Messages on Flavour Physics Beyond the Standard Model

Andrzej J. Buras

aPhysics Department, Technical University Munich
D-85748 Garching, Germany

I present a brief summary of the main results on flavour physics beyond the Standard Model that have been obtained in 2008 by my collaborators and myself at the TUM. In particular I list main messages coming from our analyses of flavour and CP-violating processes in Supersymmetry, the Littlest Higgs model with T-Parity and a warped extra dimension model with custodial protection for flavour violating Z boson couplings.

1. Overture

Elementary particle physicists are eagerly awaiting the first messages from the LHC which, if we are lucky, will signal not only the discovery of the Higgs but also the existence of a definitive new physics beyond the Standard Model (SM) of elementary interactions of quarks and leptons.

We need more than the SM in order to understand several observed facts, in particular the huge hierarchy between the Planck scale and the electroweak scale and the hierarchies in quark and lepton mass spectra and in their flavour violating interactions summarized by the CKM and PMNS mixing matrices, respectively. There are of course many other known reasons for going beyond the SM and expecting new physics at scales probed by the LHC but I will not repeat them here. While a large fraction of particle physicists bets that this new physics will be supersymmetry, the turbulences on stock markets in this decade teach us that it is wise to have many different shares.

In this note I would like to report on the results of various analyses of physics beyond the SM performed by my young and strong collaborators and myself at the Technical University Munich in 2008 [1,2,3,4,5,6,7,8,9]. All our papers deal with flavour violating processes, in particular CP-violating ones. While in these papers we have hopefully cited properly all relevant papers, the list of references presented here is incomplete and I apologize for it.

2. $\varepsilon_K$ – An Old Star Strikes Back

One of the many successes of the SM is particularly striking. The SM is consistent within theoretical and parametric uncertainties simultaneously with $|\varepsilon_K| \approx 2.2 \cdot 10^{-3}$ that measures tiny $K^0 - \bar{K}^0$-mixing induced CP violation in $K_L \to \pi\pi$ decays and $S_{\psi K_s} \approx 0.67$ that measures similar CP violation in the $B^0_d - \bar{B}^0_d$ mixing. As $S_{\psi K_s}$ is practically free of any non-perturbative uncertainties and $\varepsilon_K$ involves the non-perturbative parameter $\hat{B}_K$, it was $S_{\psi K_s}$ and not $\varepsilon_K$ that together with the ratio of the $B_{d,s} - \bar{B}_{d,s}$ mass differences $\Delta M_d/\Delta M_s$ dominated unitarity triangle fits for the last five years.

This situation may change soon due to the following recent developments:

- Improved lattice calculations of $\hat{B}_K$. In particular a recent simulation with dynamical fermions results in $\hat{B}_K = 0.72 \pm 0.04$ [10] that should be improved in the coming months,

- Inclusion of additional corrections to $\varepsilon_K$ [1] that were usually neglected in the literature in view of the 20% error on $\hat{B}_K$. As this parameter is now much better known it is mandatory to include them. Effectively
these new corrections can be summarized by an overall factor in $\varepsilon_K$: $\kappa_\varepsilon = 0.92 \pm 0.02$ \cite{11}.

- As pointed out in \cite{11} the decrease of $\hat{B}_K$ relative to previous lattice results, that were in the ballpark of 0.80, together with $\kappa_\varepsilon$ being significantly below unity implies within the SM a tension between the very precisely measured value of $S_{\psi K_S}$ and $\varepsilon_K$.

Indeed $S_{\psi K_S} = \sin 2\beta = 0.671 \pm 0.024$ implies within the SM \cite{2}:

$$|\varepsilon_K|^{\text{SM}} = (1.78 \pm 0.25) \times 10^{-3}, \quad (1)$$

to be compared with

$$|\varepsilon_K|^{\text{exp}} = (2.229 \pm 0.012) \times 10^{-3}. \quad (2)$$

If confirmed by a more precise value of $\hat{B}_K$ and more precise values of the CKM parameters, in particular $V_{cb}$, this would signal new physics in $\varepsilon_K$. Alternatively, no new physics in $\varepsilon_K$ would imply $\sin 2\beta = 0.88 \pm 0.11$ \cite{1111} which could only be made consistent with the measured value of $S_{\psi K_S}$ by introducing a new phase $\phi_{\text{new}}$ in $B_s^0 - \bar{B}_s^0$ mixing so that

