ANGULAR DISTRIBUTION AND ASYMMETRIES IN FLAVOR-CHANGING NEUTRAL-CURRENT DECAY $B \to K^* l^+ l^-$

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The fully differential angular distribution for the rare flavor-changing neutral current decay $\bar{B}_d^0 \to \bar{K}^{*0} (\to K^- \pi^+) e^+ e^-$ is studied. The emphasis is placed on accurate treatment of the contribution from the processes $\bar{B}_d^0 \to \bar{K}^{*0} (\to K^- \pi^+) V$ with intermediate vector resonances $V = \rho(770)$, $\omega(782)$, $\phi(1020)$, J/ψ, $\psi(2S), \ldots$ decaying into the e^+e^- pair. The two versions of the vector-meson-dominance model for the transition $V\gamma$ are used and tested. The branching ratio, longitudinal polarization fraction of the $\bar{K}^{*0}$ meson, transverse asymmetry $A_T^{(2)}$ and forward-backward asymmetry are compared with data from BaBar and CDF, and predictions for experiments at LHCb and B factories are made.

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1. INTRODUCTION

The investigation of rare B decays induced by the flavor-changing neutral current (FCNC) transitions $b \to s$ and $b \to d$ represents an important test of the standard model (SM) and its extensions (see [1] for a review).

Among the rare decays, the process $b \to s\ell^+\ell^-$, where the virtual photon is converted to the lepton pair, is of considerable interest. In this decay the angular distributions and lepton polarizations can probe the chiral structure of the matrix element [1] and thereby effects of the new physics (NP) beyond the SM.

In order to unambiguously measure effects of NP in the observed process $\bar{B}_d^0 \to \bar{K}^{*0} (\to K^- \pi^+) \ell^+ \ell^-$, mediated by $b \to s\ell^+\ell^-$ decay, one needs to calculate the SM predictions with a high accuracy. The amplitude in the SM consists of the short-distance (SD) and long-distance (LD) contributions. The former are expressed in terms of the Wilson coefficients C_i calculated in perturbative QCD up to a certain order in $\alpha_s(\mu)$; they carry information on processes at energy scales $\sim m_W,\ m_t$. The LD effects describing the hadronization process are expressed in terms of matrix elements of several $b \to s$ operators between the initial B and the K^* final state. These hadronic matrix elements are parameterized in terms of form factors that are calculated in various approaches (see, e.g. [2]).

The additional LD effects, originating from intermediate vector resonances $\rho(770)$, $\omega(782)$, $\phi(1020)$, $J/\psi(1S)$, $\psi(2S)$,..., in general, may complicate theoretical interpretation and make it more model dependent. The vector resonances modify the amplitude and thus may induce, for example, the right-handed currents which are absent in the SM.

In the present paper we extend calculations of [3] to the whole region of dilepton invariant mass up to $m_{ee}^{max} = m_B - m_{K^*} = 4.39$ GeV. The effective SM Hamiltonian with the Wilson coefficients in the next-to-next-to-leading order (NNLO) approximation is applied. The LD effects mediated by the resonances, *i.e.* $\bar{B}^0 \to \bar{K}^{*0}V \to \bar{K}^{*0}e^+e^-$ with $V = \rho(770)$, $\omega(782)$, $\phi(1020)$, J/ψ, $\psi(2S), \ldots$, are included explicitly in terms of the helicity amplitudes of the decays $\bar{B}^0 \to \bar{K}^{*0}V$. The information on the latter is taken from experiments if available; otherwise it is taken from theoretical predictions.

2. ANGULAR DISTRIBUTIONS AND AMPLITUDES FOR THE $\bar{B}_d^0 \to \bar{K}^{*0} e^+ e^-$ DECAY

The decay $\bar{B}_d^0 \to \bar{K}^{*0} e^+ e^-$, with $\bar{K}^{*0} \to K^-\pi^+$ on the mass shell, is completely described by four independent kinematic variables: the electron-positron pair invariant-mass squared, q^2, and the three angles θ_l, θ_K, ϕ. In the helicity frame (Fig. 1), the angle $\theta_l\,(\theta_K)$ is defined as the angle between the directions of motion of $e^+\,(K^-)$ in the $\gamma^*\,(\bar{K}^{*0})$ rest frame and the $\gamma^*\,(\bar{K}^{*0})$ in the $\bar{B}_d^0$ rest frame. The azimuthal angle ϕ is defined as the angle between the decay planes of $\gamma^* \to e^+ e^-$ and $\bar{K}^{*0} \to K^-\pi^+$ in the $\bar{B}_d^0$ rest frame. The fully differential angular distribution

