RS MODEL EFFECTS ON B_s^0 CP-VIOLATION

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We study the impact of the Randall-Sundrum setup on the width difference $\Delta\Gamma_s$ and the CP-violating phase ϕ_s in the $\bar{B}_s^0$-B_s^0 system. We find that the correction to the magnitude of the decay amplitude Γ_{12}^s is below 4% for a realistic choice of input parameters. The main modification in the $\Delta\Gamma_s/\beta_s$-plane is caused by a new CP-violating phase in the mixing amplitude, which allows for a better agreement with the experimental results of CDF and DØ from $B_s^0 \to J/\psi\phi$ decays. The best-fit value of the CP asymmetry $S_{\psi\phi}$ can be reproduced, while simultaneously the theoretical prediction for the semileptonic CP asymmetry $A_{\rm SL}^s$ can enter the 1σ range.

1 Introduction

Within the search for new physics (NP) in the decay of B_s^0-mesons, an important observable is the width difference $\Delta\Gamma_s \equiv \Gamma_L^s - \Gamma_H^s$ between the light and the heavy meson state. According to the above definition, $\Delta\Gamma_s$ happens to be positive in the Standard Model (SM). It can be computed from the dispersive and absorptive part of the $\bar{B}_s^0$-B_s^0 mixing amplitude, M_{12}^s and Γ_{12}^s. To leading order in $|\Gamma_{12}^s|/|M_{12}^s|$ one finds the simple relation

$$\Delta\Gamma_s = -\,\frac{2\,\mathrm{Re}(M_{12}^s \Gamma_{12}^{s*})}{|M_{12}^s|} = 2\,|\Gamma_{12}^s|\,\cos\phi_s\,. \tag{1}$$

We define the relative phase ϕ_s between the mixing and the decay amplitude according to the convention

$$\frac{M_{12}^s}{\Gamma_{12}^s} = -\,\frac{|M_{12}^s|}{|\Gamma_{12}^s|}\,e^{i\phi_s}\,, \qquad \phi_s = \arg(-M_{12}^s \Gamma_{12}^{s\,*})\,, \tag{2}$$

for which the SM value is positive and explicitly given by [1] $\phi_s^{\rm SM} = (4.2\pm1.4)\cdot10^{-3}$. The combined experimental results of CDF and DØ [2] differ from the SM prediction in the $(\beta_s^{J/\psi\phi}, \Delta\Gamma_s)$-plane by about 2σ, whereas the latest CDF results disagree by 1σ only [3]. Here, $\beta_s^{J/\psi\phi} \in [-\pi/2, \pi/2]$ is the CP-violating phase in the interference of mixing and decay, obtained from the time-dependent angular analysis of flavor-tagged $B_s^0 \to J/\psi\phi$ decays. In the SM it is given by [1] $\beta_s^{J/\psi\phi} = -\arg\left(-\lambda_t^{bs}/\lambda_c^{bs}\right) = 0.020 \pm 0.005$, with $\lambda_q^{bs} = V_{qb}V_{qs}^*$. In the presence of NP, $\Delta\Gamma_s$ will be modified [4,5]. We adopt the notation of ref.[6] and extend the SM relations according to

$$M_{12}^s = M_{12}^{s\,\rm SM} + M_{12}^{s\,\rm NP} = M_{12}^{s\,\rm SM} R_M\, e^{i\phi_M}\,, \qquad \Gamma_{12}^s = \Gamma_{12}^{s\,\rm SM} + \Gamma_{12}^{s\,\rm NP} = \Gamma_{12}^{s\,\rm SM} R_\Gamma\, e^{i\phi_\Gamma}\,. \tag{3}$$

