

Ho-Meoyng Choi · Chueng-Ryong Ji

Light-front zero-mode issue on the vector meson decay constant

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Abstract We discuss the light-front zero-mode issue in the light-front quark model (LFQM) prediction of a vector meson decay constant from the perspective of the vacuum fluctuation consistent with the chiral symmetry of QCD. We extend the exactly solvable manifestly covariant Bethe-Salpeter model calculation to the more phenomenologically accessible realistic LFQM and present a self-consistent covariant description of the vector meson decay constant analyzing the twist-2 and twist-3 quark-antiquark distribution amplitudes with even chirality.

Keywords Decay constant · Light-front zero-mode · Light-front quark model · Chiral symmetry · Distribution amplitudes

1 Introduction

Decay constants of mesons provide essential information about the QCD interaction between quark and antiquark. They are the lowest moments of the light-cone distribution amplitudes (DAs) for the quark and antiquark inside the meson. Among various theoretical approaches to predict these fundamental constants of mesons, the light-front quark model (LFQM) based on the framework of light-front dynamics (LFD) [1] has become a very useful phenomenological tool to study various electroweak properties of mesons. Owing to the rational energy-momentum dispersion relation, LFD has distinct features compared to other forms of Hamiltonian dynamics. In particular, the feature that the vacuum fluctuations are suppressed in LFD can be regarded as advantageous in hadron phenomenology. However, one should also realize that the success of LFD in hadron physics cannot be realized unless the treacherous points in LFD such as the zero-mode contributions in the hadron form factors and the singularities associated with the rational energy-momentum relation are well taken care of with proper methods. For instance, the zero-mode complication in the matrix element has been noticed for the electroweak form factors involving a spin-0 and spin-1 particles as well as the vector meson decay constant [2; 3; 4].

Unlike the electroweak form factor described by a three-point function involving an external probe, the meson decay amplitude is described by a two-point function and may be regarded as one of the simplest possible physical observables. It is interesting that this apparently simple amplitude bears

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H.-M. Choi
Department of Physics, Teachers College, Kyungpook National University, Daegu 702-701, Kore
E-mail: homyoung@knu.ac.kr

C.-R. Ji
Department of Physics, North Carolina State University, Raleigh, NC 27695-8202, U.S.A.
E-mail: crji@ncsu.edu

abundant fundamental information on the QCD vacuum dynamics and chiral symmetry. To discuss the nature of the LF zero-mode in the meson decay amplitude, we may denote the total LF longitudinal momentum of the meson, $P^+ = k_Q^+ + k_{\bar{Q}}^+$, where k_Q^+ and $k_{\bar{Q}}^+$ are the individual quark and antiquark LF longitudinal momenta, respectively. Similarly, the LF energy P^- is shared by k_Q^- and $k_{\bar{Q}}^-$, i.e. $P^- = k_Q^- + k_{\bar{Q}}^-$. The LF energy integration is done typically by using the Cauchy's theorem for a contour integration. For the LF energy integration of the two-point function to compute the meson decay amplitude, one may pick up a LF energy pole, e.g. either $[k_Q^-]_{\text{on}}$ (i.e. on shell value of k_Q^-) from the quark propagator or $[k_{\bar{Q}}^-]_{\text{on}}$ from the antiquark propagator. However, it is crucial to note that the poles move to infinity (or fly away in the complex plane) as the LF longitudinal momentum, either k_Q^+ or $k_{\bar{Q}}^+$, goes to zero. Unless the contribution from the pole flown into infinity vanishes, it must be kept in computing the physical observable. If such contribution exists, since one of the constituents of the meson carries the entire momentum P^+ of the meson, the other constituent carries the zero LF longitudinal momentum and thus can be regarded as the zero-mode quantum fluctuation linked to the vacuum. It is important to capture the vacuum effect for the consistency with the chiral symmetry properties of the strong interactions. With this link, the zero-mode contribution in the meson decay process can be considered effectively as the effect of vacuum fluctuation consistent with the chiral symmetry of the strong interactions. In this respect, the zero-mode issue of the vector meson decay constant in LFD is highly non-trivial and deserves careful analyses. It is a common practice to utilize an exactly solvable manifestly covariant model to check the existence (or absence) of the zero-mode and substitute the radial and spin-orbit wave functions of the exactly solvable model with the more phenomenologically accessible model wave functions that can be provided by LFQM. Indeed, we found [5] that the existence or absence of the zero mode may depend on the model, especially on the form of vector meson vertex operator, while Jaus [2] claimed that there exists zero-mode contribution even for the case of the plus component of the weak current J_W^μ .

