $\Phi_M(\mathbf{x}, Q^2)$ is a hadron distribution amplitude and it differs from a hadron wave function. But in this paper we use these two terms on the same footing.

In Eq.(1) Φ_M is the meson M w.f. In this work we use the following w.f.; for the pion and ρ-meson

$$\Phi_M(x,\mu_0^2)=\Phi_{asy}^M(x)\left[a+b(2x-1)^2\right]. \tag{2}$$

where, $a=0, b=5$ (pion), $a=0.7, b=1.5$ (longitudinally and transversely polarized ρ-meson) and for the kaon

$$\begin{aligned}\Phi_K(x,\mu_0^2) &= \Phi_{asy}^K(x)\left[a+b(2x-1)^2+c(2x-1)^3\right], \\ a &= 0.4, \quad b=3, \quad c=1.25.\end{aligned} \tag{3}$$

with $\Phi_{asy}^M(x)=\sqrt{3}f_M x(1-x)$ being the meson M asymptotic w.f. The mesons' decay constants f_M take values $f_\pi=0.093$ GeV, $f_K=0.112$ GeV, $f_\rho^L=0.2$ GeV, $f_\rho^T=0.16$ GeV.

The details of calculation of the HT subprocess cross section are described in our work [5], where expressions for $d\hat{\sigma}^{HT}/d\hat{t}$ can be found. The subprocess cross section depends on quantities $I_{1,2}$, $K_{1,2}$,

$$I_1(K_1)=\int_0^1\int_0^1\frac{dx_1dx_2\delta(1-x_1-x_2)\alpha_S(\hat{Q}_1^2(\hat{Q}_2^2))\Phi_M(x_1,x_2)}{x_2(x_1)}, \tag{4}$$

$$I_2(K_2)=\int_0^1\int_0^1\frac{dx_1dx_2\delta(1-x_1-x_2)\alpha_S(\hat{Q}_1^2(\hat{Q}_2^2))\Phi_M(x_1,x_2)}{x_1x_2}, \tag{5}$$

where for I_1, I_2 the renormalization and factorization scale is $\hat{Q}_1^2=x_2\hat{s}$, for K_1, K_2 it is given by $\hat{Q}_2^2=-x_1\hat{u}$.

In the frozen coupling approximation one puts $\hat{Q}_{1,2}^2$ equal to their mean values $\hat{s}/2, -\hat{u}/2$ and removes $\alpha_S(\hat{Q}_{1,2}^2)$ as the constant factor in Eqs(4-5). After such manipulation integrals (4-5) are trivial and can be easily computed. In this approach the single meson photoproduction cross section can be normalized in terms of the meson elm form factor only if the meson w.f. is symmetric under replacement $2x-1 \leftrightarrows 1-2x$ (pion, ρ-meson).

In the framework of the running coupling method, for example, I_1 takes the form

$$I_1(\hat{s})=\int_0^1\frac{\alpha_S((1-x)\hat{s})\Phi_M(x,\mu_0^2)dx}{1-x}. \tag{6}$$

The $\alpha_S((1-x)\hat{s})$ has the infrared singularity at $x\to 1$ and as a result integral (6) diverges. This divergence is induced by ir renormalons. Indeed, the Borel transform $B[I_1](u)$ of $I_1(\hat{s})$ has ir renormalon poles at $u=1,2,3,4$ (for w.f. (2)) [5]. The integral (6) can be regularized by means of the principal value prescription. The Borel sum (resummed expression) of I_1 is

$$\begin{aligned}\left[I_1\left(\hat{s}\right)\right]^{res} &= \frac{4\sqrt{3}\pi f_M}{\beta_0}\left[(a+b)\frac{Li(\lambda)}{\lambda}-(a+5b)\frac{Li(\lambda^2)}{\lambda^2}\right. \\ &\left. +8b\frac{Li(\lambda^3)}{\lambda^3}-4b\frac{Li(\lambda^4)}{\lambda^4}\right],\end{aligned} \tag{7}$$