From (1) it follows that

$$\Delta\Gamma_s = 2\,|\Gamma_{12}^{s\,\rm SM}|\,R_\Gamma\,\cos(\phi_s^{\rm SM} + \phi_M - \phi_\Gamma)\,, \tag{4}$$

where [7] $\Delta\Gamma_s^{\rm SM} = (0.087 \pm 0.021)\,{\rm ps}^{-1}$. A further important observable is the semileptonic CP asymmetry $A_{\rm SL}^s = {\rm Im}(\Gamma_{12}^s/M_{12}^s)$. Including NP corrections, we find

$$A_{\rm SL}^s = \frac{|\Gamma_{12}^{s\,{\rm SM}}|}{|M_{12}^{s\,{\rm SM}}|}\,\frac{R_\Gamma}{R_M}\,\sin(\phi_s^{\rm SM} + \phi_M - \phi_\Gamma)\,. \tag{5}$$

Within the SM, the leading contribution to the dispersive part of the $\bar{B}_s^0$-B_s^0 mixing amplitude appears at the one loop level. If NP involves flavor-changing neutral currents (FCNCs) at tree level, these give rise to sizable corrections to the mass difference $\Delta m_{B_s} \equiv M_H^s - M_L^s = 2\,|M_{12}^s|$. Moreover, the presence of tree FCNCs and right-handed charged-current interactions give rise to new decay diagrams. However, the NP corrections to the absorptive part of the amplitude are suppressed by m_W^2/Λ^2 with respect to the SM contribution, where Λ is the NP mass scale. Thus, they are neglected in many NP studies.

2 RS corrections to the $\bar{B}_s^0$-B_s^0 system

The Randall-Sundrum (RS) model [8] is a five-dimensional (5D) quantum field theory (QFT) with an compactified extra-dimension of the order of the Planck length. A "warped metric" is used to generate hierarchies, which are non-understood in the SM. The theory is decomposed into an effective four-dimensional QFT by means of a Kaluza-Klein (KK) decomposition. This gives rise to an infinite tower of heavy copies of the SM particles. The mass scale of the first KK excitations $M_{\rm KK}$ is taken to be a few TeV.

We consider two different scenarios. The first one consists of the SM gauge and matter fields living in the bulk of the 5D space-time, and a Higgs doublet, which is confined to the so-called infra-red boundary of the extra dimension [9]. The second scenario features an extended symmetry group $SU(2)_L \times SU(2)_R \times U(1)_X$ of the electroweak (EW) sector, which is broken down $SU(2)_L \times U(1)_Y$ by the choice of boundary conditions of the respective gauge fields [10,12,13]. An appropriate embedding of the fermions allows for a protection of $Z^0 b_L \bar{b}_L$ couplings [11].

A numerical scan accross the "RS landscape" is performed by evaluating M_{12}^s and Γ_{12}^s for appropriate random sets of input parameters, that reproduce the quark masses, mixing angles, and CKM phase. Furthermore, bounds from the $Z^0 b_L \bar{b}_L$ coupling, the oscillation frequency Δm_{B_s}, and the observable ϵ_K, are taken into account. Details of the calculations are given in ref.[15].

3 Numerical analysis

In the first panel of Figure 1 we show the RS corrections to the magnitude and CP-violating phase of the $\bar{B}_s^0$-B_s^0 decay width, R_Γ and ϕ_Γ, for a set of 10000 parameter points at $M_{\rm KK} = 2\,{\rm TeV}$. The blue (dark gray) points correspond to the minimal RS model, where we plot only those that are in agreement with the $Z^0 \to b\bar{b}$ "pseudo observables". The orange (light gray) points correspond to the custodial extension, where the latter bound vanishes. As expected, the RS corrections to $|\Gamma_{12}^s|$ are rather small, typically not exceeding $\pm 4\%$. The corrections to the magnitude and phase of the dispersive part of the mixing amplitude, R_M and ϕ_M, are plotted in the second panel of Figure 1. Here, one should keep in mind the experimental result from the time-dependent measurement of the $\bar{B}_s^0$-B_s^0 oscillation frequency [16]

$$\Delta m_{B_s}^{\rm exp} = (17.77 \pm 0.10\,({\rm stat}) \pm 0.07\,({\rm syst}))\,{\rm ps}^{-1}\,, \tag{6}$$

which is in good agreement with the SM prediction [7] $(17.3 \pm 2.6)\,{\rm ps}^{-1}$. As a consequence, all points with $R_M \notin [0.718, 1.336]$ are excluded at 95% confidence level, as indicated by the dashed lines. Compared to ϕ_M, the new phase ϕ_Γ can be neglected (what we will do from now on).

