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Bounds on new physics from $\mathrm{B_s}$ mixing*

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I summarize the observables constraining the $\mathrm{B_s} - \overline{\mathrm{B}}_\mathrm{s}$ mixing complex and present a new calculation of the element Γ_{12}^s of the decay matrix. Γ_{12}^s enters the prediction of the width difference $\Delta\Gamma_s$, for which we obtain $\Delta\Gamma_s^{\rm SM} = 0.088 \pm 0.017\,\mathrm{ps}^{-1}$, if no new physics enters $\mathrm{B_s} - \overline{\mathrm{B}}_\mathrm{s}$ mixing. Applying our formulae to Tevatron data we find a deviation of the $\mathrm{B_s} - \overline{\mathrm{B}}_\mathrm{s}$ mixing phase ϕ_s from its Standard Model value by 2 standard deviations. I stress that present data do not give any information on the sign of $\Delta\Gamma_s$.

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1. Introduction

Flavor-changing neutral current (FCNC) processes of quarks are highly sensitive to new physics at or above the electroweak scale. The highly successful physics program of the B factories has revealed that these FCNCs are dominantly governed by the Cabibbo-Kobayashi-Maskawa (CKM) mechanism[1] of the Standard Model. This is an important constraint on the new, still undiscovered theory of Tera–scale physics. Models whose only source of flavor violation is the CKM matrix are termed *minimally flavor violating (MFV)*[2]. Still, it is easy to construct models in which non–MFV are naturally suppressed while still leading to measurable effects. An example are Grand Unified Theories (GUTs) in which MFV is implemented far above the GUT scale, but subsequently altered by renormalisation group effects[3]. Particularly well-suited for the search of corrections to the CKM mechanism are

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CP–violating observables in $b \to s$ transitions: CKM–driven CP violation in $b \to s$ transitions is small, just as in the $s \to d$ transitions probed in Kaon physics. Interestingly, in supersymmetric GUT models the large atmospheric neutrino mixing angle can influence $b \to s$ transitions[3,4]. Clearly, the "holy grail" of $b \to s$ FCNC physics is the $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing amplitude M_{12}^s. New physics will affect its magnitude and phase, and already small contributions to M_{12}^s can lift the small (and in many cases unobservably tiny) CP asymmetries to sizable values.

In this talk I summarize the avenues to (over–)constrain the $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing complex. Then a new, more precise, theory prediction for the element Γ_{12}^s of the decay matrix is presented. Γ_{12}^s enters the formulae for the width difference $\Delta\Gamma_s$ of the two mass eigenstates in the B_s system. Our new result further decreases the theoretical uncertainty in the extraction of the $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing phase from the CP asymmetry in flavor–specific B_s decays. Finally, constraints from DØ data on M_{12}^s are derived with the help of the new result for Γ_{12}^s. The presented results are from Ref. [5].

2. $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing

$\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ oscillations are governed by a Schrödinger equation

$$i\frac{d}{dt}\begin{pmatrix} |B_s(t)\rangle \\ |\bar{B}_s(t)\rangle \end{pmatrix} = \left(M^s - \frac{i}{2}\Gamma^s\right)\begin{pmatrix} |B_s(t)\rangle \\ |\bar{B}_s(t)\rangle \end{pmatrix} \tag{1}$$

with the mass matrix M^s and the decay matrix Γ^s. The physical eigenstates $|B_H\rangle$ and $|B_L\rangle$ with the masses M_H, M_L and the decay rates Γ_H, Γ_L are obtained by diagonalizing $M^s - i\Gamma^s/2$. There are three physical quantities in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing:

$$|\Gamma_{12}^s|, \qquad |M_{12}^s| \quad \text{and} \quad \phi_s = \arg(-M_{12}^s/\Gamma_{12}^s). \tag{2}$$

The phase ϕ_s is responsible for *CP violation in mixing*. The mass and width differences between B_L and B_H are

$$\begin{aligned}\Delta M_s \equiv M_H^s - M_L^s \;&=\; 2\,|M_{12}^s|,\\ \Delta\Gamma_s \equiv \Gamma_L^s - \Gamma_H^s \;&=\; 2\,\mathrm{Re}\,\frac{\Gamma_{12}^s}{M_{12}^s} \;=\; 2\,|\Gamma_{12}^s|\cos\phi_s,\end{aligned} \tag{3}$$

