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# On the recently observed tensions in B decays

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**Summary.** — In the LHC era, the discovery of New Physics signals is the major ambition of the high-energy physics community and flavor physics can provide access to new heavy particles (Kaluza-Klein modes, supersymmetric particles ...) in complementary way with respect to direct searches. Signals of possible deviations with respect to the Standard Model have been recently claimed both by BABAR and LHCb through the analyses of specific semileptonic $B$-meson decays. First, I'll focus on semileptonic $b \to c$ decay with a $\tau$ lepton in the final states for which new BABAR measurements are available, showing a deviation from the Standard Model at 3.4 $\sigma$ level. I 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, I 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 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 $b \to s \ell^+ \ell^-$.

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## 1. – Semileptonic $B$-meson decays with a $\tau$ lepton into final states

The BABAR measurements of the rates of $B^-$ and $\bar{B}^0$ semileptonic decays into $D^{(*)}$ and a $\tau$ lepton significantly deviate 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 $3.4\sigma$ with respect to SM predictions [1, 2].

The semileptonic decays $B \to D^{(*)}\tau\bar{\nu}_\tau$ are suitable enough to unveil the effects of New Physics (NP) in charged-current interactions. In fact, the presence of heavy quarks and the $\tau$ lepton is 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 exclude a sizable enhancement of the purely leptonic $B$ decay rate.

The recent developments in the measurements of $B$ decays with leptons belonging to the third family in the final products, drive us to put our efforts on two separate issues. The first one is related to the level of accuracy of the SM predictions for the measured observables – the ratios $\mathcal{R}(D^{(*)})$. The second one concerns 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 $\tau$ 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]. Other variants of the 2HDM together with other models providing explicit flavor violation, might explain the measurements. Nevertheless, an enhancement of the purely leptonic $B$ decay rate is generally implied.

Concerning the first question, I 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 $\xi$ [5]. At the next-to-leading order I 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, I consider the $b \to c\ell\bar{\nu}_\ell$ effective Hamiltonian including the SM terms plus an additional operator [7-9]:

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

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 I assume that the main coupling is to the heaviest lepton). By parameterizing the effective coupling as $\epsilon_T = |a_T|e^{i\theta} + \epsilon_{T_0}$, I am able to constrain from the experimental data the allowed region of variability of $\epsilon_T$ on the complex plain, which reads: $\text{Re}[\epsilon_{T_0}] = 0.17$, $\text{Im}[\epsilon_{T_0}] = 0$, $|a_T| \in [0.24, 0.27]$ and $\theta \in [2.6, 3.7]$ rad.

I afford my attention to differential distributions and by allowing the $\epsilon_T$ to range in the region found above, I calculate the differential decay widths for both the channels $B \to D^{(*)}\tau\bar{\nu}_\tau$. I 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: $\mathcal{A}_{FB}(q^2) = [\int_0^1 \mathrm{d}\cos\theta_\ell \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_\ell} - \int_{-1}^0 \mathrm{d}\cos\theta_\ell \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_\ell}]/\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}$. While in the $B \to D$ channel I notice no significantly devia-

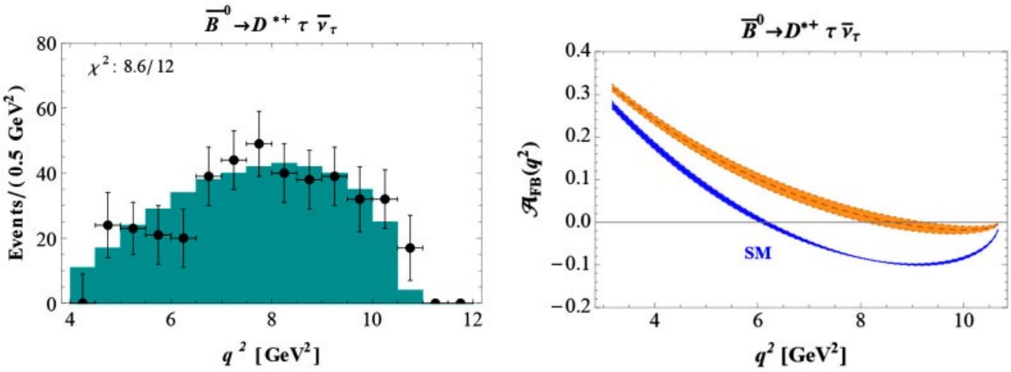


Fig. 1. – Left: $\mathrm{d}\Gamma(B \to D^* \tau \bar{\nu}_\tau)/\mathrm{d}q^2$ distributions in the NP scenario (for the central value of $\epsilon_T$, shaded histograms) compared to BaBar data (points) [10]; the distributions are normalized to the total number of events. Right: Forward-backward asymmetry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

tion in the shape of the distribution with respect to SM, in the $B \to D^*$ channel I obtain a sizable shift of the zero of the distribution (at $q^2 \approx 8.7\,\mathrm{GeV}^2$) with respect to that of the SM (at $q^2 \approx 6.2\,\mathrm{GeV}^2$).

