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Light-Cone Distribution Amplitudes for Non-Relativistic Bound States

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Abstract. We calculate light-cone distribution amplitudes for non-relativistic bound states, including radiative corrections from relativistic gluon exchange to first order in the strong coupling constant. Our results apply to hard exclusive reactions with non-relativistic bound states in the QCD factorization approach like, for instance, $B_c \to \eta_c \ell \nu$ or $e^+e^- \to J/\psi \eta_c$. They also serve as a toy model for light-cone distribution amplitudes of light mesons or heavy B and D mesons.

Keywords: QCD, Non-relativistic approximation, Light-cone distribution amplitudes
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INTRODUCTION

Exclusive hadron reactions with large momentum transfer involve strong interaction dynamics at very different momentum scales. In cases where the hard-scattering process is dominated by light-like distances, the long-distance hadronic information is given in terms of so-called light-cone distribution amplitudes (LCDAs) which are defined from hadron-to-vacuum matrix elements of non-local operators with quark and gluon field operators separated along the light-cone. Representing universal hadronic properties, LCDAs can either be extracted from experimental data, or they have to be constrained by non-perturbative methods. The most extensively studied and probably best understood case is the leading-twist pion LCDA, for which experimental constraints from the $\pi-\gamma$ transition form factor [1], as well as estimates for the lowest moments from QCD sum rules [2, 3, 4] and lattice QCD [5] exist. On the other hand, our knowledge on LCDAs for heavy B mesons [6, 7, 8], and even more so for heavy quarkonia [9, 10], had been relatively poor until recently.

The situation becomes somewhat simpler, if the hadron under consideration can be approximated as a non-relativistic bound state of two sufficiently heavy quarks. In this case we expect exclusive matrix elements – like transition form factors [11] and, in particular, the LCDAs – to be calculable perturbatively, since the quark masses provide an intrinsic physical infrared regulator. In these proceedings we report about results from [12], where we have calculated the LCDAs for non-relativistic meson bound states including relativistic QCD corrections to first order in the strong coupling constant at the non-relativistic matching scale which is set by the mass of the lighter quark in the hadron.

LIGHT-CONE DISTRIBUTION AMPLITUDES

The wave function for a non-relativistic (NR) bound state of a quark and an antiquark can be obtained from the solution of the Schrödinger equation with the QCD Coulomb potential. To first approximation it describes a quark with momentum $m_1 v_\mu$ and an antiquark with momentum $m_2 v_\mu$, where v_μ is the four-velocity of the meson. The spinor degrees of freedom for a non-relativistic pseudoscalar bound state are represented by the Dirac projector $\frac{1}{2}(1+\not{v})\gamma_5$. The non-relativistic approximation can also serve as a toy model for bound states of light (relativistic) quarks. We will in the following refer to "heavy mesons" as "B" (where we mean the realistic example of a B_c meson, or the toy model for a B_q meson, with $m_1 \gg m_2$) and "light mesons" as "π" (where the realistic example is η_c, and the toy-model application would be the pion, with $m_1 \approx m_2$).

Definition of LCDAs for light pseudoscalar mesons

Following [13, 2] we define the 2-particle LCDAs of a light pseudoscalar meson via

$$
\begin{aligned}
\langle \pi(P)|\bar{q}_1(y)\,\gamma_\mu\gamma_5\,q_2(x)|0\rangle &= -i f_\pi \int_0^1 du\, e^{i(u\,p\cdot y+\bar{u}\,p\cdot x)} \left[p_\mu\,\phi_\pi(u) + \frac{m_\pi^2}{2\,p\cdot z} z_\mu\, g_\pi(u)\right], \\
\langle \pi(P)|\bar{q}_1(y)\,i\gamma_5\,q_2(x)|0\rangle &= f_\pi\,\mu_\pi \int_0^1 du\, e^{i(u\,p\cdot y+\bar{u}\,p\cdot x)}\,\phi_p(u), \\
\langle \pi(P)|\bar{q}_1(y)\,\sigma_{\mu\nu}\gamma_5\,q_2(x)|0\rangle &= i f_\pi\,\tilde{\mu}_\pi (p_\mu z_\nu - p_\nu z_\mu) \int_0^1 du\, e^{i(u\,p\cdot y+\bar{u}\,p\cdot x)}\,\frac{\phi_\sigma(u)}{2D-2}
\end{aligned}
\tag{1}
$$