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in these coordinates is given by

$$\mathcal{W}\quad(\hat{q}^2,\theta_l,\theta_K,\phi) \equiv \frac{d^4\,\Gamma}{d\hat{q}^2 d\cos\theta_l\, d\cos\theta_K d\phi} \Big/ \frac{d\Gamma}{d\hat{q}^2}$$
$$= \frac{9}{64\,\pi}\sum_{k=1}^{9}\alpha_k(q^2) g_k(\theta_l,\theta_K,\phi)\,, \qquad (1)$$

where g_k are the angular and α_k are the amplitude terms, $\hat{q}^2 \equiv q^2/m_B^2$, m_B is the mass of the B_d^0 meson, and

$$\frac{d\,\Gamma}{d\hat{q}^2} = m_B\, N^2 \hat{q}^2 \sqrt{\hat{\lambda}}\left(|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2\right)\,. \qquad (2)$$

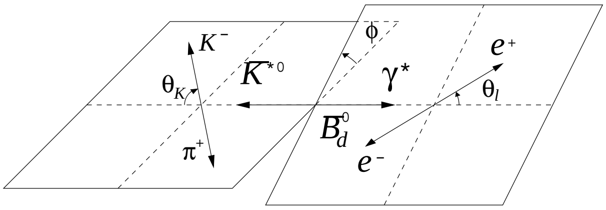

Fig. 1. *Definition of helicity angles θ_l, θ_K, and ϕ, for the decay $\bar{B}_d^0 \to \bar{K}^{*0}\, e^+\, e^-$*

We have neglected the electron mass m_e, and $A_{0L(R)}$, $A_{\parallel L(R)}$ and $A_{\perp L(R)}$ are the complex decay amplitudes of the three helicity states in the transversity basis, $\hat{\lambda} \equiv \lambda(1,\hat{q}^2,\hat{m}_{K^*}^2) = (1-\hat{q}^2)^2 - 2(1+\hat{q}^2)\hat{m}_{K^*}^2 + \hat{m}_{K^*}^4$, $\hat{m}_{K^*} \equiv m_{K^*}/m_B$, where m_{K^*} is the mass of the K^{*0} meson, and

$$N = |V_{tb}V_{ts}^*|\frac{G_F m_B^2 \alpha_{\rm em}}{32\,\pi^2\sqrt{3\,\pi}}\,.$$

Here, V_{ij} are the Cabibbo-Kobayashi-Maskawa matrix elements [4, 5], G_F is the Fermi coupling constant, $\alpha_{\rm em}$ is the electromagnetic fine-structure constant.

Next, we implement the effects of LD contributions from the decays $\bar{B}_d^0 \to \bar{K}^{*0}\, V$, where $V = \rho^0\,, \omega\,, \phi\,, J/\psi(1S)\,, \psi(2S)\,, \ldots$ mesons, followed by $V \to e^+\, e^-$ in the decay $\bar{B}_d^0 \to \bar{K}^{*0}\, e^+\, e^-$ (Fig. 2).

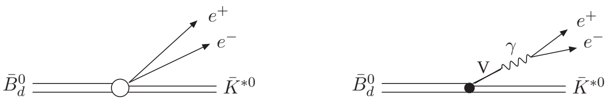

Fig. 2. *Nonresonant and resonant contributions to the decay amplitude*

We apply vector-meson dominance (VMD) approach. In general, the $V\gamma$ transition can be included into consideration using various versions of VMD model. In the "standard" version (see, e.g. [6], chapter 6), the $V\gamma$ transition vertex can be written as

$$\langle\gamma(q);\,\mu|V(q);\,\nu\,\rangle = -ef_V Q_V m_V\, g^{\mu\nu}, \qquad (3)$$

where $g^{\mu\nu}$ is the metric tensor, Q_V is the effective electric charge of the quarks in the vector meson:

$$Q_\rho = \frac{1}{\sqrt{2}}\,,\quad Q_\omega = \frac{1}{3\sqrt{2}}\,,\quad Q_\phi = -\frac{1}{3}\,,$$
$$Q_{J/\psi} = Q_{\psi(2S)} = \ldots = \frac{2}{3}\,. \qquad (4)$$

The decay constants of neutral vector mesons f_V can be extracted from their electromagnetic decay width. This version of VMD model will be called VMD1. A more elaborate model (called hereafter VMD2) originates from Lagrangian

$$\mathcal{L}_{\gamma V} = -\frac{e}{2}F^{\mu\nu}\sum_V \frac{f_V Q_V}{m_V}\, V_{\mu\nu}, \qquad (5)$$

where $V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$ and $F^{\mu\nu} \equiv \partial^\mu A^\nu - \partial^\nu A^\mu$ is the electromagnetic field tensor.

