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Origin of a large CP asymmetry in $B^{\pm} \to K^{+}K^{-}K^{\pm}$ decays

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Large *CP*-violating asymmetry effects in the $B^{\pm} \to K^{+}K^{-}K^{\pm}$ decays have been predicted in the QCD factorization model. The model includes strong $K^{+}K^{-}$ final-state long-distance interactions in the *S*-, *P*-, and also (in the recent analysis) *D*- wave two-body states. The *S*-wave two-body unitarity conditions involve interchannel couplings of the kaon-kaon states with the intermediate states of two pions and four pions. As a result, the pion-pion to kaon-kaon rescattering effects are included in the model. It is shown how the weak phase differences together with the existence of two different strong phases of the *S*-wave decay amplitudes (related to the phases of the kaon scalar strange and non-strange form factors) contribute to the *CP*-asymmetry in question. The theoretical results are compared with recent experimental data of the LHCb and BABAR Collaborations.

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1. Decay amplitudes

Large *CP* asymmetry in $B^{\pm} \to K^+K^-K^{\pm}$ decays for the K^+K^- effective masses above the $\phi(1020)$ meson peak has been predicted in a model developed in 2011 [1]. In 2013 the LHCb Collaboration measured the *CP*-violating asymmetry and found a large negative asymmetry in the region $1.1 < m^2_{K^+K\ low} < 2.0$ GeV^2 and $m^2_{K^+K\ high} < 15$ GeV^2 [2]. A similar result has been also obtained in an earlier BABAR measurement [3]. The above data from two collaborations have been recently analysed in Ref. [4]. Here we explain in more detail the origin of this large negative *CP* asymmetry.

The *CP*-violating asymmetry, measured in [2, 3], is small in the range of the K^+K^- effective masses under the $\phi(1020)$ meson maximum where the *P*-wave K^+K^- final state strong interaction apparently dominates. Thus we analyse properties of the amplitudes A_S^- and A_S^+ corresponding respectively to the $B^- \to K^+K^-K^-$ and $B^+ \to K^+K^-K^+$ decays in which the K^+K^- pair is formed in the *S*-wave. The decay amplitudes are calculated in the quasi-two-body QCD factorization model [1]. There are two weak decay transition amplitudes proportional to the following two products of the elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix: $\lambda_u = V_{ub}V^*_{us}$ and $\lambda_c = V_{cb}V^*_{cs}$. The $B^- \to K^+K^-K^-$ decay amplitude is equal to

$$A_S^- = \lambda_u F_u + \lambda_c F_c. \tag{1.1}$$

while the charge conjugated $B^+ \to K^+K^-K^+$ decay amplitude reads

$$A_S^+ = \lambda_u^* F_u + \lambda_c^* F_c. \tag{1.2}$$

In Eqs. (1.1) and (1.2) the functions F_u and F_c include the weak amplitude factors and the strong interaction factors. The strong factors do not change under the charge conjugation when one passes from the B^- to the B^+ decay. With a good accuracy, the V^*_{us}, V_{cb} and V^*_{cs} matrix elements are real, while $V_{ub} = |V_{ub}|e^{-i\gamma}$ is complex. The CKM angle γ is close to 70 degrees. The modulus of the λ_u coefficient is smaller than that of λ_c (by a factor of about 51). The phase ϕ_c of λ_c is very close to zero while the phase ϕ_u of λ_u is equal to $(-\gamma)$. The full expressions for the *S*-wave decay amplitudes are given in [4]. For a further discussion, it is useful to write the factors F_u and F_c in terms of the scalar non-strange kaon form factor Γ_2^n and the scalar strange kaon form factor Γ_2^s:

$$F_u = u_n \Gamma_2^{n*} + u_s \Gamma_2^{s*} \tag{1.3}$$

and

$$F_c = c_n \Gamma_2^{n*} + c_s \Gamma_2^{s*}. \tag{1.4}$$

Here u_n, u_s, c_n and c_s are simple functions which can be read from Eq. (2) of [4]. In F_u the first term dominates: $|u_n\Gamma_2^{n*}| \gg |u_s\Gamma_2^{s*}|$ as in u_n the tree part of the weak amplitude is much larger than the penguin components present in u_s. In F_c only the penguin terms contribute and one can verify that the coefficients c_n and c_s are comparable.