The purpose of this work is not only to clarify this zero-mode issue in the prediction of the decay constant from LFQM but also to discuss this topic in relation to the vacuum fluctuation consistent with the chiral symmetry of QCD. To further clarify the zero-mode issue, we analyze the two-particle DAs and examine a fundamental constraint anticipated from the LFQM [6; 7; 8; 9]: i.e. symmetric quark-antiquark DAs for the equal quark and antiquark bound state mesons such as ρ . As we shall show in this work, the vector meson decay constant including the nonvanishing zero mode claimed by Jaus [2] and subsequently advocated by other authors [10] does not satisfy this anticipated constraint. We also note that the two equivalent decay constants obtained from the plus component of the currents with the longitudinal polarization $(J_W^\mu, \epsilon_h) = (J_W^+, \epsilon_L)$ and the perpendicular components of the currents with the transverse polarization (J_W^μ, ϵ_T) are related to the twist-2 and twist-3 two-particle DAs of a vector meson according to the classification of Ball and Braun [11; 12], respectively. With this aim, we extend our previous analysis [5] to encompass the more phenomenologically accessible realistic LFQM [6; 7; 8; 9] and discuss a self-consistent covariant description of the vector meson decay constant in view of the link between QCD and LFQM. More detailed analysis can be found in [13].

2 Manifestly covariant model versus standard LFQM

The decay constant f of a vector meson with the four-momentum P and the mass M as a $q\bar{q}$ bound state is defined by the matrix element of the vector current

$$\langle 0 | \bar{q} \gamma^\mu q | V(P, h) \rangle = f M \epsilon_h^\mu, \quad (1)$$

where ϵ_h is the polarization vector of a vector meson.

In the manifestly covariant Bethe-Salpeter model, the matrix element $\mathcal{J}_h^\mu \equiv \langle 0 | \bar{q} \gamma^\mu q | V(P, h) \rangle$ is given in the one-loop approximation as a momentum integral

$$\mathcal{J}_h^\mu = N_c \int \frac{d^4 k}{(2\pi)^4} \frac{\text{Tr} [\gamma^\mu (\not{p} + m_1) \Gamma \cdot \epsilon_h (-\not{k} + m_2)]}{(p^2 - m_1^2 + i\varepsilon)(k^2 - m_2^2 + i\varepsilon)} H_V, \quad (2)$$

where N_c denotes the number of colors and $p = P - k$. In order to regularize the covariant loop in $(3+1)$ dimensions, we use $H_V = g/N_A^2$ for the $q\bar{q}$ bound-state vertex function, where $N_A = p^2 - \Lambda^2 + i\varepsilon$,

and g and Λ are constant parameters. Although we use this particular dipole form of the hadronic vertex for our explicit analysis of covariant amplitude, the essential features of our discussion linking the zero-mode quantum fluctuation to the vacuum consistent with the chiral symmetry of QCD in corresponding LFD are independent of the specific form taken for the regularization of the amplitude. The manifestly covariant result f^{cov} is given by [5; 13]. The meson vertex operator Γ^μ in the trace term is given by $\Gamma^\mu = \gamma^\mu - (p - k)^\mu/D$. While the Dirac coupling γ^μ is intrinsic to the vector meson vertex, the model-dependence of a vector meson is implemented through the factor D . For the explicit comparison between the manifestly covariant calculation and the LF calculation, we analyze Γ^μ with a constant D factor, i.e. $D = D_{\text{con}} = M + m_1 + m_2$.

