Form factors for semileptonic $B^+ \to K^+\ell\bar{\ell}$ decay in light-cone quark model

Nisha Dhiman* and Harleen Dahiya
Department of Physics, Dr. B. R. Ambedkar National Institute of Technology Jalandhar - 144011, INDIA

Introduction

The study of semileptonic decay processes of heavy-quark mesons not only describe the internal structure of hadrons such as the hadron wave function and the hadron transverse momentum distribution, but also provides us an ideal field to study the mixing between different generations of quarks by extracting the most accurate values of Cabibbo-Kobayashi-Maskawa (CKM) matrix elements. CKM matrix elements can help us to test the Charge-Parity (CP) violation in the Standard Model (SM) and to search for new physics beyond the SM. The great virtue of semileptonic decay processes is that the effects of the strong interaction can be separated from the effects of the weak interaction into a set of Lorentz-invariant form factors, i.e, the essential informations of the strongly interacting quark/gluon structure inside hadrons.

LHCb is a specialized B-physics experiment collecting data at the Large Hadron Collider (LHC) accelerator at CERN. LHCb is primarily designed to investigate the decays of B-particles and so provide an insight into the phenomenon of CP violation. Such studies can help to explain the Matter-Antimatter asymmetry of the Universe. It is also optimized for the study of rare B decays, which open a window onto new physics beyond the SM. The rare B decays proceeding through $b \to s$ flavour changing neutral currents (FCNCs) transitions provide particularly sensitive probes for physics beyond SM. Theoretical investigation of these rare decays is usually based on the effective Hamiltonian[1]. Applications of the operator product expansion allows one to separate short and long distance effects which are assumed to factorize. The short-distance contributions are described by the Wilson coefficients which are calculated perturbatively. The long-distance part is attributed to the set of operators, where matrix elements between initial and final meson states are usually parameterized by the set of the invariant form factors. The calculation of these form factors requires application of the nonperturbative methods. Since, the nonperturbative effects are small in heavy meson systems, it makes the study of rare B meson decays sensitive for the existence of new particles. In particular, these decays have the potential of revealing the existence of new couplings not present in the SM and are also very sensitive to heavy particles like SUSY and heavy Higgs.

In the present work, we have calculated the form factors for the decay $B^+ \to K^+\ell\bar{\ell}$ in light-cone framework.

Light-cone framework

The light-cone quark model (LCQM) is used to perform the calculation of the hadronic form factors. LCQM provides an advantage of the equal light-cone time ($x^+ = x^0 + x^3$) quantization and includes the important relativistic effects which are neglected in the traditional constituent quark model. In addition, the vacuum state in this approach is much simpler than that in other approaches. The light-cone wave functions are independent of the hadron momentum and thus are explicitly Lorentz invariant[2].

A meson bound state consisting of a quark q_1 and an antiquark $\bar{q}_2$ with total momentum

*Electronic address: nishdhiman1292@gmail.com

P and spin S can be written as[3]

$$|M(P,S,S_z)\rangle = \int \frac{dp_1^+ d^2\mathbf{p}_{1\perp}}{16\pi^3}\frac{dp_2^+ d^2\mathbf{p}_{2\perp}}{16\pi^3}16\pi^3 \times\delta^3(\tilde{P}-\tilde{p}_1-\tilde{p}_2) \times\sum_{\lambda_1,\lambda_2}\Psi^{SS_z}(\tilde{p}_1,\tilde{p}_2,\lambda_1,\lambda_2) \times|q_1(p_1,\lambda)\bar{q}_2(p_2,\lambda)\rangle, \quad (1)$$

where p_1 and p_2 are the on-mass-shell light-front momenta,

$$\tilde{p} = (p^+,\ \mathbf{p}_\perp),\ \mathbf{p}_\perp = (p^1,\ p^2),\ p^- = \frac{m^2+\mathbf{p}_\perp^2}{p^+},$$

and

$$|q(p_1,\lambda_1)\bar{q}(p_2,\lambda_2)\rangle = b^\dagger_{\lambda_1}(p_1)d^\dagger_{\lambda_2}(p_2)|0\rangle,$$
$$\{b_{\lambda'}(p'),b^\dagger_\lambda(p)\} = \{d_{\lambda'}(p'),d^\dagger_\lambda(p)\} = 2(2\pi)^3\ \delta^3(\tilde{p}'-\tilde{p})\ \delta_{\lambda'\lambda}.$$