2. Kaon scalar form factors

The final-state strong K^+K^- interactions play an important role in the description of the *CP* asymmetry. In the present application we use the coupled channel model of the scalar-isoscalar form factors. Three coupled channels are considered: $\pi\pi$ ($\pi^{+}\pi^{-}$ and $\pi^{0}\pi^{0}$) - labelled below by subscript 1, $K\bar{K}$ ($K^{+}K^{-}$ and $K^{0}\bar{K}^{0}$ - subscript 2 and the effective 4π channel (quasi-two body $\sigma\sigma$ or $\rho\rho$) - subscript 3. Then the six scalar form factors are defined as follows:

$$\Gamma^{n} = \begin{pmatrix} \Gamma_1^n \\ \Gamma_2^n \\ \Gamma_3^n \end{pmatrix}, \qquad \Gamma^{s} = \begin{pmatrix} \Gamma_1^s \\ \Gamma_2^s \\ \Gamma_3^s \end{pmatrix}. \tag{2.1}$$

The superscript n labels the non-strange form factors, while s - the strange form factors. Below we list nine meson-meson scattering amplitudes T which should be parametrized before the meson form factors are calculated:

$$T = \begin{pmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{pmatrix}. \tag{2.2}$$

The diagonal elements of T are elastic scattering amplitudes, for example T_{22} is the elastic S-wave isoscalar KK amplitude. The non-diagonal T elements are the interchannel transition amplitudes. The meson-meson amplitudes are calculated using a model described in [5]. In [6] one can find a general derivation of the scalar pion form factors used in the studies of the $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ decays. The kaon form factors are discussed in [1, 4]. Below we write a general matrix structure which shows the functional dependence of the scalar non-strange and strange form factors on the meson-meson scattering amplitudes:

$$\Gamma^{n*} = R^{n} + TGR^{n}, \qquad \Gamma^{s*} = R^{s} + TGR^{s}. \tag{2.3}$$

Here G is the diagonal matrix of the Green functions

$$G = \begin{pmatrix} G_1 & 0 & 0 \\ 0 & G_2 & 0 \\ 0 & 0 & G_3 \end{pmatrix}. \tag{2.4}$$

The R^{n} and R^{s} are matrices of the production functions whose three components are parametrized in the following way:

$$R_j^{n,s}(E) = \frac{\alpha_j^{n,s} + \tau_j^{n,s}E + \omega_j^{n,s}E^2}{1 + cE^4}, \quad j = 1,2,3, \tag{2.5}$$

where the variable E equals to the effective masses of two mesons in each channel:

$$E = m_{\pi\pi} = m_{KK} = m_{4\pi}. \tag{2.6}$$

The real parameters $\alpha_j^{n,s}$, $\tau_j^{n,s}$ and $\omega_j^{n,s}$ are constrained using the chiral perturbation model and the fitted parameter c controls the high energy behaviour of R_j. In the integral equations (2.3) one sums over all the appropriate coupled components of the scattering matrix T. More specifically, the non-strange and strange kaon form factors are expressed as

$$\Gamma_2^{n*} = R_2^{n} + T_{22}G_2R_2^{n} + T_{21}G_1R_1^{n} + T_{23}G_3R_3^{n} \tag{2.7}$$

and

$$\Gamma_2^{s*} = R_2^s + T_{22}G_2R_2^s + T_{21}G_1R_1^s + T_{23}G_3R_3^s. \tag{2.8}$$

In these two equations the following three meson-meson S-wave amplitudes are present: the $KK \to KK$ elastic scattering amplitude T_{22}, the $\pi\pi \to KK$ transition (or rescattering) amplitude T_{21} and the $4\pi \to KK$ transition amplitude T_{23}. Since the non-strange production functions R_j^n are different from the strange production functions R_j^s and the rescattering amplitudes T_{21} and T_{23} are in general non-zero, the complex functions Γ_2^{s*} and Γ_2^{n*} have different phases ($\delta_s \neq \delta_n$).

