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On the recent anomalies in semileptonic B decays

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Abstract. Both BABAR and LHCb Collaborations have recently claimed signals of possible deviations with respect to the Standard Model through the analyses of specific semileptonic B–meson decays. We firstly investigate the semileptonic $b \to c$ decay with a τ lepton in the final state for which new BABAR measurements are available, showing a deviation from the Standard Model at 3.4 σ level. We study the effects of a new tensor operator in the effective weak Hamiltonian on a set of observables, in semileptonic $B \to D^{(*)}$ modes as well as in semileptonic B and B_s decays to excited charmed mesons. Moreover, we discuss the phenomenology of the mode $B \to K^*\ell^+\ell^-$, in the framework of a warped extra-dimensional model. Since a complete set of form factor almost independent observables have been recently measured by the LHCb Collaboration, with few sizable deviations with respect to the Standard Model in some of them, it would be interesting to put constraints on such a scenario from the FCNC transition $b \to s\ell^+\ell^-$.

1 Semileptonic B–meson decays with a τ lepton in the final states

The semileptonic decays $B \to D^{(*)}\tau\bar{\nu}_\tau$ play an important role in the search of New Physics (NP) in charged–current interactions. The BABAR measurements of the rates of B^- and $\bar{B}^0$ semileptonic decays into $D^{(*)}$ and a τ lepton deviate significantly from the Standard Model (SM) expectation. The experimental results for the $B \to D^{(*)}\tau\bar{\nu}_\tau$ decay widths normalized to the widths of the corresponding modes having a light $\ell = e, \mu$ lepton in the final state are [1]: $\mathcal{R}^-(D) = \frac{\mathcal{B}(B^-\to D^0\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^-\to D^0\ell^-\bar{\nu}_\ell)} = 0.429 \pm 0.082 \pm 0.052$, $\mathcal{R}^-(D^*) = \frac{\mathcal{B}(B^-\to D^{*0}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^-\to D^{*0}\ell^-\bar{\nu}_\ell)} = 0.322 \pm 0.032 \pm 0.022$, $\mathcal{R}^-(D) = \frac{\mathcal{B}(B^-\to D^0\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^-\to D^0\ell^-\bar{\nu}_\ell)} = 0.429 \pm 0.082 \pm 0.052$ and $\mathcal{R}^0(D^*) = \frac{\mathcal{B}(\bar{B}^0\to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0\to D^{*+}\ell^-\bar{\nu}_\ell)} = 0.355 \pm 0.039 \pm 0.021$ (where the first and second error are the statistic and systematic uncertainty, respectively). The measurements deviate at the global level of 3.4σ with respect to SM predictions [1, 2].

Due to the presence of heavy quarks and the τ lepton, these channels are sensitive to particles with large couplings to the heavier fermions, such as charged scalars which could contribute to the tree–level $b \to c\ell\bar{\nu}$ transition [2]. It is worth mentioning that, before these observations in the semileptonic $b \to c$ channel, the first experimental analyses of the purely leptonic $B^- \to \tau^-\bar{\nu}_\tau$ decay also revealed an excess of events. However, new Belle [3] and BABAR [4] data seem to exclude a sizable enhancement of the purely leptonic B decay rate.

The mentioned experimental developments suggest us to put our efforts, first, on the level of accuracy of the SM predictions for the measured observables – the ratios $\mathcal{R}(D^{(*)})$. Second, we are prompted

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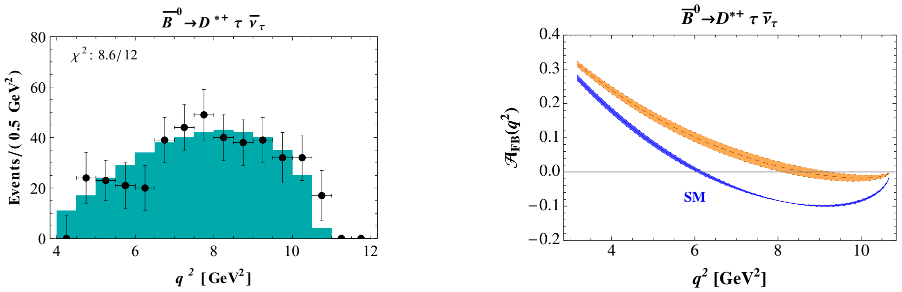

Figure 1. (left) $d\Gamma(B \to D^* \tau \bar{\nu}_\tau)/dq^2$distributions in the NP scenario (for the central value of ϵ_T, shaded histograms) compared to BaBar data (points) [10]; the distributions are normalized to the total number of events. (right) Forward-backward asymmetry $\mathcal{A}_{FB}(q^2)$. The lower (blue) curves are the SM predictions, the upper (orange) bands the NP expectations.

to speculate on which kind of NP scenario, if any, could modify the semileptonic observables without altering the purely leptonic modes. Several analyses tried to explain the anomaly within a NP framework in which new scalars couple to leptons proportionately to the lepton mass, to guarantee the enhancement of the τ modes. This is what happens in models with two Higgs doublets (2HDM), however the simplest of such scenarios has been ruled out by the BABAR Fit [1].