Here and in the following I neglect numerically irrelevant corrections of order m_b^2/M_W^2. The average width of the two eigenstates is denoted by $\Gamma_s = (\Gamma_L + \Gamma_H)/2$. The precise measurements from the DØ and CDF experiments[6]

$$\begin{aligned}17\,\mathrm{ps}^{-1} \leq \Delta M_s \leq 21\,\mathrm{ps}^{-1} \qquad\qquad & @90\%\,\mathrm{CL} \qquad \text{DØ}\\ \Delta M_s = 17.77 \pm 0.10_{(\mathrm{syst})} \pm 0.07_{\,(\mathrm{stat})}\,\mathrm{ps}^{-1} \qquad & \text{CDF.}\end{aligned} \tag{4}$$

determine $|M_{12}^s|$ sharply.

New physics affects magnitude and phase of M_{12}^s, but can barely change Γ_{12}^s, which dominantly stems from the Cabibbo-favored tree–level $b \to c\bar{c}s$ decays. In the Standard Model ϕ_s is tiny, so that $\cos\phi_s \simeq 0$ and new physics can only decrease

$\Delta\Gamma_s$ in Eq. (3)[7,8]. The success of the Standard Model suggests that new physics enters low–energy observables at the loop level. A different viewpoint has recently been taken in Ref. [9], where potentially huge contributions to Γ_{12}^s from leptoquarks with FCNC couplings have been claimed. The authors of Ref. [9] exploit the plethora of free parameters in leptoquark models to place their effect into the yet unmeasured decay $B_s \to \tau^+\tau^-$, whose branching ratio could then be enhanced to up to 18%. The effect of some new decay mode on the ratio $\Delta\Gamma_s/\Gamma_s$ can be as large as twice its branching ratio, so that Ref. [9] finds an enhancement of $\Delta\Gamma_s/\Gamma_s$ from its Standard Model value around 0.15 to up to 0.51. However, the enhanced $\overline{s}b\overline{\tau}\tau$ coupling invoked in this model would also lead to sizable new $b \to s\tau^+\tau^-$ decays modes of B^+ and B_d mesons. While there are no precise data on final states with two τ's yet, the extra decay modes would sizably alter well-measured and well-calculated inclusive quantities such as the semileptonic branching ratio B_{SL}[10], the inclusive branching ratio $\mathcal{B}(B \to \text{ no charm})$[11] and even the lifetimes of all B mesons. Thus the idea of Ref. [9] is not viable and it is safe to assume that Γ_{12}^s is unaffected by new physics.

While the pristine measurement in Eq. (4) already gives a powerful constraint on new physics, there are two reasons to seek further experimental information from other observables: first, ΔM_s only constrains $|M_{12}^s|$ but not ϕ_s and second, the translation of Eq. (4) into constraints on fundamental parameters involves a hadronic parameter, which is difficult to compute and inflicts a theoretical uncertainty of order 30% onto the analysis. New physics entering M_{12}^s can be parameterized as

$$M_{12}^s \equiv M_{12}^{s,\mathrm{SM}} \cdot \Delta_s\,, \qquad\qquad \Delta_s \;\equiv\; |\Delta_s| e^{i\phi_s^\Delta}\,. \tag{5}$$

Thus every measurement related to $\mathrm{B_s}$–$\overline{\mathrm{B}}_\mathrm{s}$ mixing gives a constraint on the complex Δ_s plane. The Standard Model corresponds to $\Delta_s = 1$. While $\arg M_{12}^s$ is unphysical and depends on phase conventions, ϕ_s^Δ is a physical CP phase. The mixing phase ϕ_s in Eq. (2) can be written as

$$\phi_s = \phi_s^\Delta \;+\; \phi_s^{\mathrm{SM}},$$

where ϕ_s^{SM} is the Standard Model prediction for ϕ_s. ϕ_s^{SM} is negligible, see Eq. (24) below.