Based on VMD approach, we obtain the total amplitude including nonresonant and resonant parts,

$$A_{0L,R} = \frac{1}{2\,\hat{m}_{K^*}\sqrt{\hat{q}^2}}\Bigg(C_0(q^2)\Big(C_{9V}^{\rm eff} \mp C_{10A}$$
$$+ 2\hat{m}_b\left(C_{7\gamma}^{\rm eff} - C_{7\gamma}^{\prime\,\rm eff}\right)\kappa_0(q^2)\Big)$$
$$+ 8\pi^2\sum_V C_V D_V^{-1}(\hat{q}^2)\Big(\left(1-\hat{q}^2-\hat{m}_{K^*}^2\right)S_1^V$$
$$+ \hat{\lambda}\frac{S_2^V}{2}\Big)\Bigg)\,, \qquad (6)$$

$$A_{\parallel L,R} = -\sqrt{2}\Bigg(C_\parallel(q^2)\Big(C_{9V}^{\rm eff} \mp C_{10A}$$
$$+ 2\frac{\hat{m}_b}{\hat{q}^2}\left(C_{7\gamma}^{\rm eff} - C_{7\gamma}^{\prime\,\rm eff}\right)\kappa_\parallel(q^2)\Big)$$
$$+ 8\pi^2\sum_V C_V D_V^{-1}(\hat{q}^2)\,S_1^V\Bigg)\,, \qquad (7)$$

$$A_{\perp L,R} = \sqrt{2\hat{\lambda}}\Bigg(C_\perp(q^2)\Big(C_{9V}^{\rm eff} \mp C_{10A}$$
$$+ 2\frac{\hat{m}_b}{\hat{q}^2}\left(C_{7\gamma}^{\rm eff} + C_{7\gamma}^{\prime\,\rm eff}\right)\kappa_\perp(q^2)\Big)$$
$$+ 4\pi^2\sum_V C_V D_V^{-1}(\hat{q}^2)\,S_3^V\Bigg)\,, \qquad (8)$$

where the form factors enter as

$$C_0(q^2) = (1-\hat{q}^2-\hat{m}_{K^*}^2)(1+\hat{m}_{K^*})A_1(q^2)$$
$$- \hat{\lambda}\frac{A_2(q^2)}{1+\hat{m}_{K^*}}, \qquad (9)$$

$$C_\parallel(q^2) = (1+\hat{m}_{K^*})A_1(q^2), \qquad (10)$$

$$C_\perp(q^2) = \frac{V(q^2)}{1+\hat{m}_{K^*}}, \qquad (11)$$

$$\kappa_0(q^2) \equiv \Big((1-\hat{q}^2+3\hat{m}_{K^*}^2)(1+\hat{m}_{K^*})T_2(q^2)$$
$$- \frac{\hat{\lambda}}{1-\hat{m}_{K^*}}T_3(q^2)\Big)\Big((1-\hat{q}^2-\hat{m}_{K^*}^2)$$
$$\times (1+\hat{m}_{K^*})^2 A_1(q^2) - \hat{\lambda}\,A_2(q^2)\Big)^{-1}, \qquad (12)$$

$$\kappa_\parallel(q^2) \equiv \frac{T_2(q^2)}{A_1(q^2)}(1-\hat{m}_{K^*}), \qquad (13)$$

$$\kappa_\perp(q^2) \equiv \frac{T_1(q^2)}{V(q^2)}(1+\hat{m}_{K^*}). \tag{14}$$

In the above formulas the definition $\hat{m}_b \equiv \overline{m}_b(\mu)/m_B$ is used, and $A_1(q^2)$, $A_2(q^2)$, $V(q^2)$, $T_1(q^2)$, $T_2(q^2)$, $T_3(q^2)$ are the $B \to K^*$ transition form factors, defined in [2]. Furthermore,