Performing the LF energy k^- integration of Eq. (2), we get the LF Bethe-Salpeter (LFBS) model of \mathcal{J}_h^μ as

$$[\mathcal{J}_h^\mu]_{\text{LFBS}} = \frac{N_c}{16\pi^3} \int_0^1 \frac{dx}{(1-x)} \int d^2\mathbf{k}_\perp \chi(x, \mathbf{k}_\perp) \text{Tr} [\gamma^\mu (\not{p} + m_1) \Gamma \cdot \epsilon_h (-\not{k}_{\text{on}} + m_2)], \quad (3)$$

where $\chi(x, \mathbf{k}_\perp) = g/[x^3(M^2 - M_0^2)(M^2 - M_\Lambda^2)]$ and $M_{0(\Lambda)}^2 = [\mathbf{k}_\perp^2 + m_1^2(\Lambda^2)]/x + (\mathbf{k}_\perp^2 + m_2^2)/(1-x)$. This result is obtained by closing the contour in the lower half of the complex k^- plane and picking up the residue at $k^- = k_{\text{on}}^-$ in the region $0 < k^+ < P^+$ (or $0 < x < 1$). To obtain the decay constant, we use two different combinations of the currents and the polarization vectors, i.e. (1) plus component of the currents with the longitudinal polarization (\mathcal{J}_L^+) and (2) perpendicular components of the currents with the transverse polarization (\mathcal{J}_T^\perp).

For the purpose of analyzing zero-mode contribution to the decay constant, we denote the decay constant as f_h^{val} (meaning the valence contribution to the decay constant) when the matrix element \mathcal{J}_h^μ is obtained for $k^- = k_{\text{on}}^-$ in the region of $0 < x < 1$. If f_h^{val} is different from the manifestly covariant result f^{cov} , this difference $f^{\text{cov}} - f_h^{\text{val}}$ corresponds to the zero-mode contribution $f_h^{\text{z.m.}}$ to the full solution $f_h^{\text{full}} = f_h^{\text{val}} + f_h^{\text{z.m.}}$. The necessary prescription to identify zero-mode operator corresponding to p^- and the effective inclusion of the zero-mode operator in the valence region is explicitly given in [5; 13]. Both decay constants f_L and f_T obtained from \mathcal{J}_L^+ and \mathcal{J}_T^\perp receive the zero-mode contributions due to the singular p^- (or equivalently $1/x$) term in the trace in the limit of $x \rightarrow 0$ when $p^- = p_{\text{on}}^-$. However, the source of the zero modes is different, i.e. while f_L receives the zero mode from the model-dependent part including the D_{con} term, f_T receives the zero mode from the model independent Dirac coupling part, $\Gamma^\mu = \gamma^\mu$. The explicit forms of $f_{L(T)}^{\text{full}}$ can be found in [5; 13]. We have checked that f_T^{full} is the same as f_L^{full} as well as the manifestly covariant result f^{cov} . We also confirmed that our f_T^{full} is exactly the same as the one obtained by Jaus [2] (see Eq. (4.22) of Ref. [2]).

On the other hand, in the standard LFQM presented in [6; 7; 8; 9], the constituent quark and antiquark in a bound state are required to be on-mass-shell, which is different from the covariant BS formalism in which the constituents are off-mass-shell. In the standard LF (SLF) approach used in the LFQM [6; 7; 8; 9], the vector meson decay constant f^{SLF} is obtained by the matrix element of the plus component of the currents and the longitudinal polarization vector in 3-dimensional LF momentum space. Effectively, the matrix element \mathcal{J}_h^μ in SLF is given by

$$[\mathcal{J}_h^\mu]_{\text{SLF}} = \sqrt{N_c} \sum_{\lambda_1 \lambda_2} \int \frac{dx d^2\mathbf{k}_\perp}{16\pi^3} \phi(x, \mathbf{k}_\perp) \mathcal{R}_{\lambda_1 \lambda_2}^{SS_z}(x, \mathbf{k}_\perp) \frac{\bar{v}_{\lambda_2}(p_2)}{\sqrt{p_2^+}} \gamma^\mu \frac{u_{\lambda_1}(p_1)}{\sqrt{p_1^+}}, \quad (4)$$