Finally, in order to get more predictive the model, I investigate also the phenomenology of those exclusive semileptonic $B$ and $B_s$ transitions into excited charmed mesons, which can be affected by the new structure in the effective Hamiltonian. The lightest multiplet of such hadrons considered in the analysis corresponds to the the quark-model $p$-wave ($\ell = 1$) mesons, and it is generically denoted $D^{**}_{(s)}$ comprising four positive-parity states which, in the heavy-quark limit, form two spin doublets $[D^*_{(s)0},\, D'_{(s)1}]$ and $[D_{(s)1},\, D^*_{(s)2}]$. I find that the tensor operator produces a sizable increase in the ratios $\mathcal{R}(D^{**}_{(s)})$, which is correlated for the two members in each doublet (fig. 2). Moreover, the hadronic uncertainty is mild.

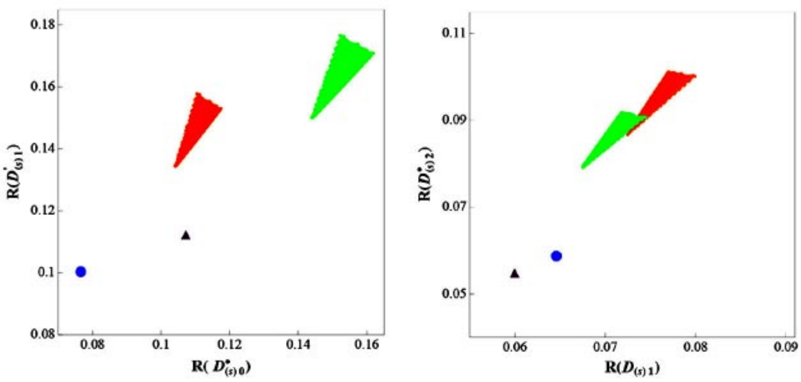


Fig. 2. – Left: Correlations between the ratios $\mathcal{R}(D^*_{(s)0})$ and $\mathcal{R}(D'_{(s)1})$ for mesons belonging to the $(D^*_{(s)0},\, D'_{(s)1})$ doublet without (orange, dark) and with strangeness (green, light). Right: Correlation between $\mathcal{R}(D_{(s)1})$ and $\mathcal{R}(D^*_{(s)2})$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

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

The rare semileptonic $B \to K^*\ell^+\ell^-$ decay is another process 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. Although several measurements were already available from $B$ factories, analyses at LHC have enlarged the set of measured observables. 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]. Several discussions aimed at understanding the discrepancies and in which directions NP searches should be addressed, arose from these results.

In this paper I illustrate the study in [20], in which I consider the phenomenology of $B \to K^*\ell^+\ell^-$ mode in the framework of the Randall-Sundrum (RS) model [13]. This is an appealing NP scenario for several theoretical motivations, mainly connected with the solution of the hierarchy problem and the origin of the flavor puzzle. From extensive studies about flavor phenomenology in RS, the main problematic issue that emerged is related to the $\epsilon_K$ parameter (that describes the $CP$ violation in the Kaon sector) from which the strongest bound (at the order of dozen of TeV) on the mass scale $M_{KK}$ of the model can be assessed. In order to soften this bound at level accessible to LHC, without to much fine tuning, several solutions have been proposed. One of the most tempting ideas is the so-called custodial symmetry [14], which also ensures the flavor protection of $Zb_L\overline{b_L}$ coupling against large tree-level corrections. I adopt the scenario with an implemented custodial symmetry (RS$_C$) in order to evaluate the selected observables.