The moduli and the phases of the kaon form factors Γ_2^{n*} and Γ_2^{s*} are shown in Fig. 1.

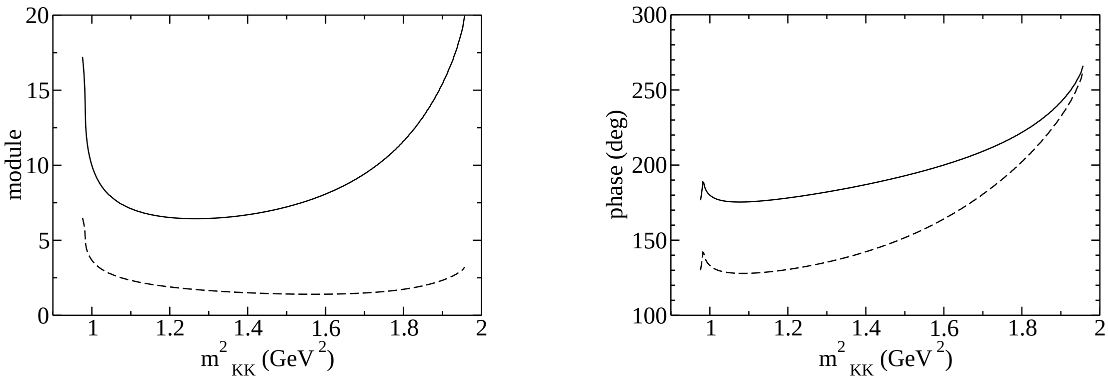

Figure 1: The moduli (left panel) and the phases (right panel) of the kaon non-strange and strange scalar form factors Γ_2^{n*} and Γ_2^{s*} (solid and dashed lines, respectively).

Near the effective K^+K^- mass close to 1 GeV one sees maxima of the moduli and the phases. This behaviour is related to the presence of the $f_0(980)$ resonance. One should also notice that the modulus of the non-strange form factor is a few times larger that the modulus of the strange form factor. This inequality contributes to the smallness of the ratio $|F_c/F_u|$. In a wide range of the effective masses above the position of the $f_0(980)$ resonance the phases δ_n and δ_s differ by about 45 degrees, leading in consequence to a large negative asymmetry.

3. *CP* asymmetry

In a region of the effective K^+K^- masses, where the S-wave part of the decay amplitude dominates, the *CP* asymmetry can be written as

$$A_{CP} = \frac{|A_S^-|^2 - |A_S^+|^2}{|A_S^-|^2 + |A_S^+|^2} = -\frac{2r sin(\phi_c - \phi_u) sin(\delta_c - \delta_u)}{1 + r^2 + 2r cos(\phi_c - \phi_u) cos(\delta_c - \delta_u)}, \tag{3.1}$$

where ϕ_u and ϕ_c are the phases of functions F_u and F_c, respectively and the factor r is defined as the ratio $|\frac{\lambda_c F_c}{\lambda_u F_u}|$. Let us define phases δ_n and δ_s of the non-strange and strange kaon form factors: $\Gamma_2^{n*} = |\Gamma_2^n| e^{i\delta_n}$ and $\Gamma_2^{s*} = |\Gamma_2^s| e^{i\delta_s}$. Then from the functional dependence of the factors F_u and F_c we can derive an approximate relation

$$\delta_c - \delta_u \approx \delta_s - \delta_n. \tag{3.2}$$

One can also calculate numerically the ratio $|F_c|/|F_u| \approx 0.02$ for $m^2_{K^+K\ low} \approx 1.2$ GeV^2. Recalling that $\lambda_c/\lambda_u \approx 51$, one obtains $r \approx 1$. As the inspection of the form of Eq. (3.1) shows, $r = 1$ is the value for which the modulus of the *CP* asymmetry reaches its maximal value. Since $\phi_c - \phi_u = \gamma \approx 68^0$ and for $1.0 < m^2_{K^+K\ low} < 1.5$ GeV^2 the difference $\delta_s - \delta_n$ is approximately 45^0, in this range of effective K^+K^- masses the *CP* asymmetry reaches a large negative value of about -0.5.