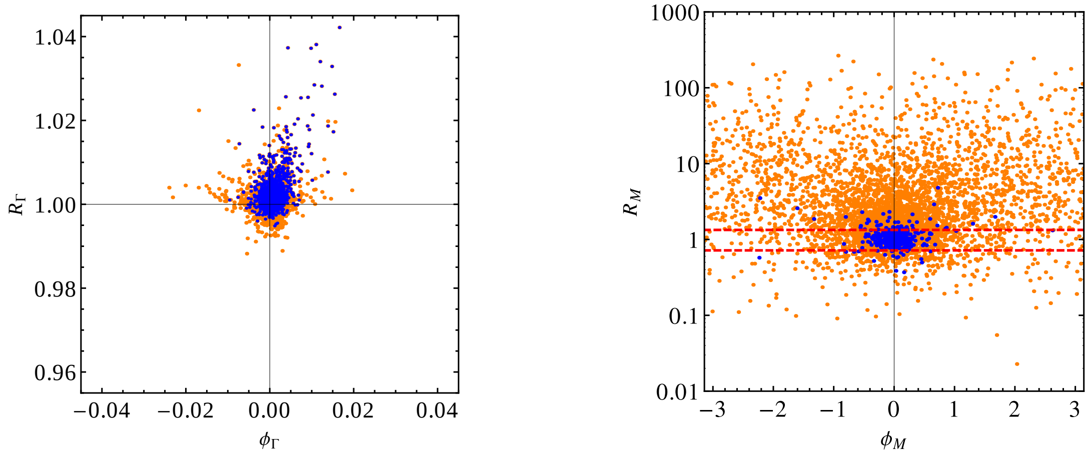

Figure 1: RS corrections to the magnitude and CP-violating phase of the $\bar{B}_s^0$-B_s^0 decay amplitude, R_Γ and ϕ_Γ, as well as for the mixing amplitude, R_M an ϕ_M. Blue points correspond to the minimal, orange to the custodial RS model. The red dashed lines mark the 99% confidence region with respect to the measurement of Δm_{B_s}.