with two light-like vectors $z_\mu = y_\mu - x_\mu$ and $p_\mu = P_\mu - m_\pi^2/(2P\cdot z)\,z_\mu$, with the usual gauge link factor $[y,x]$ (Wilson line) understood implicitly. Here $u = 1-\bar{u}$ denotes the light-cone momentum fraction of the quark in the pion, with $\phi_\pi(u)$ being the twist-2 LCDA, while $\phi_p(u)$ and $\phi_\sigma(u)$ are of twist-3. For completeness, we have also quoted the twist-4 LCDA $g_\pi(u)$ which, like the 3-particle LCDAs, will not be considered further. All LCDAs are normalized to 1, such that the prefactors in (1) are defined in the local limit $x \to y$. In the definition of $\phi_\sigma(u)$, we have included a factor $3/(D-1)$, such that the relation between μ_π and $\tilde{\mu}_\pi$ from the equations of motion (eom),

$$
\tilde{\mu}_\pi = \mu_\pi - (m_1+m_2)\,, \tag{2}
$$

is maintained in $D \neq 4$ dimensions. In the local limit the eom further imply

$$
\mu_\pi = \frac{m_\pi^2}{m_1+m_2}, \qquad \int_0^1 du\, u\,\phi_p(u) = \frac{1}{2} + \frac{m_1-m_2}{2\mu_\pi}. \tag{3}
$$

Notice that (2,3) hold for the *bare* parameters and distribution amplitudes.

At tree level, and in leading order of the expansion in the non-relativistic velocities, the two quarks in the non-relativistic wave function simply share the momentum of the meson according to their masses, $p_i^\mu \simeq m_i/(m_1+m_2)\,P^\mu$. For "light mesons" this implies

$$
\phi_\pi(u) \simeq \phi_p(u) \simeq g_\pi(u) \simeq \delta(u-u_0)\,, \tag{4}
$$

where $u_0 = m_1/(m_1+m_2)$. Consequently, all positive and negative moments of the distribution amplitudes are simply given in terms of the corresponding power of u_0. Notice that $\tilde{\mu}_\pi \simeq 0$ at tree-level, and the corresponding LCDA $\phi_\sigma(u)$ can only be determined by considering the corresponding one-loop expressions (see [12]).

Definition of LCDAs for heavy pseudoscalar mesons

We define the 2-particle LCDAs of a heavy pseudoscalar B meson following [6, 14],

$$\langle 0|\bar{q}^\beta(z)\, h_v^\alpha(0)|B(v)\rangle = -\frac{i\hat{f}_B(\mu)M}{4}\left[\frac{1+\not{v}}{2}\left\{2\tilde{\phi}_B^+(t) + \frac{\tilde{\phi}_B^-(t)-\tilde{\phi}_B^+(t)}{t}\not{z}\right\}\gamma_5\right]^{\alpha\beta} , \quad (5)$$

where v^μ is the heavy meson's velocity, $t \equiv v\cdot z$ and $z^2 = 0$. Here $\hat{f}_B$ is the (renormalization-scale dependent) decay constant in HQET. The Fourier-transformed expressions, which usually appear in factorization formulas, are given through

$$\tilde{\phi}_B^\pm(t) = \int_0^\infty d\omega\, e^{-i\omega t}\,\phi_B^\pm(\omega)\,, \quad (6)$$

where ω denotes the light-cone energy of the light quark in the B meson rest frame.