$$D_V(\hat{q}^2) = \hat{q}^2 - \hat{m}_V^2 + i\hat{m}_V\hat{\Gamma}_V(\hat{q}^2)$$

is the usual Breit-Wigner function for the V meson resonance shape with the energy-dependent width $\Gamma_V(q^2)$ $[\hat{\Gamma}_V(\hat{q}^2) = \Gamma_V(q^2)/m_B]$, $\hat{m}_V \equiv m_V/m_B$, $\hat{\Gamma}_V \equiv \Gamma_V/m_B$, $m_V(\Gamma_V)$ is the mass (width) of a V meson, and

$$C_V = \frac{Q_V m_V f_V}{q^2} \text{ (VMD1) }, \; C_V = \frac{Q_V f_V}{m_V} \text{ (VMD2) }. \tag{15}$$

In Eqs. (6)-(8), S_i^V $(i = 1, 2, 3)$ are the invariant amplitudes of the decay $B_d^0 \to K^{*0}\, V$.

The energy-dependent widths of light vector resonances ρ, ω and ϕ are chosen as in Ref. [3]. The up-dated branching ratios for resonances decays to different channels are taken from [7]. For the $c\bar{c}$ resonances J/ψ, $\psi(2S)$, … we take the constant widths.

In order to calculate the resonant contribution to the amplitude of the $\bar{B}_d^0 \to \bar{K}^{*0}\, e^+\, e^-$ decay, one has to know the amplitudes of the decays $\bar{B}_d^0 \to \bar{K}^{*0}\, \rho$, $\bar{B}_d^0 \to \bar{K}^{*0}\, \omega$, $\bar{B}_d^0 \to \bar{K}^{*0}\, \phi$, $\bar{B}_d^0 \to \bar{K}^{*0}\, J/\psi$, $\bar{B}_d^0 \to \bar{K}^{*0}\, \psi(2S)$, … At present the amplitudes of the $\bar{B}_d^0 \to \bar{K}^{*0}\, \phi$, $\bar{B}_d^0 \to \bar{K}^{*0}\, J/\psi$, $\bar{B}_d^0 \to \bar{K}^{*0}\, \psi(2S)$ decays are known from experiment [7], therefore, we use these amplitudes for calculation of invariant amplitudes. For the light resonances ρ and ω we use the theoretical prediction [8] for the decay amplitudes. At the same time, we are not aware of a similar prediction for the higher $c\bar{c}$ resonances, such as $\psi(3770)$ an so on, therefore we do not include contribution of these resonances to amplitudes in our calculation. The SM Wilson coefficients have been obtained in [9] at the scale $\mu = 4.8$ GeV to NNLO accuracy. In the numerical estimations, we use the form factors from the light-cone sum rules (LCSR) calculation [2].

3. RESULTS

In Figs. 3 we present results for the dependence on the dilepton invariant mass squared of the differential branching ratio,

$$\frac{dB}{d\hat{q}^2} = \tau_B \frac{d\Gamma}{d\hat{q}^2}\,, \tag{16}$$

the longitudinal polarization fraction of K^* meson,

$$f_L = |a_0|^2\,, \tag{17}$$

the forward-backward asymmetry

$$A_{\rm FB} = -\frac{3}{2}{\rm Re}(a_{\parallel\, L}\, a_{\perp\, L}^* - a_{\parallel\, R}\, a_{\perp\, R}^*)\,, \tag{18}$$