$$S_{\psi K_S} = \sin(2\beta + 2\phi_{\text{new}}) = 0.671 \pm 0.024 \quad (3)$$

with $\phi_{\text{new}} \approx -9^\circ$. Other possibilities in which new physics would enter simultaneously in the $K$ and $B$ systems are discussed in \cite{112}. Moreover it is observed in \cite{11} that a new phase $\phi_{\text{new}}$ in $B_s^0 - \bar{B}_s^0$ mixing with $\phi_{\text{new}} \approx \phi_{\text{new}}$ would imply the sign and the magnitude of the CP asymmetry $S_{\psi\phi}$ in accordance with the findings of CDF and D0 which will be discussed below.

Assuming that significant new physics contributions are present in $\varepsilon_K$, we explore in \cite{2} a number of possibilities to achieve an agreement with the experimental value of $\varepsilon_K$. In particular we point out that within the CMFV framework (constrained minimal flavour violation) this tension could be removed with interesting implications for the allowed values of the $B$-meson decay constants and/or branching ratios of rare $K$ decays. On the other hand the MSSM with MFV and large $\tan \beta$ appears to worsen the situation. A few observations are also made in the context of non-MFV new physics scenarios.

3. LHT Facing CP-Violation in $B_s^0 - \bar{B}_s^0$ Mixing

Another highlight of flavour physics in 2008 were the hints of a large new CP phase in $B_s^0 - \bar{B}_s^0$ mixing indicated by CDF and D0 data \cite{11313134}. They imply the mixing induced CP asymmetry $S_{\psi\phi}$ in the ballpark of 0.4, one order of magnitude larger than its SM value: $(S_{\psi\phi})_{\text{SM}} \approx 0.04$. Related studies by theorists can be found for instance in \cite{15161718}. If this large value is confirmed with a small error, we will have a clear signal of new CP-violating interactions beyond CKM, falsifying thereby the concept of minimal flavour violation (MFV).

A prominent model that goes beyond MFV is the LHT model in which the interactions between the SM quarks and the new heavy mirror quarks mediated by new heavy weak gauge bosons involve a mixing matrix different from the CKM matrix and consequently a new source of flavour and CP violation. Already in 2006 we have pointed out that in this model $S_{\psi\phi}$ as large as 0.3 could be obtained \cite{19}. Our updated 2008 analysis \cite{3} shows that $S_{\psi\phi}$ can easily reach in the LHT model values $0.15 - 0.20$, while higher values are rather unlikely though not excluded.

Large enhancements are also possible in the branching ratios for $K_L \rightarrow \pi^0 \nu \bar{\nu}$, $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 l^+ l^-$ \cite{20212220} with much more modest effects in $B_{s,d} \rightarrow \mu^+ \mu^-$ \cite{20}. Finally the tension between $\varepsilon_K$ and $S_{\psi K_S}$ mentioned above can easily be resolved in this model.

4. Low Energy Probes of CP Violation in a Flavour Blind MSSM

All tensions between the SM and the data mentioned above can be removed in a general MSSM with new flavour violating interactions coming predominantly from the soft sector. However, the large number of parameters in this framework does not allow for clear-cut conclusions. On the other hand the MSSM with MFV is already rather constrained and CP violation and flavour violation being governed solely by the CKM matrix in MSSM-MFV are SM-like.

In this context an interesting alternative is the
flavour blind MSSM (FBMSSM) \cite{22,23,24,25,26} in which CKM remains to be the only source of flavour violation but new CP-violating and \textit{flavour conserving} phases are present in the soft sector. This new physics scenario is characterized by a number of new parameters that is much smaller than encountered in a general MSSM (GMSSM) and RS models discussed below. This implies striking correlations between various observables that can confirm or exclude this scenario in the coming years.

The main actors in the analysis of the FBMSSM in \cite{4} are the CP asymmetry $S_{\phi K_S}$ that experimentally is found below its SM value, electric dipole moments of neutron and electron, the direct CP asymmetry $A_{\text{CP}}(b \to s\gamma)$ and again $\varepsilon_K$.