Including a finite spectator quark mass m and the effect of the 3-particle LCDAs Ψ_A, Ψ_V as defined in [15], the eom become

$$\begin{aligned} &\omega\,\phi_B^-(\omega) - m\,\phi_B^+(\omega) + \frac{D-2}{2}\int_0^\omega d\eta\ \left[\phi_B^+(\eta)-\phi_B^-(\eta)\right] \\ &\quad = (D-2)\int_0^\omega d\eta \int_{\omega-\eta}^\infty \frac{d\xi}{\xi}\,\frac{\partial}{\partial\xi}\,\left[\Psi_A(\eta,\xi)-\Psi_V(\eta,\xi)\right], \end{aligned} \quad (7)$$

which is trivially fulfilled at tree-level, where $\phi_B^+(\omega) \simeq \phi_B^-(\omega) \simeq \delta(\omega-m)$, and $\Psi_{V,A}(\eta,\xi) = \mathscr{O}(\alpha_s)$. We have shown in [12] that this relation also holds after including α_s corrections to the NR limit. (A second relation, which has been presented in [15] and extended here to the case $m \neq 0$, is found to be not valid beyond tree-level.) Moreover, at tree level, the moments of the "heavy meson's" LCDAs can be related to matrix elements of local operators in HQET [6].

RELATIVISTIC CORRECTIONS AT ONE-LOOP

The NR bound states are described by parton configurations with fixed momenta. Relativistic gluon exchange as in Fig. 1 leads to modifications: First, there is a correction from matching QCD (or, in the case of heavy mesons, the corresponding low-energy effective theory HQET) on the NR theory,

$$\phi_M = \phi_M^{(0)} + \frac{\alpha_s C_F}{4\pi}\,\phi_M^{(1)} + \mathscr{O}(\alpha_s^2)\,. \quad (8)$$

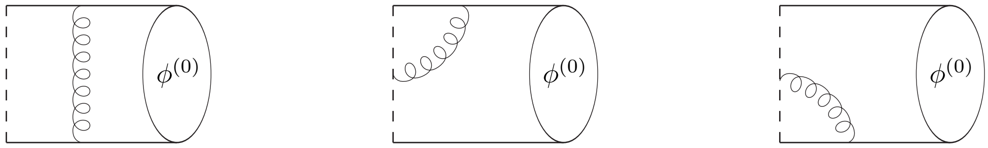

FIGURE 1. *Relativistic corrections to the light-cone distribution amplitudes. The dashed line indicates the Wilson line in the definition of the LCDAs.*

Secondly, there is the usual evolution under the change of the renormalization scale [16, 7]. In particular, the support region for the parton momenta is extended to $0 \leq u \leq 1$ for light mesons and $0 \leq \omega < \infty$ for heavy mesons, respectively.

Light mesons

We first consider the leading-order relativistic corrections to the local matrix elements. We will focus on the case of equal quark masses (results for $m_1 \neq m_2$ can be found in [12]). Our result for the decay constant,

$$f_\pi = f_\pi^{\rm NR} \left[1 - 6 \, \frac{\alpha_s C_F}{4\pi} + \mathscr{O}(\alpha_s^2) \right], \tag{9}$$

is in agreement with [17], and the result for μ_π and $\tilde{\mu}_\pi$ is consistent with the eom-constraint in (2,3), using $m_\pi \simeq m_1^{\rm os} + m_2^{\rm os}$ in the on-shell scheme.

The remaining contributions to the NLO correction to the leading-twist LCDA contain an UV-divergent piece,

$$\phi_\pi^{(1)}(u)\big|_{\rm div.} = \frac{2}{\varepsilon} \int_0^1 dv \, V(u,v) \, \phi^{(0)}(v) \,, \tag{10}$$

which involves the well-known Efremov-Radyushkin-Brodsky-Lepage (ERBL) evolution kernel [16], and a finite term,

$$\begin{aligned} \phi_\pi^{(1)}(u;\mu) = 4 \left\{ \left(\ln \frac{\mu^2}{m_\pi^2 \, (1/2-u)^2} - 1 \right) \left[\left(1 + \frac{1}{1/2-u} \right) u \, \theta(1/2-u) + (u \leftrightarrow \bar{u}) \right] \right\}_+ & \\ + 4 \left\{ \frac{u(1-u)}{(1/2-u)^2} \right\}_{++} . & \end{aligned} \tag{11}$$