The momenta p_1 and p_2 in terms of light-cone variables are

$$p_1^+ = xP^+, \quad p_2^+ = (1-x)P^+,$$
$$\mathbf{p}_{1\perp} = x\mathbf{P}_\perp + \mathbf{k}_\perp, \quad \mathbf{p}_{2\perp} = (1-x)\mathbf{P}_\perp - \mathbf{k}_\perp.$$

The momentum-space light-cone wave function Ψ^{SS_z} in 1 can be expressed as

$$\Psi^{SS_z}(\tilde{p}_1,\tilde{p}_2,\lambda_1,\lambda_2) = R^{SS_z}_{\lambda_1\lambda_2}(x,\mathbf{k}_\perp)\ \phi(x,\mathbf{k}_\perp), \quad (2)$$

where $\phi(x,\mathbf{k}_\perp)$ describes the momentum distribution of the constituents in the bound state and $R^{SS_z}_{\lambda_1\lambda_2}$ constructs a state of definite spin (S,S_z) out of the light-cone helicity (λ_1,λ_2) eigenstates. For convenience, we use the covariant form for $R^{SS_z}_{\lambda_1\lambda_2}$ which is given by

$$R^{SS_z}_{\lambda_1\lambda_2}(x,\mathbf{k}_\perp) = \frac{\sqrt{p_1^+p_2^+}}{\sqrt{2}\ \widetilde{M_0}}\ \bar{u}(p_1,\lambda_1)\Gamma v(p_2,\lambda_2). \quad (3)$$

Form factors for semileptonic $B^+ \to K^+$ decay

The decay $B^+ \to K^+\ell\bar{\ell}$ is explained through $b \to s\ell\bar{\ell}$ transition at quark level. With the light-cone wave functions given above, we can evaluate the form factors $f_+(q^2)$ and $F_T(q^2)$ in $q^+ = 0$ frame for $B^+ \to K^+$ transition from the hadronic matrix elements given by[1]

$$\langle K^+|\bar{s}\gamma^\mu b|B^+\rangle = f_+(q^2)[P^\mu_{B^+} + P^\mu_{K^+} - \frac{M^2_{B^+}-M^2_{K^+}}{q}^2 q^\mu] + f_0(q^2)\frac{M^2_{B^+}-M^2_{K^+}}{q^2}q^\mu,$$

$$\langle K^+|i\bar{s}\sigma^{\nu\mu}\gamma_5 q_\nu b|B^+\rangle = \frac{1}{M_{B^+}+M_{K^+}} \left[q^2(P^\mu_{B^+}+P^\mu_{K^+}) - (P\cdot q)q^\mu\right] F_T(q^2).$$

The form factors $f_+(q^2)$ and $F_T(q^2)$ can be expressed in explicit form as

$$f_+(q^2) = \int_0^1 \mathrm{d}x \int \frac{\mathrm{d}^2\mathbf{k}_\perp}{16\pi^3}\phi^*(x,\mathbf{k}'_\perp)\phi(x,\mathbf{k}_\perp) \times\frac{\mathcal{A}_s\mathcal{A}_b + \mathbf{k}'_\perp\cdot\mathbf{k}_\perp}{\sqrt{\mathcal{A}_s^2+\mathbf{k}'^2_\perp}\sqrt{\mathcal{A}_b^2+\mathbf{k}^2_\perp}},$$

$$F_T(q^2) = \int_0^1 \mathrm{d}x \int \frac{\mathrm{d}^2\mathbf{k}_\perp}{16\pi^3}\phi^*(x,\mathbf{k}'_\perp)\phi(x,\mathbf{k}_\perp) \times\frac{x(M_{B_+}+M_{K_+})\left[\mathcal{A}_b + (m_s-m_b)\frac{\mathbf{k}_\perp\cdot\mathbf{q}_\perp}{\mathbf{q}^2_\perp}\right]}{\sqrt{\mathcal{A}_s^2+\mathbf{k}'^2_\perp}\sqrt{\mathcal{A}_b^2+\mathbf{k}^2_\perp}},$$

where $\mathbf{k}'_\perp = \mathbf{k}_\perp - x\mathbf{q}_\perp$, $\mathcal{A}_s = m_s x + m_q(1-x)$ and $\mathcal{A}_b = m_b x + m_q(1-x)$

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