We find that $S_{\phi K_S}$ can be made consistent with the experimental data but this requires sufficiently large values of the new flavour conserving phases and automatically implies:

- lower bounds on the electron and neutron electric dipole moments $d_{e,n} \geq 10^{-28}$e cm,
- positive and sizable (non-standard) $A_{\text{CP}}(b \to s\gamma)$ in the ballpark of 2% - 6%, that is roughly by an order of magnitude larger than its SM value.
- under very mild assumptions also the $(g - \frac{2}{3})_\mu$ anomaly can be explained.

On the other hand $S_{\phi \psi}$, $S_{\phi K_S}$ and $\Delta M_d/\Delta M_s$ remain SM like but $|\varepsilon_K|$ turns out to be uniquely enhanced over its SM value up to a level of 15%.

This is certainly welcome in view of the discussion in Section 2. Clearly, it will be very exciting to monitor the upcoming LHC, LHCb, Belle upgrade and eventually Super-B factory in this and in the next decade to see whether this simple and predictive framework can be made consistent with the data.

5. A Goldmine of Observables: $B \to K^*\mu^+\mu^-$

In the difficult times at financial markets a goldmine is a very useful thing to have. Such a goldmine is provided by the exclusive decay $B \to K^*(\to K\pi)\mu^+\mu^-$ which will be studied in detail at LHCb. Indeed various CP averaged symmetries and CP asymmetries resulting from angular distributions offer 24 observables which will provide an impressive amount of experimental numbers that will help to distinguish between various NP scenarios. Model independent analyses of \cite{26,27,28} have recently been generalized in \cite{5}, where also specific models like MFV, the MSSM with MFV, the FBMSSM, the LHT and the GMSSM have been analyzed. Moreover a number of correlations have been identified. Several of the CP averaged observables discussed in \cite{5} can be considered as generalizations of the forward-backward asymmetry in $B \to K^*\mu^+\mu^-$. The pattern of the zeros for these new asymmetries in a given model should be useful in identifying the correct model or at least bound severely its parameters. One of the important results of our studies is that new CP-violating phases will produce clean signals in CP-violating asymmetries.

Probably the most interesting results are found in the FBMSSM, in which several symmetries and asymmetries differ significantly, even by orders of magnitude, from the SM results and there exists a number of striking correlations between these new observables and $A_{\text{CP}}(b \to s\gamma)$ and $S_{\phi K_S}$. The NP effects in the LHT model are rather modest except for a few CP asymmetries which are very strongly suppressed in the SM.

6. Observables of $b \to s\nu\bar{\nu}$ Decays in the SM and Beyond

The rare decay $B \to K^*\nu\bar{\nu}$ is regarded as one of the important channels in $B$ physics as it allows a transparent study of $Z$ penguin and other electroweak penguin effects in NP scenarios in the absence of dipole operator contributions and Higgs (scalar) penguin contributions that are often more important than $Z$ contributions in $B \to K^*\mu^+\mu^-$ and $B_s \to \mu^+\mu^-$ decays \cite{29,30}. In \cite{6} we presented a new analysis of $B \to K^*\nu\bar{\nu}$ with improved formfactors and an update of $B \to K\nu\bar{\nu}$ and $B \to X_s\nu\bar{\nu}$ in the SM and in a number of NP scenarios. In particular various MSSM scenarios, the LHT model and a singlet scalar extension of the SM. The results for the
SM and NP scenarios can be transparently summarized in an \((\bar{\epsilon}, \bar{\eta})\) plane analogous to the known \((\bar{q}, \bar{\eta})\) plane with a non-vanishing \(\eta\) signalling this time not CP violation but the presence of new right-handed down-quark flavour-violating couplings which can be ideally probed by the decays in question. Measuring the three branching ratios and one additional observable in \(B \to K^* \nu \bar{\nu}\) allows to overconstrain the resulting point in the \((\bar{\epsilon}, \bar{\eta})\) plane with \((\bar{\epsilon}, \bar{\eta}) = (1, 0)\) corresponding to the SM. We point out that correlations with other rare decays offer powerful tests of new physics with new right-handed couplings and non-MFV interactions.