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

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

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. Therefore, the operators considered in the analysis are magnetic penguins: $O_7^{(\prime)} = \frac{e}{16\pi^2}m_b(\bar{s}_{L(R)}\sigma^{\mu\nu}b_{R(L)})\,F^{\mu\nu}$ and $O_8^{(\prime)} = \frac{g_s}{16\pi^2}m_b\left[\bar{s}_{L(R)\alpha}\sigma^{\mu\nu}\left(\frac{\lambda^a}{2}\right)_{\alpha\beta}b_{R(L)\beta}\right]\ G^a_{\mu\nu}$ and semileptonic electroweak penguins: $O_9^{(\prime)} = \frac{e^2}{16\pi^2}(\bar{s}_{L(R)\alpha}\gamma^\mu b_{L(R)\alpha})\ \bar{\ell}\gamma_\mu\ell$ and $O_{10}^{(\prime)} = \frac{e^2}{16\pi^2}(\bar{s}_{L(R)\alpha}\gamma^\mu b_{L(R)\alpha})\ \bar{\ell}\gamma_\mu\gamma_5\ell$. $F_{\mu\nu}$ and $G^a_{\mu\nu}$ denote the electromagnetic and the gluonic field strength tensors, respectively, and $e$ and $g_s$ are the electromagnetic and the strong coupling constants. $m_b$ is the $b$ quark mass, while the operators proportional to the strange quark mass $m_s$ are neglected.

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

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

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 ($\theta_K$), the angle between the charged lepton direction and the direction opposite to that the $B$-meson in the lepton pair rest frame ($\theta_\ell$), and finally the angle between the plane containing the lepton pair and the plane containing the $K^*$ decay products, ($\phi$). 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, I consider: 1) the lepton forward-backward (FB) asymmetry $A_{FB}$; 2) the longitudinal $K^*$ polarization fraction $F_L$; 3) 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 [16]

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

related to $F_L$ and $S_i$. The measurement is carried out in 6 bins of $q^2$ for each one of the four observables in (4): a discrepancy is found in the case of $P'_5$ in the third $q^2$ bin, where the datum is sensibly lower than the SM prediction. A small deviation is also found in $P'_4$ for another value of $q^2$. 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 I adopt [20], the effective weak Hamiltonian emerges from the specific RS$_C$ model. The resulting Wilson coefficients are therefore correlated, and such a correlation has precise phenomenological consequences to be considered in the various observables, namely those in (4).

The RS$_C$ model is defined in a five dimensional space-time manifold with coordinates $(x, y)$ ($x$ the ordinary Minkowskian coordinates) and metric

$$\mathrm{d}s^2 = e^{-2ky}\eta_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu - \mathrm{d}y^2, \tag{5}$$

where $\eta_{\mu\nu} = \mathrm{diag}(+1, -1, -1, -1)$. The scale parameter $k$ is chosen $k \simeq \mathcal{O}(M_{Planck})$ to address the hierarchy problem; and set to $k = 10^{19}$ GeV. The (fifth) coordinate $y$ varies in a range between two branes, $0 \le y \le L$; $y = 0$ corresponds to the so-called UV brane, $y = L$ to the IR one. Here, I consider the scenario in which the SM gauge symmetry group is enlarged to the gauge group

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{L,R}, \tag{6}$$

which, together with the metric, defines the Randall-Sundrum model with custodial protection RS$_C$ [14, 21]. The custodial protection is implemented via the additional symmetry $P_{L,R}$ which is a $Z_2$-type symmetry, that prevent large $Z$ coupling to left-handed fermions, strongly constrained by experiments. Two symmetry breakings occur: first, the gauge group (6) is broken to the SM gauge group imposing suitable boundary conditions (BC) on the UV brane. Afterwards, the spontaneous symmetry breaking occurs, which is Higgs-driven as in SM. All the SM fields are allowed to propagate in the bulk, except for the Higgs field which is localized at $y = L$.

The two $SU(2)$ groups require a larger number of gauge bosons. Those corresponding to $SU(2)_L$ are $W_L^{a,\mu}$ $(a = 1, 2, 3)$, while $W_R^{a,\mu}$ correspond to $SU(2)_R$. The $P_{L,R}$ symmetry imposes the equality $g_L = g_R = g$ for the $SU(2)_{L,R}$ gauge couplings. The number of remaining gauge bosons is the same as in SM. Fermions are embedded in suitable representations of the gauge group (6). I refer to ref. [22] for the realization of the fermion sector. The following issues are worth stressing: 1) left-handed doublets are in a bidoublet of $SU(2)_L \times SU(2)_R$, together with two new fermions; 2) right-handed up-type quarks are singlets; no corresponding fields exist in the case of leptons, since the neutrinos are kept left-handed; 3) right-handed down-type quarks and charged leptons are in multiplets that transform as $(3,1)\oplus(1,3)$ under $SU(2)_L \times SU(2)_R$, the multiplets contain additional new fermions; 4) the electric charge reads, in terms of the third component of the $SU(2)_L$ and $SU(2)_R$ isospins and of the charge $Q_X$ : $Q = T^3_L + T^3_R + Q_X$.