Concerning the first point, we reanalyze the SM prediction for $B \to D^{(*)} \ell \bar{\nu}_\ell$, taking into account the main source of uncertainties and possible improvements. The hadronic matrix elements which characterize these decays depend on several hadronic form factors, which in the infinite heavy quark mass limit formalized by the heavy-quark effective theory (HQET), can all be related to the Isgur-Wise function ξ [5]. At the next–to–leading order we include corrections, based on both experimental and theoretical inputs. It is worth noticing that both $1/m_Q$ corrections and the QCD ones (worked out by Caprini et al. in [6]), are not sizably effective on the central value of the heavy quark predictions, which turn out to be $\mathcal{R}^0(D)|_{SM} = 0.324 \pm 0.022$ and $\mathcal{R}^0(D^*)|_{SM} = 0.250 \pm 0.003$, respectively.

Coming to the second point, we consider the $b \to c \ell \bar{\nu}_\ell$ effective Hamiltonian including the SM terms plus an additional operator [7–9]:

$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{cb} \left[\bar{c}\gamma_\mu(1-\gamma_5)b\,\bar{\ell}\gamma^\mu(1-\gamma_5)\bar{\nu}_\ell + \epsilon_T^\ell\,\bar{c}\sigma_{\mu\nu}(1-\gamma_5)b\,\bar{\ell}\sigma^{\mu\nu}(1-\gamma_5)\bar{\nu}_\ell \right] \ , \tag{1}$$

where G_F is the Fermi constant and V_{ij} are elements of the CKM mixing matrix. Such an operator could naturally emerge in models with leptoquarks (moreover we assume that the main coupling is to the heaviest lepton). By parameterizing the effective coupling as $\epsilon_T = |a_T|e^{i\theta} + \epsilon_{T_0}$, we are able to constrain from the experimental data the allowed region of variability of ϵ_T on the complex plain, which reads: $Re[\epsilon_{T_0}] = 0.17$, $Im[\epsilon_{T_0}] = 0$, $|a_T| \in [0.24, 0.27]$ and $\theta \in [2.6, 3.7]$ rad.

We afford our attention to differential distributions and by allowing the ϵ_T to range in the region found above, we calculate the differential decay widths for both the channels $B \to D^{(*)} \tau \bar{\nu}_\tau$. We may observe no deviations in the normalized distributions with respect to SM, as the BABAR Collaboration found (Fig. 1). Moreover, an observable in which the sensitivity to the new Dirac structure is maximal is provided by the leptonic forward-backward $\mathcal{A}_{FB}(q^2)$ asymmetry, defined as: $\mathcal{A}_{FB}(q^2) = [\int_0^1 d\cos\theta_\ell \frac{d\Gamma}{dq^2 d\cos\theta_\ell} - \int_{-1}^0 d\cos\theta_\ell \frac{d\Gamma}{dq^2 d\cos\theta_\ell}]/\frac{d\Gamma}{dq^2}$. While in the $B \to D$ channel we notice no significant deviation in the shape of the distribution with respect to SM, in the $B \to D^*$ channel we obtain a sizable shift of the zero of the distribution (at $q^2 \approx 8.7$ GeV^2) with respect to that of the SM (at $q^2 \approx 6.2$ GeV^2) (Fig. 1).