Concerning SM predictions, our result \(Br(B \to K^* \nu \bar{\nu}) = (6.8 \pm 1.0) \cdot 10^{-6}\) is significantly lower than the ones present in the literature. On the other our improved calculation of \(Br(B \to X_d \nu \bar{\nu}) = (2.7 \pm 0.2) \cdot 10^{-5}\) avoids the normalization to the \(Br(B \to X_e e \bar{\nu}_e)\) and, with less than 10\% total uncertainty, is the most accurate to date.

7. **\(\Delta F = 2\) Observables in a Warped Extra Dimension with Custodial Protection Mechanism**

Among the most ambitious proposals to explain the hierarchy between the electroweak scale and the Planck scale [31] as well as of the observed hierarchical pattern of fermion masses and mixings [32,33,34,35,36] are models with a warped extra spatial dimension, where the SM fields, except the Higgs boson, are allowed to propagate in the bulk. These models, called Randall-Sundrum (RS) models, provide a geometrical explanation of the hierarchies in question.

Recently in a series of papers [7,8,9] we have analyzed the electroweak and flavour structure of a specific RS model based on the bulk gauge group

\[ SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{LR}. \]

In this model the \(T\) parameter [37,38] and the coupling \(Z b_L \bar{b}_L\) [39] are protected from new tree level contributions. This allows to satisfy the very precise electroweak constraints with Kaluza-Klein (KK) masses of order \((2 - 3)\) TeV which are in the reach of the LHC.

Here I report first the results of a complete study of \(\Delta S = 2\) and \(\Delta B = 2\) processes in this model including \(\varepsilon_K, \Delta M_K, \Delta M_s, \Delta M_d, A^q_{\text{SL}}, A_{\text{CP}}(B_d \to \psi K_S)\) and \(A_{\text{CP}}(B_s \to \psi \phi)\). These processes are affected in this model by tree level contributions from Kaluza-Klein gluons [30,40,41] and new heavy electroweak gauge bosons \(Z_H\) and \(Z'\), with the latter implied by the custodial protection mechanism.

It is in fact the first analysis in an RS model with this gauge group that

- simultaneously considers all the observables listed above,
- performs the full renormalization group analysis including the full basis of operators \(Q_{\text{VLL}}, Q_{\text{VRR}}, Q_{\text{LR}}\text{ }\text{and } Q_{\text{LL}}\),
- in addition to tree level KK gluon exchanges considered in particular in [41], includes tree level contributions of the two heavy weak gauge bosons \(Z_H\) and \(Z'\) and of the KK photon \(A^{(1)}\).

It is well known by now that in this framework explaining the hierarchies of fermion masses and weak mixing angles through different positions of fermions in the bulk, necessarily leads to non-universalities of gauge couplings to fermions. This in turn implies FCNC transitions at tree level mediated by all neutral gauge bosons present in a given RS model including the SM Z boson.

In the case of \(\Delta S = 2\) transitions most dangerous are KK-gluon exchanges that in the case of \(\varepsilon_K\) lead typically to values of this parameter by one to two orders of magnitude larger than the measured value [41]. Our more detailed analysis in [7] that includes all relevant contributions confirms these findings: the fully anarchic approach to Yukawa couplings where all the hierarchies in quark masses and weak mixing angles are geometrically explained seems implausible and we confirm that the KK mass scale \(M_{KK}\) generically has to be at least \(\sim 20\) TeV to satisfy the \(\varepsilon_K\) constraint. We point out, however, that there exist regions in parameter space with only modest fine-tuning in the 5D Yukawa couplings which satisfy all existing \(\Delta F = 2\) and electroweak precision constraints for scales \(M_{KK} \gtrsim 3\) TeV in the reach.
of the LHC. A recent detailed analysis of $\varepsilon_K$ in the so-called little RS model can be found in [12].

The additional specific new messages from our analysis are as follows [7]:

- The EW tree level contributions to $\Delta F = 2$ observables mediated by new $Z_H$ and $Z'$ weak gauge bosons, while subleading in the case of $\varepsilon_K$ and $\Delta M_K$, turn out to be of roughly the same size as the KK gluon contributions in the case of $B_{d,s}$ physics observables.

- The contributions of KK gauge boson tree level exchanges involving new flavour and CP-violating interactions allow not only to satisfy all existing $\Delta F = 2$ constraints but also to remove a number of tensions between the SM and the data (see above), claimed in particular in $\varepsilon_K$, $S_{\psi K_S}$ and $S_{\psi}$ [11,15].