The relationship of Δ_s to the parameters used in [12,13] is

$$\Delta_s = r_s^2 e^{2i\theta_s}.$$

We find it more transparent to plot $\mathrm{Im}\,\Delta_s$ vs. $\mathrm{Re}\,\Delta_s$ than to plot $2\theta_s$ vs. r_s^2. Next we list the key measurements which (over–)constrain Δ_s:

1) ΔM_s in Eq. (4) determines $|\Delta_s|$.
2) Measuring the lifetime in an untagged $b \to c\overline{c}s$ decay $\overset{(-)}{\mathrm{B}}_s \to f_{CP}$, where f_{CP} is a CP eigenstate, determines $\Delta\Gamma_s \cos(\phi_s^\Delta - 2\beta_s) = |\Delta\Gamma_s \cos(\phi_s^\Delta - 2\beta_s)|$[7,8].

The time-dependent decay rate reads

$$\Gamma[\overset{(-)}{\mathrm{B}}_s \to f_{CP\pm}, t] \propto \frac{1 \pm \cos(\phi_s^\Delta - 2\beta_s)}{2} e^{-\Gamma_L t} \;+\; \frac{1 \mp \cos(\phi_s^\Delta - 2\beta_s)}{2} e^{-\Gamma_H t}$$
$$= e^{-\Gamma_s t} \left[\cosh \frac{\Delta\Gamma_s\, t}{2} \mp \cos(\phi_s^\Delta - 2\beta_s) \sinh \frac{\Delta\Gamma_s\, t}{2} \right]. \quad (6)$$

Here the sign convention of

$$\beta_s = -\arg\left(-\frac{\lambda_t^s}{\lambda_c^s}\right) \;=\; 0.020 \pm 0.005 \;=\; 1.1^\circ \pm 0.3^\circ \quad (7)$$

is that of Ref. [14]. Currently this measurement is applied to $\overset{(-)}{\mathrm{B}}_s \to J/\psi\phi$. Here the CP quantum number of the final state depends on the orbital angular momentum, the P–wave state is f_{CP-} and the S–wave and D–wave components correspond to f_{CP+} in Eq. (6). Neglecting β_s, $\phi_s^{\rm SM}$ and expanding to first order in $\Delta\Gamma_s$ one verifies from Eq. (6) that the lifetime measurement determines[7,8]

$$\Delta\Gamma_s \cos\phi_s^\Delta = 2|\Gamma_{12}^s| \cos^2\phi_s^\Delta. \quad (8)$$

3) The angular analysis of an untagged $\overset{(-)}{\mathrm{B}}_s \to J/\psi\phi$ sample not only determines $\Delta\Gamma_s \cos\phi_s^\Delta$ as discussed in item 2, but also contains information on $\sin(\phi_s^\Delta - 2\beta_s)$ through a CP-odd interference term.

4) The CP asymmetry in *flavor-specific* $B_s \to f$ decays is

$$a_{\rm fs}^s = {\rm Im}\, \frac{\Gamma_{12}^s}{M_{12}^s} \;=\; \frac{|\Gamma_{12}^s|}{|M_{12}^s|} \sin\phi_s \;=\; \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s. \quad (9)$$

$a_{\rm fs}^s$ is typically measured by counting the number of positively and negatively charged leptons in semileptonic $\overset{(-)}{\mathrm{B}}_s$ decays. Observing further the time evolution of these untagged $\overset{(-)}{\mathrm{B}}_s \to X^\mp \ell^\pm \overset{(-)}{\nu}_\ell$ decays,

$$\frac{\Gamma[\overset{(-)}{\mathrm{B}}_s \to X^-\ell^+\nu_\ell, t] \;-\; \Gamma[\overset{(-)}{\mathrm{B}}_s \to X^+\ell^-\overline{\nu}_\ell, t]}{\Gamma[\overset{(-)}{\mathrm{B}}_s \to X^-\ell^+\nu_\ell, t] \;+\; \Gamma[\overset{(-)}{\mathrm{B}}_s \to X^+\ell^-\overline{\nu}_\ell, t]} = \frac{a_{\rm fs}^s}{2} \left[1 - \frac{\cos(\Delta M_s\, t)}{\cosh(\Delta\Gamma_s\, t/2)} \right], \quad (10)$$

may help to control systematic experimental effects[15].

Often the average lifetime of the two B_s eigenstates is included into global experimental analyses of $\Delta\Gamma_s$. Heavy quark physics implies that the average widths Γ_d and Γ_s in the B_d and B_s systems are equal up to corrections of order 1%. The average B_s lifetime will then exceed the B_d lifetime by a term which is quadratic in $\Delta\Gamma_s^2/(\Gamma_s^2)$[7,8]. For realistic values of $\Delta\Gamma_s$ this term is too small to determine $\Delta\Gamma_s$.