Here the plus-distributions are defined as

$$\begin{aligned} \int_0^1 du \, \{\ldots\}_+ \, f(u) &\equiv \int_0^1 du \, \{\ldots\} \, \Big(f(u) - f(1/2) \Big) \,, \\ \int_0^1 du \, \{\ldots\}_{++} \, f(u) &\equiv \int_0^1 du \, \{\ldots\} \, \Big(f(u) - f(1/2) - f'(1/2)\,(u-1/2) \Big) \,. \end{aligned} \tag{12}$$

TABLE 1. Convergence of $\langle \xi^n \rangle_\pi$ moments ($\eta = \alpha_s(\mu)/\alpha_s(m)$).

n	2	4	6	8	10
NLO ($\mu = m$, in units of α_s)	0.333	0.053	0.019	0.009	0.005
LL ($\eta = 1/5$)	0.126	0.048	0.025	0.015	0.010
LL ($\eta = 1/25$)	0.173	0.070	0.038	0.024	0.016
asymptotic	0.200	0.086	0.048	0.030	0.021

An independent calculation of the leading-twist LCDAs for the η_c and J/ψ meson has been presented in [9]. Our result is not in complete agreement with their findings. In particular, we find that the LCDA quoted in [9] is not normalized to unity as it should be.

At the non-relativistic scale, $\mu \simeq m$, the usual expansion of $\phi_\pi(u)$ into Gegenbauer polynomials (the eigenfunctions of the leading-order ERBL evolution equations), does not converge very well, i.e. the Gegenbauer coefficients a_n drop off slower than $1/n$. A better characterization of the LCDAs at NLO is given in terms of the moments

$$\langle \xi^n \rangle_\pi \equiv \int_0^1 du\,(2u-1)^n\,\phi_\pi(u)\,, \tag{13}$$

which are linear combinations of Gegenbauer coefficients of order $\leq n$. This corresponds to an expansion in terms of δ-function and its derivatives,

$$\phi_\pi(u) = 2\sum_n \langle \xi^n \rangle_\pi \frac{(-1)^n}{n!}\,\delta^{(n)}(2u-1)\,. \tag{14}$$

Results for the first few moments $\langle \xi^n \rangle_\pi$ are shown in Table 1. (Notice that the moments $\langle \xi^n \rangle_\pi$ also receive corrections from sub-leading terms in the non-relativistic expansion, see [10].)

Table 1 also contains the moments generated by ERBL evolution of the LO result (4) for two values of $\eta = \alpha_s(\mu)/\alpha_s(m)$ and in the asymptotic limit. To illustrate the change of the shape of $\phi_\pi(u)$ under evolution, we employ a parametrization which is obtained from a slight modification of the strategy developed in [18],

$$\phi_\pi(u) \equiv \frac{3u\bar{u}}{\Gamma[a,-\ln t_c]}\int_0^{t_c} dt\,(-\ln t)^{a-1}\left(f(2u-1,it^{1/b}) + f(2u-1,-it^{1/b})\right)\,. \tag{15}$$

It involves three real parameters $a > 0$, $b > 0$, $t_c \leq 1$, which can be fitted to the first three moments $\langle \xi^{2,4,6} \rangle$, and the generating function for the Gegenbauer polynomials,

$$f(\xi,\theta) = \frac{1}{(1-2\xi\theta+\theta^2)^{3/2}} = \sum_{n=0}^{\infty} C_n^{3/2}(\xi)\,\theta^n\,. \tag{16}$$

Fig. 2(a) shows the evolution of the model LCDA as a function of u. For $\eta = 1/5$ the functional form still "remembers" the non-relativistic profile, while for $\eta = 1/25$ the LCDA gets close to the asymptotic form.

The twist-3 LCDAs for the 2-particle Fock states are obtained in the same way as the twist-2 one. Details can be found in [12]. In particular, all our results are in manifest agreement with the eom-constraint from (3).