where ϕ is the radial wave function and $\mathcal{R}_{\lambda_1 \lambda_2}^{SS_z} = \bar{u}_{\lambda_1}(p_1) \Gamma v_{\lambda_2}(p_2) / [2(M_0^2 - (m_1 - m_2)^2)]^{1/2}$ is the spin-orbit wave function that is obtained by the interaction-independent Melosh transformation from the ordinary spin-orbit wave function assigned by the quantum numbers J^{PC} . The common feature of the standard LFQM is to use the sum (i.e. invariant mass M_0) of the light-front energy of the constituent quark and antiquark for the meson mass in $\mathcal{R}_{\lambda_1 \lambda_2}^{SS_z}$. The virtue of using M_0 is to satisfy the normalization of $\mathcal{R}_{\lambda_1 \lambda_2}^{SS_z}$ automatically regardless of any kinds of vector mesons, i.e. $\sum_{\lambda_1 \lambda_2} \mathcal{R}_{\lambda_1 \lambda_2}^{SS_z \dagger} \mathcal{R}_{\lambda_1 \lambda_2}^{SS_z} = 1$. The explicit helicity components of $\mathcal{R}_{\lambda_1 \lambda_2}^{SS_z}$ for a vector meson are given in [13]. For the radial wave function ϕ , we use the gaussian wave function $\phi(x, \mathbf{k}_\perp) = (4\pi^{3/4}/\beta^{3/2}) \sqrt{\partial k_z / \partial x} \exp(-\mathbf{k}^2/2\beta^2)$, where β is the variational parameter fixed by the analysis of meson mass spectra [9] and $\partial k_z / \partial x$ is the Jacobian of the variable transformation $\{x, \mathbf{k}_\perp\} \rightarrow \mathbf{k} = (\mathbf{k}_\perp, k_z)$.

3 Correspondence between manifestly covariant model and standard LFQM

In the last section, we started from the manifestly covariant Bethe-Salpeter model given by Eq. (2) and performed the LF energy integration to get the LFBS model given by Eq. (3). We also discussed the SLF model from the standard LFQM approach where the constituent quark and antiquark are taken as the on-mass-shell degrees of freedom. In this section, we shall analyze the relations between (f_L, f_T) obtained from $[\mathcal{J}_h^\mu]_{\text{LFBS}}$ and f^{SLF} from $[\mathcal{J}_h^\mu]_{\text{SLF}}$. If the on-mass-shell spin structure of the matrix element in SLF approach is exactly reproducible from the manifestly covariant model, the SLF result is identified to be Lorentz covariant.

For the direct comparison between $f_{(L,T)}$ and f^{SLF} , we find [13] that f^{SLF} is exactly reproducible from the LFBS model if and only if the following correspondence is applied

$$\sqrt{2N_c} \frac{\chi(x, \mathbf{k}_\perp)}{1-x} \rightarrow \frac{\phi(x, \mathbf{k}_\perp)}{\sqrt{x(1-x)[M_0^2 - (m_1 - m_2)^2]}}, \quad M \rightarrow M_0. \quad (5)$$

in the integrand of the formulae for f_L^{full} and f_T^{full} . The essential point of this replacement is to apply the replacement of $M \rightarrow M_0$ to all physical mass terms in the integrands of f_L^{full} and f_T^{full} . With such self-consistent replacement, we find numerically that the three different forms f_L^{full} , f_T^{full} and f_V^{SLF} indeed yield the identical result. Moreover, we find that the on-shell contribution f_T^{on} to f_T^{full} also gives the same result with the other three, i.e. $f_T^{\text{on}} = f_T^{\text{full}} = f_L^{\text{full}} = f^{SLF}$ in the standard LFQM. From those observations, we conclude that the replacement given by Eq. (5) provides the self-consistent correspondence in connecting the covariant BS model and the standard LFQM. This self-consistent correspondence implies the proper absorption of the zero-mode contribution essential for the link between chiral symmetry of QCD and LFQM. More detailed discussions can be found in [13].

Although those four different forms give the same result with each other when applying the replacement in Eq. (5), their quark DAs are quite different. Therefore, by checking the DAs as an important constraint of the model, we are able to further pindown the self-consistent LF covariant forms of the decay constant. The quark DA of a vector meson, $\phi_V(x, \mu)$, is the probability of finding collinear quarks up to the scale μ in the $L_z = 0$ projection of the meson wave function. The dependence on the scale μ is given by the QCD evolution and can be calculated perturbatively. However, the DAs at a certain low scale can be obtained by the necessary nonperturbative input from LFQM. Moreover, the presence of the damping gaussian wave function allows us to perform the integral up to infinity without loss of generality. The quark DA for a vector meson is constrained by [13]

$$\int_0^1 \phi_V(x, \mu) dx = \frac{f_V}{2\sqrt{6}}. \quad (6)$$

One may also redefine the normalized quark DA as $\Phi_V(x) = (2\sqrt{6}/f_V)\phi_V(x)$ so that $\int_0^1 dx \Phi_V(x) = 1$.