We close this section with an important remark: up to now there is *no* experimental information on the sign of $\Delta\Gamma_s$ available! From Eq. (3) one verifies immediately that ${\rm sign}\,\Delta\Gamma_s = {\rm sign}\,\cos\phi_s$ and (see Eq. (8)) the untagged analysis described in item 2 is only sensitive to $|\Delta\Gamma_s|$. Also the CP–odd quantities described in items 3 and 4 only determine $\sin\phi_s^\Delta$, which comes with a two–fold ambiguity for ϕ_s^Δ: the two solutions correspond to different signs of $\cos\phi_s^\Delta$ and thereby different signs of

$\Delta\Gamma_s$. The determination of sign $\Delta\Gamma_s$ is discussed in Ref. [8]. It is easy to check that the formula for the angular distribution in $\overset{(-)}{\mathrm{B}}_s \to J/\psi\phi$[16,8] is unchanged if one simultaneously flips the sign of $\Delta\Gamma_s$ (i.e. interchanges Γ_L and Γ_H) and the sign of $\cos\phi_s$. Thus current experimental results should be quoted for $|\Delta\Gamma_s|$ rather than $\Delta\Gamma_s$.

3. New theory prediction for Γ_{12}^s

The predictions of M_{12}^s and Γ_{12}^s involve hadronic matrix elements of four–quark operators. These matrix elements are computed with the help of lattice gauge theory and dominate the theoretical uncertainty. In the Standard Model prediction for M_{12}^s one only encounters the operator

$$Q = \overline{s}_\alpha \gamma_\mu (1-\gamma_5) b_\alpha \, \overline{s}_\beta \gamma^\mu (1-\gamma_5) b_\beta, \tag{11}$$

where α and β are color indices. The matrix element is usually parameterized as

$$\langle B_s | Q | \overline{B}_s \rangle = \frac{8}{3} M_{B_s}^2 \, f_{B_s}^2 B, \tag{12}$$

where M_{B_s} and f_{B_s} are mass and decay constant of the B_s, respectively. B is called a bag factor. Then[17]

$$\begin{aligned} \Delta M_s^{\mathrm{SM}} &= (19.3 \pm 0.6)\ \mathrm{ps}^{-1} \left(\frac{|V_{ts}|}{0.0405}\right)^2 \cdot \left(\frac{f_{B_s}}{240\,\mathrm{MeV}}\right)^2 \frac{B}{0.85} && (13)\\ &= (19.30 \pm 6.68)\ \mathrm{ps}^{-1}. && (14) \end{aligned}$$

The number in Eq. (14) is found from Eq. (13) with $f_{B_s} = 240 \pm 40\,\mathrm{MeV}$ and $B = 0.85 \pm 0.06$[18,19].

The situation with Γ_{12}^s is more complicated: its prediction requires the expansion in two parameters, $\overline{\Lambda}/m_b$ and $\alpha_s(m_b)$. Here $\overline{\Lambda} \sim (M_{B_s} - m_b)$ is the relevant hadronic scale and α_s is the strong coupling constant[20,21,22,23]. In the first step one finds that three operators contribute to Γ_{12}^s at leading order in $\overline{\Lambda}/m_b$: Q defined in Eq. (11),

$$\begin{aligned} Q_S &= \overline{s}_\alpha (1+\gamma_5) b_\alpha \, \overline{s}_\beta (1+\gamma_5) b_\beta && (15)\\ \text{and} \qquad \widetilde{Q}_S &= \overline{s}_\alpha (1+\gamma_5) b_\beta \, \overline{s}_\beta (1+\gamma_5) b_\alpha, && (16) \end{aligned}$$

We parameterize the new matrix elements with bag factors B_S' and $\widetilde{B}_S'$. Subsequently one trades one of the operators for

$$R_0 \equiv Q_S \ + \ \alpha_1 \tilde{Q}_S \ + \ \frac{1}{2} \alpha_2 Q, \tag{17}$$