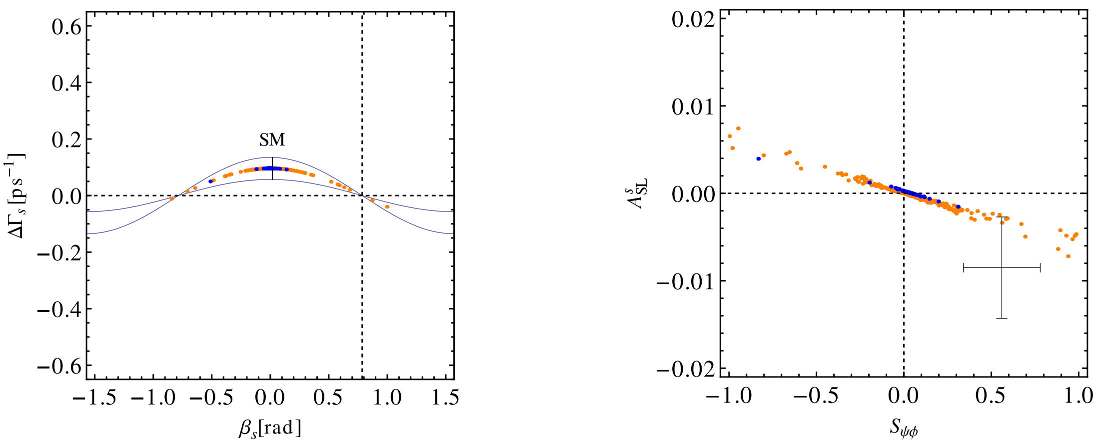

Figure 2: Left panel: Corrections within the $\Delta\Gamma_s^{\mathrm{SM}}/\beta_s$ -plane for the minimal (blue/dark gray) and custodial (orange/light gray) RS model. Bounds from $Z^0 b\bar{b}$, Δm_{B_s}, and ϵ_K are satisfied. LRight panel: Corrections within the $A_{\mathrm{SL}}^s/S_{\psi\phi}$ -plane for the minimal and custodial RS model.

Neglecting the small SM phases, the width difference (4) can be written as

$$\Delta\Gamma_s = \Delta\Gamma_s^{\mathrm{SM}}\, R_\Gamma\, \cos 2\beta_s\,, \tag{7}$$

where $2\beta_s \approx -\phi_M^{\mathrm{RS}}$. The preliminary CDF analysis [3] uses the older SM prediction [1] $\Delta\Gamma_s^{\mathrm{SM}} = (0.096 \pm 0.039)\mathrm{ps}^{-1}$, which we will take as central value for our calculation. Taking the more recent value will not change our conclusions. The resulting RS predictions for $\Delta\Gamma_s$ are plotted against β_s in the left panel of Figure 2. Comparing to the latest preliminary CDF results [3], we conclude that the RS model can enter the 68% confidence region and come close to the best fit value. It stays below the desired value for $\Delta\Gamma_s$, as there are no sizable positive corrections to $|\Gamma_{12}^s|$.

The SM prediction [7] $(A_{\mathrm{SL}}^s)_{\mathrm{SM}} = (1.9 \pm 0.3) \cdot 10^{-5}$, which is often named a_{sl}^s or a_{fs}^s in the literature, agrees with the direct measurement [17] $(A_{\mathrm{SL}}^s)_{\mathrm{exp}} = -0.0017 \pm 0.0092$ within the (large) error. However, recent measurements of the like-sign dimuon charge asymmetry [18] A_{SL}^b, which connect $A^s_{\rm SL}$ to its counterpart $A^d_{\rm SL}$ of the B^0_d-meson sector [20], imply a deviation of almost 2σ. If one neglects the tiny SM phases and the NP phase corrections related to decay, $A^s_{\rm SL}$ is proportional to the quantity [19] $S_{\psi\phi}$, which is given by the amplitude of the time-dependent asymmetry in $B^0_s \to J/\psi\phi$ decays, $A^s_{\rm CP}(t) = S_{\psi\phi}\sin(\Delta m_{B_s} t)$. Setting just the NP phase in the decay to zero, one obtains the well known expression [21] $S_{\psi\phi} = \sin(2\beta_s^{J/\psi\phi} - \phi_M)$, and thus

$$A^s_{\rm SL} \approx -\frac{|\Gamma^{s\,\rm SM}_{12}|}{|M^{s\,\rm SM}_{12}|}\frac{R_\Gamma}{R_M}\,S_{\psi\phi}\,. \tag{8}$$

The RS result is shown in the right panel of Figure 2, where we have sketched the experimental favored values $S_{\psi\phi} = 0.56 \pm 0.22$ [22] and $A^s_{\rm SL} = -0.0085 \pm 0.0058$ [17]. The latter number combines the direct measurement with the results derived from the measurement of $A^b_{\rm SL}$ in semileptonic B-decays together with the average $A^d_{\rm SL} = -0.0047 \pm 0.0046$ from B-factories. It is evident from the plot that the best fit value of $S_{\psi\phi}$ can be reproduced (with some tuning in the minimal RS variant), which has already been noted in ref.[14]. Furthermore, the custodial RS model can enter the 1σ range of the measured value of $A^s_{\rm SL}$. The necessary choice of input parameters is similar to that one, which is suggested by the $\Delta\Gamma_s/\beta_s$-confidence region.

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