For the equal quark and antiquark bound state meson such as ρ , we find that only two forms of the decay constant, i.e. f^{SLF} from the longitudinal polarization and f_T^{on} [13] (with the replacement given by Eq. (5)) from the transverse one, yield the anticipated symmetric quark DA. The other two forms, i.e. f_T^{full} and f_L^{full} , that involve the corresponding zero-mode contributions do not reproduce this fundamental constraint when $m_1 = m_2$. The normalized quark DAs obtained from f^{SLF} and f_T^{on} (with the replacement given Eq. (5)) correspond to the twist-2 $\phi_{2;V}^{\parallel}(x)$ and twist-3 $\phi_{3;V}^{\perp}(x)$, respectively. Our complete results for the twist-2 and twist-3 DAs in the standard LFQM are as follows [13]:

$$\phi_{2;V}^{\parallel}(x) = \frac{2\sqrt{6}}{f_V} \int \frac{d^2\mathbf{k}_\perp}{16\pi^3} \frac{\phi(x, \mathbf{k}_\perp)}{\sqrt{\mathbf{k}_\perp^2 + \mathcal{A}^2}} \left[\mathcal{A} + \frac{2\mathbf{k}_\perp^2}{D_{\text{LF}}} \right], \quad (7)$$

$$\phi_{3;V}^{\perp}(x) = \frac{2\sqrt{6}}{f_V} \int \frac{d^2\mathbf{k}_\perp}{16\pi^3} \frac{\phi(x, \mathbf{k}_\perp)}{\sqrt{\mathbf{k}_\perp^2 + \mathcal{A}^2}} \frac{1}{M_0} \left\{ \frac{\mathbf{k}_\perp^2 + \mathcal{A}^2}{2x(1-x)} - \mathbf{k}_\perp^2 + \frac{(m_1 + m_2)}{D_{\text{LF}}} \mathbf{k}_\perp^2 \right\}, \quad (8)$$

where $\mathcal{A} = (1-x)m_1 + xm_2$ and $D_{\text{LF}} = M_0 + m_1 + m_2$. We note that while $f_V = f^{SLF} = f_T^{\text{on}}$, f_V used in $\phi_{2;V}^{\parallel}(x)$ and $\phi_{3;V}^{\perp}(x)$ correspond to f^{SLF} (Eq. (7)) and f_T^{on} (Eq. (8)), respectively.

Table 1 Decay constants (in MeV) of ($\rho, K^*, D^*, J/\psi$) mesons obtained from our self-consistent covariant forms [13] (see also Eqs. (7) and (8)) compared with the experimental data [14].

	f_ρ	f_{K^*}	f_{D^*}	$f_{J/\psi}$
$f^{Th.}$	215	223	212	395
$f^{EXP.}$	220 (2) ¹ , 209 (4) ²	217 (5)	-	416 (6)

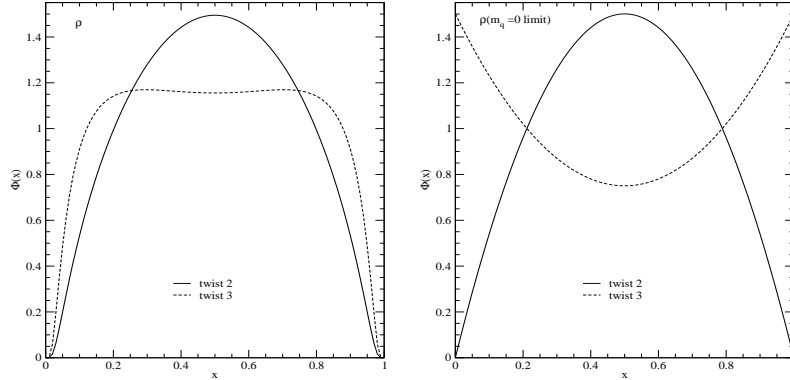


Fig. 1 The twist-2 DAs $\phi_{2;V}^{\parallel}(x)$ and twist-3 DAs $\phi_{3;V}^{\perp}(x)$ for ρ meson with nonzero constituent quark masses (left panel) compared to those with massless quark case (right panel) [13].