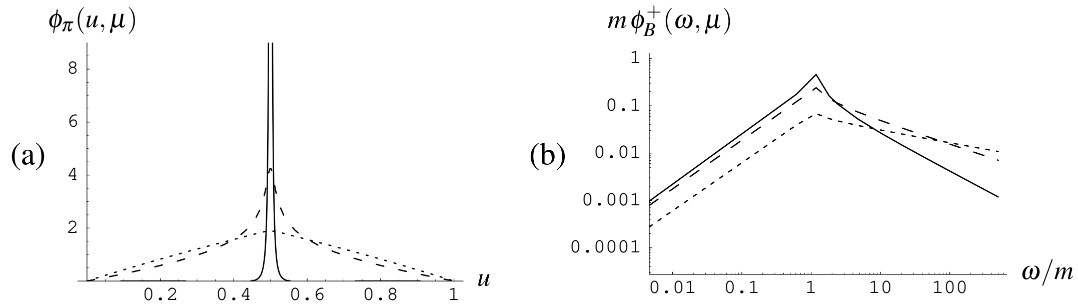

FIGURE 2. (a) Solid line: approximation for $\phi_\pi(u) = \delta(u-1/2)$ in terms of the parametrization (15), and its evolution for $\eta = 1/5$ (dashed line) and $\eta = 1/25$ (dotted line). (b) Evolution of the heavy-meson LCDA $\phi_B^+(\omega) = \delta(\omega - m)$. The three curves (solid, long-dashed, short-dashed) correspond to $\eta = 1/2, 1/5, 1/10$.

Heavy mesons

The calculation of the LCDA for a heavy meson goes along the same lines as for the light-meson case. However, important differences arise because the heavier quark is to be treated in HQET which modifies the divergence structure of the loop integrals. As a consequence, the evolution equations for the LCDA of heavy mesons [7] differ from those of light mesons.

Let us focus on the distribution amplitude $\phi_B^+(\omega)$ which enters the QCD factorization formulas for exclusive heavy-to-light decays. In the local limit we derive the corrections from soft gluon exchange to the decay constant in HQET,

$$\hat{f}_M(\mu) = f_M^{\rm NR}\left[1 + \frac{\alpha_s C_F}{4\pi}\left(3\ln\frac{\mu}{m} - 4\right) + \mathcal{O}(\alpha_s^2)\right]. \qquad (17)$$

Notice that the decay constant of a heavy meson exhibits the well-known scale dependence [19]. The remaining NLO corrections to the distribution amplitude $\phi_B^+(\omega)$ contain an UV-divergent piece, which involves the Lange-Neubert evolution kernel $\gamma_+(\omega,\omega',\mu)$ [7]. As has been shown by Lee and Neubert [20], the solution of the evolution equation can be written in closed form. The resulting evolution of $\phi_B^+(\omega,\mu)$ is illustrated in Fig. 2(b), starting from $\delta(\omega - m)$ at the non-relativistic scale, for three different values of $\eta = \alpha_s(\mu)/\alpha_s(m)$ and taking $\alpha_s(m) = 1$. From the double-logarithmic plot we can read off the asymptotic behaviour of the LCDA for $\omega \to 0$ and $\omega \to \infty$. As argued on general grounds [7], $\phi_B^+(\omega)$ develops a linear behaviour for $\omega \to 0$, whereas for $\omega \to \infty$ the evolution generates a radiative tail which tends to fall off slower than $1/\omega$ at higher scales.

The finite NLO correction to $\phi_B^+(\omega)$ reads

$$\frac{\phi_B^{(+,1)}(\omega;\mu)}{\omega} = 2\left[\left(\ln\left[\frac{\mu^2}{(\omega-m)^2}\right]-1\right)\left(\frac{\theta(m-\omega)}{m(m-\omega)}+\frac{\theta(\omega-m)}{\omega(\omega-m)}\right)\right]_+ \\ +4\left[\frac{\theta(2m-\omega)}{(\omega-m)^2}\right]_{++}+\frac{4\,\theta(\omega-2m)}{(\omega-m)^2}-\frac{\delta(\omega-m)}{m}\left(\frac{1}{2}\ln^2\frac{\mu^2}{m^2}-\ln\frac{\mu^2}{m^2}+\frac{3\pi^2}{4}+2\right) \tag{18}$$

with an analogous definition of plus-distributions as in (12). In contrast to the light-meson case, the normalization of the heavy meson distribution amplitude is ill-defined. Imposing a hard cutoff $\Lambda_{\rm UV} \gg m$ and expanding to first order in $m/\Lambda_{\rm UV}$, we derive