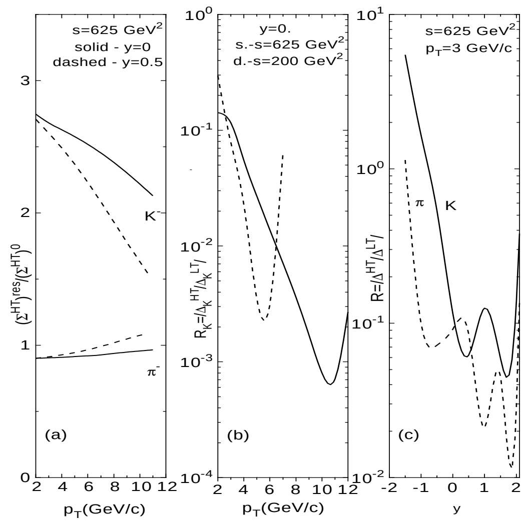

Figure 1. a) Ratio $r_M = (\Sigma_M^{HT})^{res}/(\Sigma_M^{HT})^0$, where $\Sigma^{res,(0)}$ are HT contributions to the photoproduction cross section calculated using the running and frozen coupling approximations, respectively;b) R_M for the kaon, as a function of p_T; c) R for $\pi,\ K$ as a function of y

where $Li(\lambda)$ is the logarithmic integral, for $\lambda > 1$ defined in its principal value

$$Li(\lambda) = P.V. \int_0^{\lambda} \frac{dx}{\ln x}, \qquad \lambda = \hat{s}/\Lambda^2. \tag{8}$$

The similar expressions can be found for I_2 and $K_{1,2}$.

Important question here is the normalization of the meson photoproduction cross section in terms of the meson elm form factor. The pion and kaon form factors have been calculated by means of the running coupling method in our papers [6-7]. Using the expressions obtained in this works and our recent results, it is not difficult to conclude that, in the running coupling approach the HT subprocess cross section cannot be normalized in terms of the meson form factor neither for mesons with symmetric w.f. nor for non-symmetric ones.

Some of our numerical results for the photon-proton process are plotted in Fig.1. Here, for calculation of ratios $r_M,\ R_M$ the $\Sigma_{M^{+(-)}} = d\sigma(\gamma p \to M^{+(-)} X)$ inclusive cross sections and the difference $\Delta_M = \Sigma_{M^+} - \Sigma_{M^-}$ are used. In $\Sigma_{M^{+(-)}},\ \Delta_M$ the dominant leading twist LT ($\gamma q \to gq$ with $q \to M$) and HT ($\gamma q \to Mq$) contributions to the photoproduction have been taken into account.

As seen from Fig.1(a), effect of ir renormalons is considerable for K^-, whereas for π^- we have $r_M \simeq 1$. In Fig.1(b) the ratio $R_M = \mid \Delta_K^{HT}/\Delta_K^{LT} \mid$ is shown. For all particles the LT cross section difference is positive $\Delta_M^{LT} > 0$, since $\Sigma_{M^+}^{LT} \sim u_p(x, -\hat{t})e_u^2$, while $\Sigma_{M^-}^{LT} \sim d_p(x, -\hat{t})e_d^2$. The smaller quark charge e_d and the smaller distribution function d_p both suppress $\Sigma_{M^-}^{LT}$. The HT cross section difference may change sign at small p_T and become negative $\Delta_M^{HT} < 0$. Therefore, we plot the absolute value of R_M. The similar picture has been also found for other mesons. The rapidity dependence of R_M at $\sqrt{s} = 25$ GeV, $p_T = 3$ GeV/c plotted in Fig.1(c) illustrates not only the tendency of the HT contributions to be enhanced in the region of negative rapidity, but also reveals an interesting feature of the HT terms; as is seen from Fig.1(c) the ratio R_M is an oscillating function of the rapidity. This property of the HT terms has important phenomenological consequences in the case of ρ-meson photoproduction; comprehensive analysis of these effects can be found in ref.[5].

Summing up we can state that:
i) for mesons with non-symmetric w.f. in the framework of the frozen coupling approximation the higher twist subprocess cross section cannot be normalized in terms of a meson electromagnetic form factor;
ii) in the context of the running coupling constant method the HT subprocess cross section cannot be normalized in terms of meson's elm form factor neither for mesons with symmetric w.f. nor for non-symmetric ones;
iii) the resummed HT cross section differs from that found using the frozen coupling approximation, in some cases, considerably;
iv) HT contributions to the single meson photoproduction cross section have important phenomenological consequences, specially in the case of ρ-meson photoproduction. In this process the HT contributions wash the LT results off, qualitatively changing the LT predictions.

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