- Interestingly the model allows naturally for $S_{\psi}$ as high as 0.4 that is hinted at by the most recent CDF and DØ data [12,13] and by an order of magnitude larger than the SM expectation: $S_{\psi} \approx 0.04$.

- The tree level $Z$ contributions to $\Delta F = 2$ processes are of higher order in $\sin\theta_{SM}/M_{KK}$ and can be neglected.

- We have pointed out that the custodial symmetry $P_{LR}$ implies automatically the protection of flavour violating $Zd_L^i d_L^j$ couplings so that tree level $Z$ contributions to all processes in which the flavour changes appear in the down quark sector are dominantly represented by $Zd_R^i d_R^j$ couplings. This has profound implications for rare $K$ and $B$ decays that we discuss next.

A recent more detailed review of our results on $\Delta F = 2$ appeared in [15].

8. Rare $K$ and $B$ Decays in a Warped Extra Dimension with Custodial Protection

In [8] we present a complete study of rare $K$ and $B$ meson decays in the RS model with a custodial protection of left-handed $Z$ couplings just mentioned, including $K^+ \to \pi^+ \nu \bar{\nu}$, $K_L \to \pi^0 \nu \bar{\nu}$, $K_L \to \pi^0 \ell^+ \ell^-$, $K_L \to \mu^+ \mu^-$, $B_{s,d} \to \mu^+ \mu^-$, $B \to K \nu \bar{\nu}$, $B \to K^* \nu \bar{\nu}$ and $B \to X_{s,d} \nu \bar{\nu}$. It turns out that new physics contributions to these processes, as opposed to $\Delta F = 2$ transitions, are governed by tree level contributions from $Z$ boson exchanges (dominated by $Zd_R^i d_R^j$ couplings) with the KK new heavy electroweak gauge bosons playing a subdominant role. Imposing all existing constraints from $\Delta F = 2$ transitions discussed above and fitting all quark masses and CKM mixing parameters we find that a number of branching ratios for rare $K$ decays can differ significantly from the SM predictions, while the corresponding effects in rare $B$ decays are modest. In particular the branching ratios for $K_L \to \pi^0 \nu \bar{\nu}$ and $K^+ \to \pi^+ \nu \bar{\nu}$ can be by a factor of 5 and 2 larger than the SM predictions, respectively. The latter enhancement could be welcomed one day if the central experimental value [14] will remain in the ballpark of $15 \cdot 10^{-11}$ and its error will decrease. However, it is very unlikely to get simultaneously large NP effects in rare $K$ decays and $S_{\psi}$, which constitutes a good test of the model.

We study correlations between various observables within the $K$ system, within the $B$ system and in particular between $K$ and $B$ systems. For instance sizable departures from the MFV relations between $\Delta M_{s,d}$ and $Br(B_{s,d} \to \mu^+ \mu^-)$ and between $S_{\psi K_S}$ and the $K \to \pi \nu \bar{\nu}$ decay rates are possible. We also find that the pattern of deviations from the SM differs from the deviations found in the the LHT model [20].

We next show how our results would change if the custodial protection of $Zd_L^i d_L^j$ couplings was absent. As the custodial protection turns out to be more effective in $B$ decays, its removal implies a possibility of large enhancements of rare $B$ decay branching ratios like $Br(B_s \to \mu^+ \mu^-)$. On the other hand without this protection it is harder to obtain an agreement with electroweak precision data for KK scales in the reach of the LHC as summarized in [37]. For a recent study of electroweak precision data in a RS model without custodial protection see [15].

It is interesting that in spite of many new flavour parameters present in this model a clear
pattern of new flavour violating effects has been identified in our analysis. Large effects in $\Delta F = 2$ transitions, large effects in $\Delta F = 1$ rare $K$ decays, small effects in $\Delta F = 1$ rare $B$ decays and the absence of simultaneous large effects in the $K$ and $B$ system. This pattern implies that an observation of a large $S_{\psi\phi}$ asymmetry would in the context of this model preclude sizable NP effects in rare $K$ and $B$ decays. On the other hand, finding $S_{\psi\phi}$ to be SM-like will open the road to large NP effects in rare $K$ decays, even if such large effects are only a possibility and are not guaranteed. On the other hand, an observation of large NP effects in rare $B$ decays would put this model in serious difficulties. A recent more detailed review of our results appeared in [46].