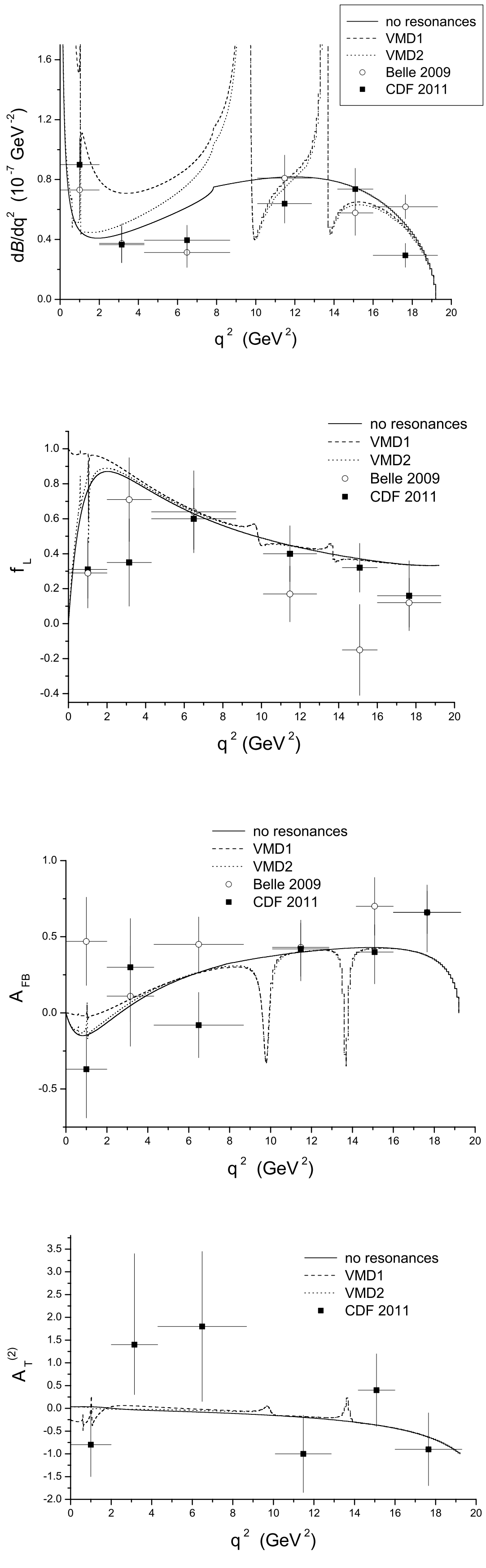

Fig. 3. *Solid line corresponds to the SM calculation without resonances taken into account. Dashed and dotted lines are calculated with account of resonances in the VMD1 and VMD2 model respectively*

and the coefficient

$$A_{\rm T}^{(2)} \equiv \frac{a_\perp - a_\parallel}{a_\perp + a_\parallel}\,, \qquad (19)$$

for the $\bar{B}_d^0 \to \bar{K}^{*0}\, e^+\, e^-$ decay. Here

$$a_i a_j^* \equiv a_{iL}(q^2)a_{jL}^*(q^2) + a_{iR}(q^2)a_{jR}^*(q^2) \qquad (20)$$

and

$$a_{iL(R)} \equiv \frac{A_{iL(R)}}{\sqrt{\sum_j |A_j|^2}}\,, \qquad (21)$$

$i, j = (0, \|, \perp)$, τ_B is the lifetime of a B_d^0 meson. The data from Belle [10] and CDF [11, 12] are shown by the circles and boxes respectively. The interval of q^2 is taken from $(30\ \text{MeV})^2$ up to $(m_B - m_{K^*})^2 \approx 19.22\,\text{GeV}^2$. The phase δ_0^V is chosen zero for all resonances except the ϕ meson, for which $\delta_0^\phi = 2.82\,\text{rad}$ is taken from experiment.

As it is seen from the figures, VMD1 and VMD2 give different prediction for observables in the region of small $q^2 \le 2\ \text{GeV}^2$ while at bigger values of q^2 they yield similar results. Note that the difference between predictions of these two models is especially large for the high-lying $c\bar{c}$ resonances.

The experimental uncertainties are still large, nevertheless the version VMD2 seems more preferable as compared with data for the differential branching ratio and longitudinal polarization fraction.

4. CONCLUSIONS

The rare FCNC decay $\bar{B}_d^0 \to \bar{K}^{*0}\,(\to K^-\,\pi^+)\,e^+\,e^-$ has been studied in the whole region of electron-positron invariant masses up to $m_B - m_{K^*}$. The fully differential angular distribution over the three angles and dilepton invariant mass for the four-body decay $\bar{B}_d^0 \to K^-\,\pi^+\,e^+\,e^-$ is analyzed. We defined a convenient set of asymmetries which allows one to extract them from measurement of the angular distribution once sufficient statistics is accumulated. We performed calculations of differential branching, polarization fractions of K^* meson and asymmetries. These asymmetries may have sensitivity to various effects of the NP, although in order to see signatures of these effects, the resonance contribution should be accurately evaluated.