The presence of a compact fifth dimension implies the existence of a tower of Kaluza-Klein (KK) excitations for all particle. The boundary conditions discriminate among particles having a SM correspondent form those without SM partners. For each one of the considered fields a KK decomposition of the form : $F(x,y) = \frac{1}{\sqrt{L}} \sum_k F^{(k)}(x) f^{(k)}(y)$, can be performed. The functions $f^{(k)}(y)$ are the 5D field profiles, while $F^{(k)}(x)$ are the corresponding effective 4D fields. The profile can be obtained by solving the 5D equations of motion, before the EWSB is implemented. In this approach, one can treat the ratio $v/M_{KK}$ of the Higgs vacuum expectation value (vev) $v$ and the mass of the lowest KK mode $M_{KK}$ as a perturbation. The effective 4D Lagrangian is obtained after integration over $y$, and the Feynman rules of the model are worked out neglecting terms of $\mathcal{O}(v^2/M^2_{KK})$or higher. Moreover, the bulk profiles $f^{(k)}(y)$ depend on specific parameters that characterize the localization of the fields along the extra-dimension; in the case of fundamental quarks these parameters are constrained by the quark masses, through relations that have been worked out in [23].

In the RS$_C$ model the Wilson coefficient in the effective Hamiltonian (2) are modified with respect to SM as: $C_i^{(\prime)} = C_i^{(\prime)SM} + \Delta C_i^{(\prime)}$, with $i = 7, 9, 10$. 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. The case of $\Delta C_7^{(\prime)}$ is different. This coefficient originates from loop driven elementary processes involving dipole operator in the transition $b \to s\gamma$. I calculate 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 I consider only the zero modes (for details see [20]). In fig. 3 some correlations among $\Delta C_i'$ are depicted. The largest deviations with respect to SM that I obtained scanning over the parameter space of the model are: $|\Delta C_7|_{\max} \simeq 0.046$, $|\Delta C_7'|_{\max} \simeq 0.05$, $|\Delta C_9|_{\max} \simeq 0.0023$, $|\Delta C_9'|_{\max} \simeq 0.038$, $|\Delta C_{10}|_{\max} \simeq 0.030$, $|\Delta C_{10}'|_{\max} \simeq 0.50$. I am now able to compare the observables measured by LHCb with the results obtained by allowing the Wilson coefficients to simultaneously vary in those ranges that emerged by scanning the parameter space. The outcomes are collected in fig. 4, in which the SM results include the hadronic uncertainties. I 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, I 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. Finally, motivated by the experimental results of semileptonic and leptonic $B$ decays to

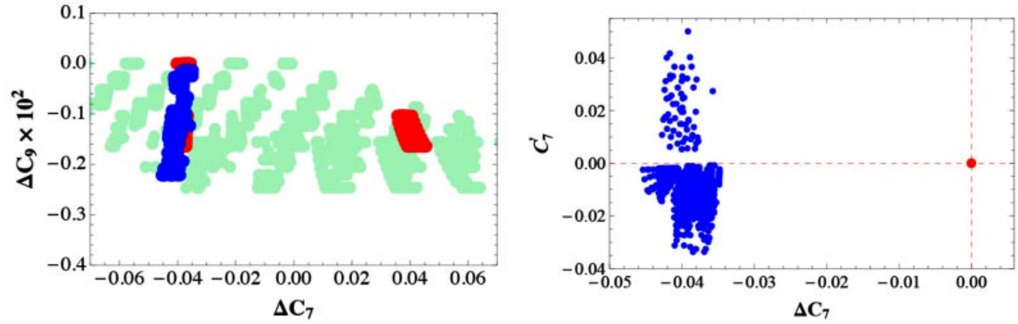


Fig. 3. – Left: $\Delta C_7(m_b)$ *vs.* $\Delta C_9$ obtained implementing sequential constraints. The light green points correspond to the constraints from $|V_{us}|$ and $|V_{ub}|$, the red points to the constraint from $|V_{cb}|$ and $|V_{ub}|$, the blue points to the further constraints from $\mathcal{B}(B \to K^* \mu^+ \mu^-)_{exp}$ and $\mathcal{B}(B \to X_s \gamma)_{exp}$. Right: Correlations between the $\mathrm{RS}_C$ contribution to the Wilson coefficients $C_7^{(\prime)}$. The coefficients $\Delta C_7^{(\prime)}$ are evaluated at the scale $\mu_b = m_b$. No correction corresponds to the red dot.