9. Electroweak and Flavour Structure of Warped Extra Dimension Models with Custodial Protection

Finally let me mention that the two phenomenological analyses in [7,8] were based on a very detailed theoretical analysis [9], in which the electroweak and flavour structure of the model in question has been worked out.

Other selected recent studies of flavour violation in RS models can be found in [47,49,50,51,52,53]. In particular in [47,53] large contributions to dipole operator dominated processes $\mu \rightarrow e\gamma$ and $B \rightarrow X_s\gamma$ have been found. On the other hand in [48,50] new strategies for the suppression of FCNC processes have been proposed.

10. Final Messages

As hopefully demonstrated above and in numerous papers on flavour physics in the literature, new exciting phenomena at scales of order 1 TeV are possibly waiting for us. Let us hope we will meet them soon!

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REFERENCES

1. A. J. Buras and D. Guadagnoli, Phys. Rev. D 78 (2008) 033005 [arXiv:0805.3887 [hep-ph]].
2. A. J. Buras and D. Guadagnoli, arXiv:0901.2056 [hep-ph].
3. M. Blanke, A. J. Buras, S. Recksiegel and C. Tarantino, arXiv:0805.4383 [hep-ph].
4. W. Altmannshofer, A. J. Buras and P. Paradisi, arXiv:0808.0707 [hep-ph].
5. W. Altmannshofer, A. Bharucha, A. J. Buras, D. M. Straub and M. Wick, arXiv:0811.1211 [hep-ph].
6. W. Altmannshofer, A. J. Buras, D. M. Straub and M. Wick, arXiv:0902.0160 [hep-ph].
7. M. Blanke, A. J. Buras, B. Duling, S. Gori and A. Weiler, arXiv:0809.1073 [hep-ph].
8. M. Blanke, A. J. Buras, B. Duling, K. Gemmler and S. Gori, arXiv:0812.3853 [hep-ph].
9. M. Albrecht, M. Blanke, A. J. Buras, B. Duling and K. Gemmler to appear soon.
10. D. J. Antonio et al. [RBC Collaboration and UKQCD Collaboration], Phys. Rev. Lett. 100 (2008) 032001 [arXiv:hep-ph/0702042].
11. E. Lunghi and A. Soni, Phys. Lett. B 666 (2008) 162 [arXiv:0803.4340 [hep-ph]].
12. CDF Collaboration, T. Aaltonen et. al., [http://xxx.lanl.gov/abs/0712.2397 arXiv:0712.2397].
13. D0 Collaboration, V. M. Abazov et. al., [http://xxx.lanl.gov/abs/0802.2255 arXiv:0802.2255].
14. G. Brooijmans on behalf of the CDF and D0 Collaboration, http://xxx.lanl.gov/abs/0808.0726 arXiv:0808.0726.
15. A. Lenz and U. Nierste, JHEP 06 (2007) 072, [http://xxx.lanl.gov/abs/hep-ph/0612167 hep-ph/0612167].
16. UTfit Collaboration, M. Bona et. al., [http://xxx.lanl.gov/abs/0803.0659 arXiv:0803.0659].
17. S. Faller, R. Fleischer and T. Mannel,
18. A. J. Lenz, arXiv:0808.1944 [hep-ph].
19. M. Blanke, A. J. Buras, A. Poschenrieder, C. Tarantino, S. Uhlig and A. Weiler, JHEP 0612 (2006) 003 [arXiv:hep-ph/0605214].
20. M. Blanke, A. J. Buras, A. Poschenrieder, S. Recksiegel, C. Tarantino, S. Uhlig and A. Weiler, JHEP 0701 (2007) 066 [arXiv:hep-ph/0610298].
21. T. Goto, Y. Okada and Y. Yamamoto, arXiv:0809.4753 [hep-ph].