Contribution from intermediate vector resonances in the process $\bar{B}_d^0 \to \bar{K}^{*0}\,(\to K^-\,\pi^+)\,V$ with $V = \rho(770)$, $\omega(782)$, $\phi(1020)$, J/ψ, $\psi(2S)$ decaying into the e^+e^- pair has been taken into account. Different aspects of treatment of this LD contribution have been studied.

The important aspect is the choice of the VMD model, describing the $V\gamma^*$ transition. We used two variants of the VMD model, called here VMD1 and VMD2 versions. Based on comparison of calculation for the differential branching ratio, longitudinal polarization fraction and forward-backward asymmetry with the data from Belle and CDF, we can conclude that the VMD2 version is somewhat more preferable.

For the vertex $\bar{B}_d^0 \to \bar{K}^{*0}\,V$ we used an off-mass-shell extension of the helicity amplitudes describing production of on-shell vector mesons. For the latter the experimental information is used if available, and otherwise theoretical predictions.

All asymmetries are calculated and the resonance contributions are studied. The coefficient $A_{\rm T}^{(2)}$ take sizable value at large m_{ee}, while in the wide region of invariant masses this observable is small. Account of resonances changes this asymmetry, mainly in the vicinity of the resonance positions, i.e. at $m_{ee} \approx m_V$. In general, this observable is important in view of its sensitivity to the chiral-odd dipole transition $b_L \to s_R + \gamma_R$ and thereby to the effects of the NP which are related to the right-handed currents.

Calculations performed in the present work may be useful for experiments aiming at search of effects of the NP in the decay $\bar{B}_d^0 \to \bar{K}^{*0}\,(\to K^-\,\pi^+)\,\ell^+\,\ell^-$.

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УГЛОВЫЕ РАСПРЕДЕЛЕНИЯ И АСИММЕТРИИ В РАСПАДЕ $B \to K^* l^+ l^-$, ИНДУЦИРОВАННОМ НЕЙТРАЛЬНЫМ ТОКОМ, ИЗМЕНЯЮЩИМ АРОМАТ

А.Ю. Корчин, В.А. Ковальчук, Д.О. Лазаренко

Изучено полное дифференциальное угловое распределение редкого распада $\bar{B}_d^0 \to \bar{K}^{*0} (\to K^- \pi^+) e^+ e^-$, индуцированного нейтральным током, изменяющим аромат. Акцентировано внимание на аккуратном рассмотрении вкладов от процессов $\bar{B}_d^0 \to \bar{K}^{*0} (\to K^- \pi^+) V$ с промежуточными векторными резонансами $V = \rho(770),\ \omega(782),\ \phi(1020),\ J/\psi,\ \psi(2S), \ldots$, распадающимися на e^+e^--пару. Использованы две версии модели векторной доминантности для перехода $V\gamma$. Относительная вероятность распада, доля продольной поляризации $\bar{K}^{*0}$ мезона, поперечная асимметрия $A_T^{(2)}$ и асимметрия “вперед-назад” сравниваются с данными BaBar и CDF, а также выполнены предсказания для экспериментов LHCb и B-фабрик.

КУТОВІ РОЗПОДІЛИ ТА АСИМЕТРІЇ У РОЗПАДІ $B \to K^* l^+ l^-$, ІНДУКОВАНОМУ НЕЙТРАЛЬНИМ СТРУМОМ, ЯКИЙ ЗМІНЮЄ АРОМАТ

О.Ю. Корчин, В.А. Ковальчук, Д.О. Лазаренко

Досліджено повний диференційний кутовий розподіл рідкого розпаду $\bar{B}_d^0 \to \bar{K}^{*0} (\to K^- \pi^+) e^+ e^-$, індукованого нейтральним струмом, який змінює аромат. Акцентовано увагу на акуратному розгляді вкладів від процесів $\bar{B}_d^0 \to \bar{K}^{*0} (\to K^- \pi^+) V$ з проміжними векторними резонансами $V = \rho(770)$, $\omega(782),\ \phi(1020),\ J/\psi,\ \psi(2S), \ldots$, які розпадаються на e^+e^--пару. Використані дві версії моделі векторної домінантності для переходу $V\gamma$. Відносна ймовірність розпаду, частка повздовжньої поляризації $\bar{K}^{*0}$ мезона, поперечна асиметрія $A_T^{(2)}$ та асиметрія “вперед-назад” порівнюються з даними BaBar та CDF, а також виконані передбачення для експериментів LHCb та B-фабрик.