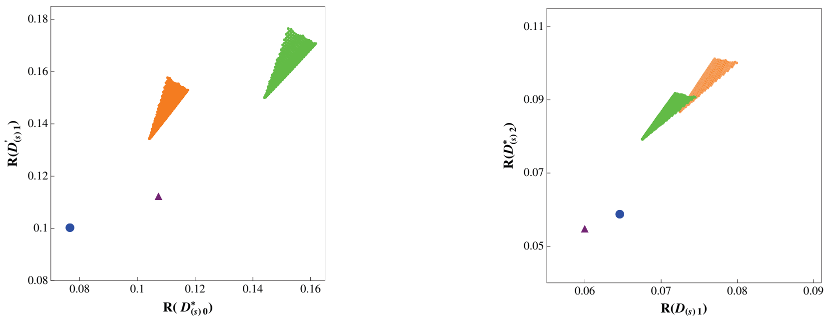

Figure 2. (left) Correlations between the ratios $\mathcal{R}(D^*_{(s)0})$ and $\mathcal{R}(D'_{(s)1})$ for mesons belonging to the $(D^*_{(s)0}, D'_{(s)1})$ doublet without (orange, dark) and with strangeness (green, light). (right) Correlation between $\mathcal{R}(D_{(s)1})$ and $\mathcal{R}(D^*_{(s)2})$ for mesons in the $(D_{(s)1}, D^*_{(s)2})$ doublet. The dots (triangles) correspond to the SM results for mesons without (with) strangeness.

Finally, in order to make our model more predictive , we investigate also the phenomenology of the exclusive semileptonic B and B_s transitions into excited charmed mesons, which can be affected by the new structure in the effective Hamiltonian. We consider the lightest of such hadrons corresponding to the the quark-model p-wave ($\ell = 1$) mesons, generically denoted as $D^{**}_{(s)}$ consisting of four positive parity states which, in the heavy-quark limit, are collected into two spin doublets $[D^*_{(s)0}, D'_{(s)1}]$ and $[D_{(s)1}, D^*_{(s)2}]$. We find a sizable and correlated increase in the ratios $\mathcal{R}(D^{**}_{(s)})$, in each doublet (Fig. 2).

2 $B \to K^*\ell^+\ell^-$ decays in RS$_C$ model

The rare semileptonic $B \to K^*\ell^+\ell^-$ decay is usually recognized as particularly sensitive to NP effects, mainly due to the numerous observables that can be studied to disentangle additional new particle contributions in this loop-driven transition. The analyses at LHC have enlarged the set of measured observables, although several measurements were already available from B factories. Recent LHCb investigations show some discrepancies with respect to the SM in a set of 24 measurements, which comprise selected angular distributions of the mode $B^0 \to K^{*0}\mu^+\mu^-$ [11, 12]. These outstanding results, induced a stimulating debate aimed at understanding the anomalies and in which directions NP searches should be addressed. In this paper we describe the study in [14] that reconsiders the phenomenology of $B \to K^*\ell^+\ell^-$ mode in the specific framework of a warped extra dimensional scenario provided by the Randall–Sundrum (RS) model [13], which has been originally proposed in order to solve the hierarchy problem within the electroweak theory.

The effective $\Delta B = -1$, $\Delta S = 1$ Hamiltonian governing the rare transition $b \to s\ell^+\ell^-$ can be written as

$$H^{eff} = -4\,\frac{G_F}{\sqrt{2}} V_{tb}V^*_{ts}\left\{C_1O_1 + C_2O_2 + \sum_{i=3,..,6} C_iO_i + \sum_{i=7,..,10}\left[C_iO_i + C'_iO'_i\right]\right\}, \tag{2}$$

Among the operators, the primed ones have opposite chirality with respect to the unprimed. Only the unprimed ones, for $i = 7, \ldots 10$, are present in the SM (for definitions see [14]). Considering the subsequent resonant $K^* \to K\pi$ decay, the $B \to K^*(\to K\pi)\ell^+\ell^-$ fully differential decay width can be written in a compact form as [15]:

$$\frac{d^4\Gamma(B \to K^*[\to K\pi]\ell^+\ell^-)}{dq^2 d\cos\theta_\ell d\cos\theta_K d\phi} = \frac{9}{32\pi} I(q^2, \theta_\ell, \theta_K, \phi)\ , \tag{3}$$

where $I(q^2, \theta_\ell, \theta_K, \phi)$ is a function of the dilepton invariant mass (q^2), the angle between the Kaon direction and the direction opposite to the B meson one in the K^* rest frame (θ_K), the angle between the charged lepton direction and the direction opposite to that the B meson in the lepton pair rest frame (θ_ℓ), and finally the angle between the plane containing the lepton pair and the plane containing the K^* decay products, (ϕ). The function I can be written in terms of transversity amplitudes, which in turn are functions of the $B \to K^*$ form factors (see [15] for the definitions). Starting from these quantities, several observables can be introduced. In particular, here we consider the binned observables S_i, with their numerators and denominators separately integrated over q^2 bins $[q_1^2, q_2^2]$, of the kind $< S_i >_{[q_1^2, q_2^2]}$, that will be compared to the experimental results. Results that have raised interest are those reported by the LHCb Collaboration, with the measurement of the observables [15, 16]:

$$P'_{i=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1-F_L)}} \tag{4}$$

related to F_L (the longitudinal K^* polarization fraction) and S_i. A discrepancy is found in the case of P'_5 in the third q^2 bin, while a small deviation is also found in P'_4 for another value of q^2. The quoted combined discrepancy, in the region $1.0 < q^2 < 6.0$ GeV^2, is of 2.5σ. Efforts have been devoted to identify the kind of NP effects which may explain the full data set without altering the observables in agreement with SM predictions. The general idea is to try to understand which one of the Wilson coefficients (and how many of them) should be modified (increased/suppressed), including those not present in SM, to reproduce the data [17–19]. In the phenomenological approach that we adopt [14, 20], the effective weak Hamiltonian emerges from the specific RS$_C$ model, whose flavor structure generates from the enlarged gauge group: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{L,R}$ (see [21–23] for details). The resulting Wilson coefficients in the effective Hamiltonian (2), which are modified with respect to SM as: $C_i^{(\prime)} = C_i^{(\prime)SM} + \Delta C_i^{(\prime)}$ with $i = 7, 9, 10$, are therefore correlated, and such a correlation has precise phenomenological consequences to be considered in the various observables, namely those in (4).

The contributions $\Delta C_{9,10}^{(\prime)}$, derived in [24], originate from the tree–level flavor changing neutral currents where a neutral X boson is exchanged. These X_s are in order, the SM Z boson plus three exotic states, namely two Z' type bosons and the first excitation of the photon. Instead $\Delta C_7^{(\prime)}$ originate from loop driven elementary processes involving dipole operator in the transition $b \to s\gamma$. In [14] we have calculated the coefficient in the effective 4D scenario keeping only the dominant contribution of the first KK mode in the case of the intermediate gluon and Higgs fields exchanged in the loops. For the intermediate fermions we consider only the zero modes (for details see [14]). The largest deviations with respect to SM that we obtained scanning over the parameter space of the model are: $|\Delta C_7|_{max} \simeq 0.046$, $|\Delta C'_7|_{max} \simeq 0.05$, $|\Delta C_9|_{max} \simeq 0.0023$, $|\Delta C'_9|_{max} \simeq 0.038$, $|\Delta C_{10}|_{max} \simeq 0.030$, $|\Delta C'_{10}|_{max} \simeq 0.50$. Then, we can compare the observables measured by LHCb with our results obtained by allowing the Wilson coefficients to simultaneously vary in those ranges that emerged by scanning the parameter space. The results for $P'_{(4,5)}$ are collected in Fig. 3, in which the SM results include the hadronic uncertainties. We may observe that the deviations induced in RS$_C$ are smaller than the non-perturbative theory uncertainties, since the corrections $\Delta C_{9,10}$ are tiny fractions of $C_{9,10}^{SM}$ and that also the coefficients of operators absent in SM, $\Delta C'_{9,10}$ are small; this is a non trivial result. A little effect is found at small q^2, where the changes due to $\Delta C_7^{(\prime)}$ are slightly larger. As a remark, we note that in P'_5 the hadronic uncertainty is at the level of 10% in all the q^2 range; the discrepancy with the measurement in the third q^2 bin still persists, while there is agreement in the other bins.

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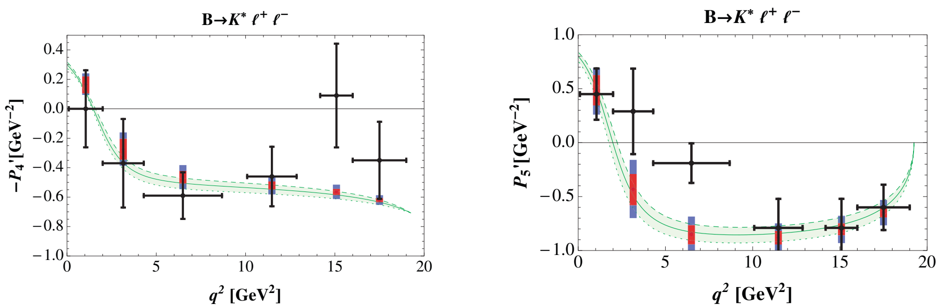

Figure 3. (left) Observable P'_4 in $B^0 \to K^{*0}\mu^+\mu^-$. The red and blue vertical bars correspond to the RS$_c$ result, without or with the uncertainty in form factors. The black dots, with their error bars, are the LHCb measurements in Ref. [12], the sign is fixed to make the definition (4) and the one in [12] compatible. (right) Observable P'_5 in $B^0 \to K^{*0}\mu^+\mu^-$.

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