Here $\alpha_{1,2} = 1 + \mathcal{O}(\alpha_s(m_b))$ are QCD correction factors[21,5]. This is done, because the matrix element of R_0 is suppressed by $\overline{\Lambda}/m_b$, so that it belongs to the subleading order[20]. In Refs. [20,21,23] Eq. (17) has been used to eliminate $\widetilde{Q}_S$ from the operator basis. This results in the prediction

$$\begin{aligned} \Delta\Gamma_{s,\mathrm{old}}^{\mathrm{SM}} = 2|\Gamma_{12,\mathrm{old}}^s| \ = \ & \left(\frac{f_{B_s}}{240\,\mathrm{MeV}}\right)^2 [0.002B + 0.094 B_S' - \\ & \big(0.033 B_{\tilde{R}_2} + 0.019 B_{R_0} + 0.005 B_R\big)\big]\ \mathrm{ps}^{-1}, \quad (18) \end{aligned}$$

where B_{R_0} and $B_{\tilde{R}_2}$ are the bag factors of R_0 and another subleading operator, $\tilde{R}_2$, and the uncertainties of the coefficients are not shown. The other sub-leading operators come with smaller coefficients and are accounted for with a common bag factor B_R in Eq. (18). This result is pathological in several respects: the $\overline{\Lambda}/m_b$ corrections exceed their natural size of 20% and are negative, the next–to–leading order QCD corrections of Refs. [21,23] (which are contained in the numbers 0.002 and 0.094) are also large and decrease the result further and finally $\Delta\Gamma_{s,\text{old}}^{\text{SM}}$ is dominated by B_S', so that the cancellation of hadronic physics from the ratio $\Delta M_s/\Delta\Gamma_s$ is imperfect.

The starting point of the improvement in Ref. [5] is the observation that the matrix element of $\widetilde{Q}_S$ is small[24]. Keeping in mind that the matrix element of R_0 is power–suppressed and therefore also small, Eq. (17) encodes a strong numerical correlation between B and B_S'. Eq. (17) implies for the bag parameters:

$$\alpha_1 \widetilde{B}_S' - 5B_S' \; + \; 4\alpha_2 B = \mathcal{O}\left(\frac{\overline{\Lambda}}{m_b}\right). \tag{19}$$

Hence trading $\widetilde{B}_S'$ for a linear combination of B, B_S' and B_{R_0} expresses a small number in terms of the difference of two big numbers: $\widetilde{B}_S' = 5B_S' - 4B + \mathcal{O}(\overline{\Lambda}/m_b, \alpha_s)$. So one tends to introduce a theoretical uncertainty into the problem, which is not inherent to the calculated quantity. The most straightforward way to take care of this is to keep Q and $\widetilde{Q}_S$ in the basis and to abandon Q_S instead. This results in[5]

$$\begin{aligned}\Delta\Gamma_s^{\text{SM}} = \left(\frac{f_{B_s}}{240\,\text{MeV}}\right)^2 \Big[&(0.105 \pm 0.016)B + (0.024 \pm 0.004)\tilde{B}_S' \\ &- \big[(0.030 \pm 0.004)B_{\tilde{R}_2} - (0.006 \pm 0.001)B_{R_0} + 0.003B_R\big]\Big]\,\text{ps}^{-1}.\end{aligned} \tag{20}$$

The quoted result further includes the resummation of logarithms of the charm mass to all orders in perturbation theory. Now all pathologies have disappeared. The smallness of the coefficient of B_{R_0} compared to Eq. (18) can be understood with the help of the $1/N_c$ expansion. ($N_c = 3$ is the number of colors.) The coefficients of Q and $\widetilde{Q}_S$ are leading in $1/N_c$, while the coefficient of Q_S is color–suppressed. If one eliminates Q_S in terms of R_0, the coefficient of Q_S becomes the coefficient of R_0, so that the number multiplying B_{R_0} is small. In the old result in Eq. (18), however, the coefficient of B_{R_0} stems from the color-favored coefficient of $\widetilde{Q}_S$ and is large. On the other hand, the (equally welcome) reduction of the NLO QCD correction, which is related to the QCD factors $\alpha_{1,2}$, appears accidental.