4 Numerical Results

In our numerical calculations within the standard LFQM, we use the set of the model parameters for the harmonic oscillator confining potentials, i.e. $(m_q, m_s, m_c) = (0.25, 0.48, 1.8)$ [GeV] and $(\beta_{qq}, \beta_{qs}, \beta_{qc}, \beta_{cc}) = (0.3194, 0.3419, 0.4216, 0.6998)$ [GeV] with $q = u$ or d , which was obtained from the calculation of meson mass spectra using the variational principle in our LFQM [9].

In Table 1, we show the results of the decay constants for ($\rho, K^*, D^*, J/\psi$) mesons obtained from $(f_L^{\text{full}}, f_T^{\text{on}}, f_T^{\text{full}})$ after applying the correspondence in Eq. (5) and f^{SLF} and compare them with the experimental data [14]. We should note that the three different forms $(f_L^{\text{full}}, f_T^{\text{on}}, f_T^{\text{full}})$ and f^{SLF} are found [13] to yield the same numerical results $f^{Th.}$. While four different forms of the vector meson decay constant give the identical results, they have different quark DAs. Since f_L^{full} and f_T^{full} involve the corresponding zero-mode contributions, they impose the intrinsic characteristic of the zero-modes, i.e. antisymmetric under $x \leftrightarrow (1-x)$, inherited from the vacuum property [13]. Thus, the quark DAs from f_L^{full} and f_T^{full} do not satisfy the expected constraint, i.e. symmetric DAs for the meson with $m_1 = m_2$ such as ρ . However, f^{SLF} and f_T^{on} , which is free from the explicit zero-mode contribution, yield the anticipated symmetric DAs for the meson with $m_1 = m_2$ and thus provide self-consistent LF covariant descriptions of vector meson decay constants in the standard LFQM. Since f^{SLF} [f_T^{on}] is obtained from using (J_W^+, ϵ_L) [(J_W^+, ϵ_T)], the normalized quark DAs obtained from f^{SLF} and f_T^{on} correspond to the twist-2 DA $\phi_{2;V}^{\parallel}(x)$ (Eq. (7)) and twist-3 DA $\phi_{3;V}^{\perp}(x)$ (Eq. (8)), respectively.

In Fig. 1, we show $\phi_{2;V}^{\parallel}(x)$ (solid line) and $\phi_{3;V}^{\perp}(x)$ (dashed line) of the ρ meson in cases of finite constituent quark masses (left panel) and massless quark respecting chiral symmetry (right panel). We should note that our LFQM predictions of twist-2 and twist-3 DAs in the chiral symmetry ($m_q \rightarrow 0$) limit remarkably reproduce the exact asymptotic DAs, i.e. $[\phi_{2;V}^{\parallel}(x)]_{\text{as}} = 6x(1-x)$ and $[\phi_{3;V}^{\perp}(x)]_{\text{as}} = (3/4)(1+\xi^2)$ where $\xi = 2x-1$ anticipated from QCD sum rule predictions [11]. This example may show again that our LFQM prediction satisfies the chiral symmetry consistent with the QCD if one correctly implement the zero-mode link to the QCD vacuum. The quark mass correction is not large for the twist-2 $\phi_{2;V}^{\parallel}(x)$, however, it is very significant for the case of twist-3 $\phi_{3;V}^{\perp}(x)$ especially at the end point regions.

5 Summary

In this work, we extended our previous analysis [5] of the vector meson decay constant from the exactly solvable manifestly covariant BS model to the more phenomenologically accessible realistic LFQM [6; 7; 8; 9]. We discussed a self-consistent covariant description of the vector meson decay constant in view of the link between the chiral symmetry of QCD and the expected numerical results of the LFQM.