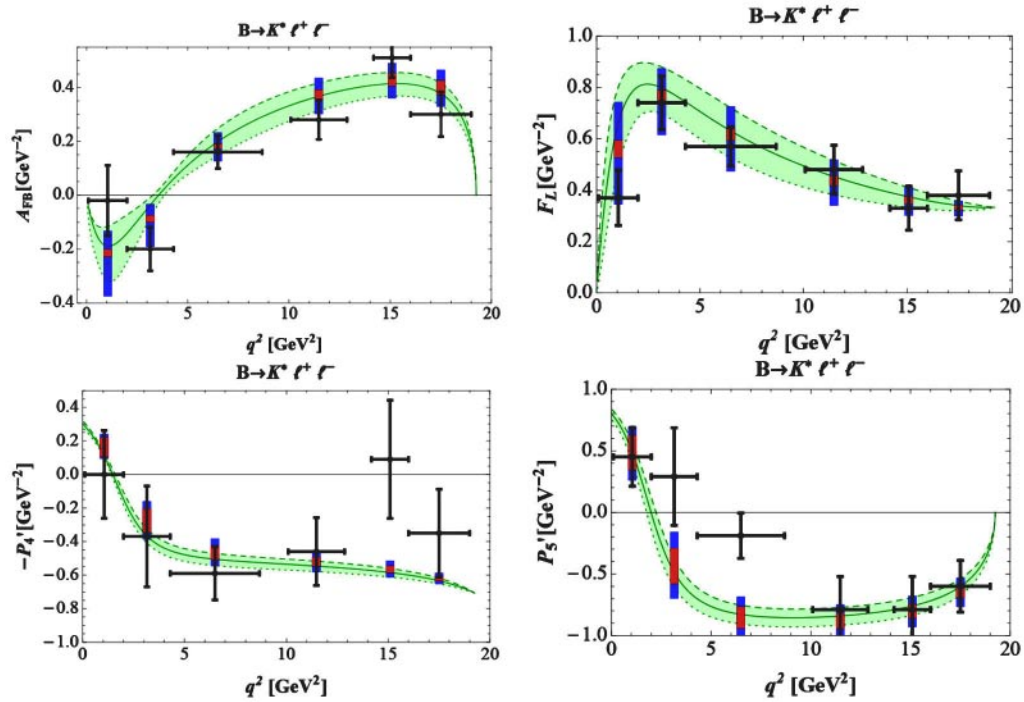


Fig. 4. – Top left: Lepton FB asymmetry in $B^0 \to K^{*0} \mu^+ \mu^-$; the red and blue vertical bars correspond to the $\mathrm{RS}_c$ result, without or with the uncertainty in form factors. The black dots, with their error bars, are the LHCb measurements in [12]. Top right: $K^*$ longitudinal polarization fraction in $B^0 \to K^{*0} \mu^+ \mu^-$. Bottom left: Observable $P_4'$ in $B^0 \to K^{*0} \mu^+ \mu^-$.The sign is fixed to make the definition (4) and the one in ref. [12] compatible. Bottom right: Observable $P_5'$ in $B^0 \to K^{*0} \mu^+ \mu^-$.

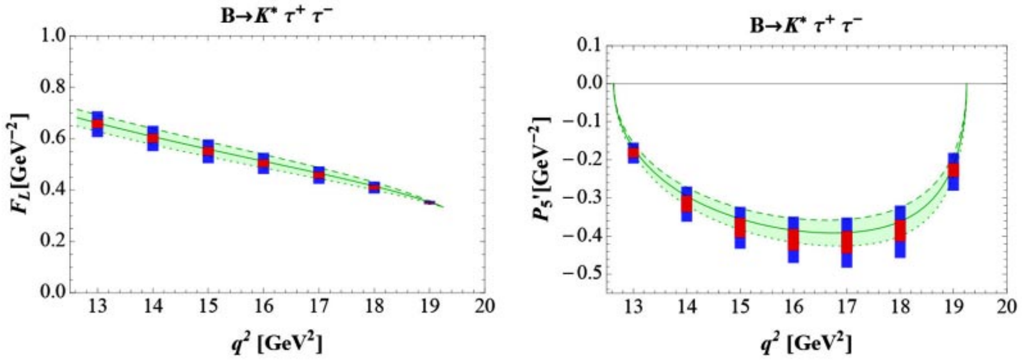


Fig. 5. – Left: Observable $F_L$ in $B^0 \to K^{*0}\mu^+\mu^-$, the symbols have the same meaning as in fig. 4. Right: Observable $P'_5$ in $B^0 \to K^{*0}\tau^+\tau^-$.

$\tau$ leptons, I also study observables for the case of massive final leptons. The results for the case of $\tau^+\tau^-$ final state are shown in fig. 5. The kinematically accessible $q^2$ range starts at $q^2 \simeq 12.628\,\text{GeV}^2$, so that the small effects in the muon mode at low $q^2$ do not appear in this case.

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