In addition to the *S*-wave part of the decay amplitude discussed above, the *P*- and *D*- waves of the K^+K^- scattering are also included in the model. The full model has five parameters fitted from the data.

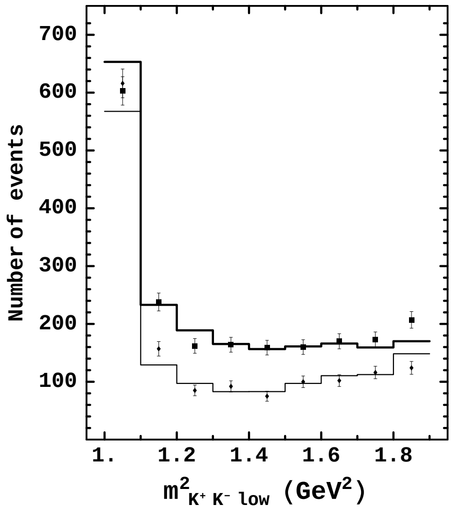

Figure 2: Distribution of the LHCb signal events for the $B^\pm \to K^+K^-K^\pm$ decays. The data points are from [2] (B^+ - squares, B^- - diamonds). The model results are shown as thick (B^+) and thin (B^-) histograms.

The results of the fits are compared with the LHCb data in Figs. 2 and 3. In the data presented in Fig. 2, except for the first bin dominated by the $\phi(1020)$ meson contribution, one observes a significant surplus of the number of events corresponding to the B^+ decays over the number of events coming from the B^- decays. This is also visualized in Fig. 3 where the negative *CP* asymmetry is shown up to $m^2_{K^+K\ low}$ equal to about 1.9 GeV^2. The *CP* asymmetry data of the BABAR Collaboration [3] can also be fitted using the theoretical model of Ref. [4].

4. Short summary

Large CP-violating asymmetry effects in the $B^\pm \to K^+K^-K^\pm$ decays have been predicted in the QCD factorization model. The model includes strong K^+K^- final-state long-distance interactions in the *S*-, *P*- and *D*- waves. We have shown how a large negative *CP* asymmetry appears for the K^+K^- effective mass squares between 1.1 and 1.9 GeV^2 . The asymmetry originates mainly in the *S*-wave amplitudes. It stems from the presence of two significantly differing weak phases together with the existence of two different strong phases related to the phases of the kaon scalar strange and non-strange form factors. With the $\pi\pi \to KK$ and $4\pi \to KK$ rescattering effects included in the model, the interchannel couplings of the kaon-kaon state to the two pion and four pion states naturally produce the difference in the relevant strong phases.

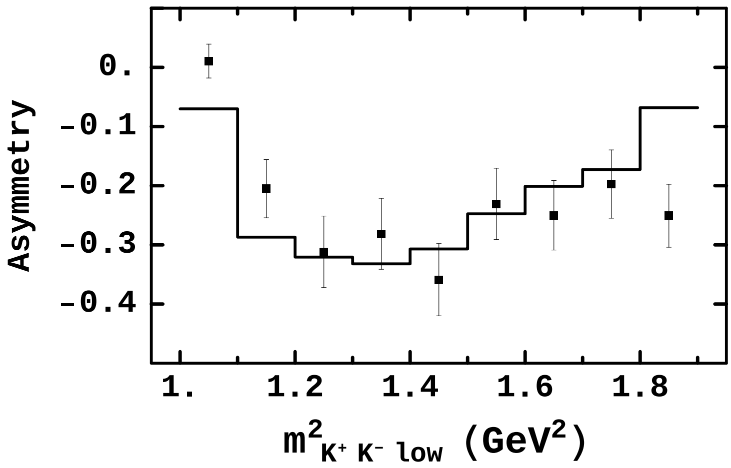

Figure 3: Distribution of the *CP*- violating asymmetry for the $B^{\pm} \to K^+K^-K^{\pm}$ decays. The data points are from [2], the model results are shown as solid histogram in bins of 0.1 GeV^2.

5. Acknowledgements

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