As the SLF approach within the LFQM by itself is not amenable to determine the zero-mode contribution, we utilized the manifestly covariant model to check the existence (or absence) of the zero-mode. Performing a LF calculation in the covariant BS model, we computed the decay constants using two different combinations of LF weak currents J_W^μ and polarization vectors ϵ_h , i.e. $f_{h=L}$ obtained from $(J_W^\mu, \epsilon_h) = (J_W^+, \epsilon_L)$ and $f_{h=T}$ from (J_W^\perp, ϵ_T) , and checked the LF covariance of the decay constants. We found in the manifestly covariant model that both combinations gave the same result with some particular LF vertex functions if the missing zero-mode contributions were properly taken into account. We then substituted the radial and spin-orbit wave functions with the phenomenologically accessible model wave functions provided by the LFQM and compared $f_{(L,T)}$ obtained from the BS model with the decay constant f^{SLF} obtained directly from the SLF approach used in the LFQM [6; 7; 8; 9]. Linking the covariant BS model to the standard LFQM, we found the matching condition given by Eq. (5) between the two to give a self-consistent covariant description of the decay constant within the LFQM. Using that correspondence, we were able to pin down two independent covariant forms of vector meson decay constants, one obtained from (J_W^+, ϵ_L) and the other from (J_W^\perp, ϵ_T) . Although both of them yield the identical decay constant, each of them corresponds to different twist DA: (J_W^+, ϵ_L) and (J_W^\perp, ϵ_T) correspond to twist-2 and twist-3 two-particle DAs, respectively. Our twist-2 and twist-3 DAs not only satisfy the fundamental constraint of the DAs anticipated from the isospin symmetry, i.e. symmetric DAs for the equal quark and antiquark bound state mesons (e.g. ρ meson), but also reproduce the correct asymptotic DAs in the chiral symmetry limit. Further analysis including the chirality odd and higher twist DAs is under consideration.

References

1. S. J. Brodsky, H.-C. Pauli, and S. Pinsky (1998) Quantum chromodynamics and other field theories on the light cone. Phys. Rep. **301**: 299.
2. W. Jaus (1999) Covariant analysis of the light front quark model. Phys. Rev. D **60**: 054026.
3. B.L.G. Bakker, H.-M. Choi, and C.-R. Ji (2003) Transition form-factors between pseudoscalar and vector mesons in light front dynamics. Phys. Rev. D **67**: 113007.
4. H.-M. Choi and C.-R. Ji (2009) Semileptonic and radiative decays of the B(c) meson in light-front quark model. Phys. Rev. D **80**: 054016.
5. H.-M. Choi and C.-R. Ji (2013) Relativistic Covariance of Light-Front Few-Body Systems in Hadron Physics. Few. Body. Syst. **54**: 1633.
6. W. Jaus (1990) Semileptonic Decays of B and d Mesons in the Light Front Formalism. Phys. Rev. D **41**: 3394.
7. H.-Y. Cheng, C.-Y. Cheung, and C.-W. Hwang (1997) Mesonic form-factors and the Isgur-Wise function on the light front. Phys. Rev. D **55**: 1559.
8. L. A. Kondratyuk and D. V. Tchekin (2001) Transition form-factors and widths of semileptonic decays of B and D mesons in the covariant light front dynamics. Phys. Atom. Nucl. **64**: 727.
9. H.-M. Choi and C.-R. Ji (1999) Mixing angles and electromagnetic properties of ground state pseudoscalar and vector meson nonets in the light cone quark model. Phys. Rev. D **59**: 074015.
10. H.-Y. Cheng, C.-K. Chua, and C.-W. Hwang (2004) Covariant light front approach for s wave and p wave mesons: Its application to decay constants and form-factors. Phys. Rev. D **69**: 074025.
11. P. Ball, V. M. Braun, Y. Koike, K. Tanaka (1998) Higher twist distribution amplitudes of vector mesons in QCD: Formalism and twist - three distributions. Nucl. Phys. B **529**: 323.
12. P. Ball and G. W. Jones (2007) Twist-3 distribution amplitudes of K^* and ϕ mesons. JHEP **03**: 069.
13. H.-M. Choi and C.-R. Ji, Self-consistent covariant description of vector meson decay constants and chirality even quark-antiquark distribution amplitudes up to twist-3 in light-front quark model. arXiv: 1308.4453 [hep-ph].
14. J. Beringer *et al.* (2012) Particle Data Group Phys. Rev. D **86**: 010001.