22. S. Baek and P. Ko, Phys. Rev. Lett. 83 (1999) 488 [arXiv:hep-ph/9812229].
23. S. Baek and P. Ko, Phys. Lett. B 462 (1999) 95 [arXiv:hep-ph/9904283].
24. A. Bartl, T. Gajdosik, E. Lunghi, A. Masiero, W. Porod, H. Stremnitzer and O. Vives, Phys. Rev. D 64 (2001) 076009 [arXiv:hep-ph/0103324].
25. J. R. Ellis, J. S. Lee and A. Pilaftsis, Phys. Rev. D 76 (2007) 115011 [arXiv:0708.2079 [hep-ph]].
26. C. Bobeth, G. Hiller and G. Piranishvili, JHEP 0807 (2008) 106 [arXiv:0805.2525 [hep-ph]].
27. U. Egede, T. Hurth, J. Matias, M. Ramon and W. Reece, JHEP 0811 (2008) 032 [arXiv:0807.2559 [hep-ph]].
28. T. Hurth, G. Isidori, J. F. Kamenik and F. Mescia, Nucl. Phys. B 808 (2009) 326 [arXiv:0807.5039 [hep-ph]].
29. P. Colangelo, F. De Fazio, P. Santorelli and E. Scrimieri, Phys. Lett. B 395 (1997) 339 [arXiv:hep-ph/9610297].
30. G. Buchalla, G. Hiller and G. Isidori, Phys. Rev. D 63 (2001) 014015 [arXiv:hep-ph/0006136].
31. L. Randall and R. Sundrum, Phys. Rev. Lett. 83 (1999) 3370 [arXiv:hep-ph/9905221].
32. T. Gherghetta and A. Pomarol, Nucl. Phys. B 586 (2000) 141 [arXiv:hep-ph/0003129].
33. S. Chang, J. Hisano, H. Nakano, N. Okada and M. Yamaguchi, Phys. Rev. D 62 (2000) 084025 [arXiv:hep-ph/9912498].
34. Y. Grossman and M. Neubert, Phys. Lett. B 474 (2000) 361 [arXiv:hep-ph/9912408].
35. S. J. Huber, Nucl. Phys. B 666 (2003) 269 [arXiv:hep-ph/0303183].
36. K. Agashe, G. Perez and A. Soni, Phys. Rev. D 71 (2005) 016002 [arXiv:hep-ph/0408134].
37. K. Agashe, A. Delgado, M. J. May and R. Sundrum, JHEP 0308 (2003) 050 [arXiv:hep-ph/0308036].
38. C. Csaki, C. Grojean, L. Pilo and J. Terning, Phys. Rev. Lett. 92 (2004) 101802 [arXiv:hep-ph/0308038].
39. K. Agashe, R. Contino, L. Da Rold and A. Pomarol, Phys. Lett. B 641 (2006) 62 [arXiv:hep-ph/0605341].
40. G. Burdman, Phys. Lett. B 590 (2004) 86 [arXiv:hep-ph/0310144].
41. C. Csaki, A. Falkowski and A. Weiler, arXiv:0804.1954 [hep-ph].
42. M. Bauer, S. Casagrande, L. Gruender, U. Haisch and M. Neubert, arXiv:0811.3678 [hep-ph].
43. B. Duling, arXiv:0901.4599 [hep-ph].
44. A. V. Artamonov et al. [E949 Collaboration], Phys. Rev. Lett. 101 (2008) 191802 [arXiv:0808.2459 [hep-ex]].
45. S. Casagrande, F. Goertz, U. Haisch, M. Neubert and T. Pfoh, JHEP 0810 (2008) 094 [arXiv:0807.4937 [hep-ph]].
46. S. Gori, arXiv:0901.4704 [hep-ph].
47. K. Agashe, A. E. Blechman and F. Petriello, Phys. Rev. D 74 (2006) 053011 [arXiv:hep-ph/0606021].
48. G. Cacciapaglia, C. Csaki, J. Galloway, G. Marandella, J. Terning and A. Weiler, JHEP 0804 (2008) 006 [arXiv:0709.1714 [hep-ph]].
49. A. L. Fitzpatrick, F. Petriello and L. Randall, arXiv:0710.1809 [hep-ph].
50. C. Cheung, A. L. Fitzpatrick and L. Randall, JHEP 0801 (2008) 069 [arXiv:0711.4421 [hep-th]].
51. C. Csaki, A. Falkowski and A. Weiler, arXiv:0806.3757 [hep-ph].
52. J. Santiago, JHEP 0812 (2008) 046 [arXiv:0806.1230 [hep-ph]].
53. K. Agashe, A. Azatov and L. Zhu, arXiv:0810.1016 [hep-ph].