$$\int_0^{\Lambda_{\rm UV}} d\omega\, \phi_B^+(\omega;\mu) \simeq 1-\frac{\alpha_s C_F}{4\pi}\left[\frac{1}{2}\ln^2\frac{\mu^2}{\Lambda_{\rm UV}^2}+\ln\frac{\mu^2}{\Lambda_{\rm UV}^2}+\frac{\pi^2}{12}\right]+\ldots \tag{19}$$

$$\int_0^{\Lambda_{\rm UV}} d\omega\, \omega\, \phi_B^+(\omega;\mu) \simeq \frac{\alpha_s C_F}{4\pi}\left[2\ln\frac{\mu^2}{\Lambda_{\rm UV}^2}+6\right]\Lambda_{\rm UV}+\ldots \tag{20}$$

The last two expressions provide model-independent properties of the distribution amplitude which agree with the general results in [20]. The two phenomenologically relevant moments in the factorization approach to heavy-to-light decays read

$$\lambda_B^{-1}(\mu) \equiv \int_0^\infty d\omega\; \frac{\phi_B^+(\omega;\mu)}{\omega} = \frac{1}{m}\left(1-\frac{\alpha_s C_F}{4\pi}\left[\frac{1}{2}\ln^2\frac{\mu^2}{m^2}-\ln\frac{\mu^2}{m^2}+\frac{3\pi^2}{4}-2\right]\right),$$

$$\sigma_B(\mu) \equiv \lambda_B(\mu)\int_0^\infty d\omega\,\frac{\phi_B^+(\omega;\mu)}{\omega}\,\ln\frac{\mu}{\omega} = \ln\frac{\mu}{m}+\frac{\alpha_s C_F}{4\pi}\,[8\zeta(3)]\,. \tag{21}$$

A similar analysis can be performed for the LCDA $\phi_B^-(\omega)$, for details we refer to [12]. In particular, we can read off the anomalous dimension,

$$\gamma_-^{(1)}(\omega,\omega';\mu) = \left(4\ln\frac{\mu}{\omega}-2\right)\delta(\omega-\omega')-4\,\frac{\theta(\omega'-\omega)}{\omega'} \\ -4\,\omega\left[\frac{\theta(\omega'-\omega)}{\omega'(\omega'-\omega)}\right]_+-4\,\omega\left[\frac{\theta(\omega-\omega')}{\omega(\omega-\omega')}\right]_+, \tag{22}$$

which describes the evolution of $\phi_B^-(\omega,\mu)$ in the Wandzura-Wilczek approximation, where 3-particle LCDAs (and the light quark mass m) are neglected. Among others, γ_- is needed to show the factorization of correlation functions in SCET sum rules for heavy-to-light form factors [21]. Another new result are the first positive moments of $\phi_B^-(\omega)$ as a function of the UV cutoff,

$$\int_0^{\Lambda_{\rm UV}} d\omega\, \phi_B^-(\omega;\mu) \simeq 1-\frac{\alpha_s C_F}{4\pi}\left[\frac{1}{2}\ln^2\frac{\mu^2}{\Lambda_{\rm UV}^2}-\ln\frac{\mu^2}{\Lambda_{\rm UV}^2}+\frac{\pi^2}{12}\right]+\ldots \tag{23}$$

$$\int_0^{\Lambda_{\rm UV}} d\omega\, \omega\, \phi_B^-(\omega;\mu) \simeq \frac{\alpha_s C_F}{4\pi}\left[2\ln\frac{\mu^2}{\Lambda_{\rm UV}^2}+2\right]\Lambda_{\rm UV}+\ldots \tag{24}$$

where the divergent pieces again are expected to be model-independent.

SUMMARY

Non-relativistic $q\bar{q}$ bound states have been used as a starting point to construct light-cone distribution amplitudes in QCD and in HQET. We considered relativistic gluon corrections at NLO in the strong coupling at the non-relativistic scale, as well as the leading logarithmic evolution towards higher scales needed in QCD factorization theorems. We also studied certain model-independent properties of light and heavy LCDAs, including new results for the LCDA $\phi_-^B(\omega,\mu)$ in HQET.

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