From our new result for Γ_{12}^s we also get a new prediction for a_{fs}^s and the CP phase ϕ_s in the Standard Model. Our predictions are

$$\Delta\Gamma_s^{\rm SM} = (0.096 \pm 0.039)\ \mathrm{ps}^{-1} \quad \Rightarrow \quad \frac{\Delta\Gamma_s^{\rm SM}}{\Gamma_s} = \Delta\Gamma_s^{\rm SM} \cdot \tau_{B_d} = 0.147 \pm 0.060 \tag{21}$$

$$a_{\rm fs}^{s,\rm SM} = (2.06 \pm 0.57) \cdot 10^{-5} \tag{22}$$

$$\frac{\Delta\Gamma_s^{\rm SM}}{\Delta M_s^{\rm SM}} = (49.7 \pm 9.4) \cdot 10^{-4} \tag{23}$$

$$\phi_s^{\rm SM} = (4.2 \pm 1.4) \cdot 10^{-3} \ = \ 0.24^\circ \pm 0.08^\circ \tag{24}$$

For the precise values of the input parameters I refer to Ref. [5].

The prediction of the ratio $\Delta\Gamma_s/\Delta M_s$ in Eq. (23) got much sharper, because most of the hadronic uncertainies now cancel, since $\Delta\Gamma_s$ in Eq. (20) is dominated by the term involving B. With Eq. (4) one finds from Eq. (23):

$$\Delta\Gamma_s^{\rm SM} \ = \ \frac{\Delta\Gamma_s^{\rm SM}}{\Delta M_s^{\rm SM}} \cdot \Delta M_s^{\rm exp} = 0.088 \pm 0.017\,\mathrm{ps}^{-1} \tag{25}$$

$$\Rightarrow \frac{\Delta\Gamma_s^{SM}}{\Gamma_s} = \Delta\Gamma_s^{\rm SM} \cdot \tau_{B_d} = 0.127 \pm 0.024\,. \tag{26}$$

Any future measurement of $\Delta\Gamma_s$ outside this range will signal new physics in ΔM_s or $\Delta\Gamma_s$.

For predictions of the corresponding quantities in the $\mathrm{B_d} - \overline{\mathrm{B}}_\mathrm{d}$ mixing complex I refer to Refs. [5,25].

4. Constraining new physics

The formulae relating ΔM_s, $\Delta\Gamma_s$ and $a_{\rm fs}^s$ to Δ_s defined in Eq. (5) are

$$\Delta M_s = \Delta M_s^{\rm SM}\,|\Delta_s| = (19.30 \pm 6.74)\,\mathrm{ps}^{-1} \cdot |\Delta_s| \tag{27}$$

$$\Delta\Gamma_s = 2|\Gamma_{12}^s|\, \cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right) = (0.096 \pm 0.039)\,\mathrm{ps}^{-1} \cdot \cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right) \tag{28}$$

$$\frac{\Delta\Gamma_s}{\Delta M_s} = \frac{|\Gamma_{12}^s|}{|M_{12}^{\rm SM,s}|} \cdot \frac{\cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)}{|\Delta_s|} = (4.97 \pm 0.94) \cdot 10^{-3} \cdot \frac{\cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)}{|\Delta_s|} \tag{29}$$

$$a_{\rm fs}^s = \frac{|\Gamma_{12}^s|}{|M_{12}^{\rm SM,s}|} \cdot \frac{\sin\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)}{|\Delta_s|} = (4.97 \pm 0.94) \cdot 10^{-3} \cdot \frac{\sin\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)}{|\Delta_s|} \tag{30}$$

For our analysis we use the the CDF data on ΔM_s in Eq. (4) and DØ data on the angular distribution in $\overset{(-)}{\mathrm{B}}_s \to J/\psi\phi$[26], the semileptonic CP asymmetry $a_{\rm sl}^s = a_{\rm fs}^s$[27] and on the same–sign di–muon asymmetry $a_{\rm sl}$[28], which is related to $a_{\rm sl}^s$ and $a_{\rm sl}^d$ as (updated from Ref. [12])

$$a_{\rm sl} = (0.582 \pm 0.030)\ a_{\rm sl}^d + (0.418 \pm 0.047)\ a_{\rm sl}^s. \tag{31}$$

The angular analysis of $\overset{(-)}{\mathrm{B}}_s \to J/\psi\phi$[16,8] involves two strong phases δ_1 and δ_2. They can be determined from the data, albeit with discrete ambiguities which imply a four–fold ambiguity in ϕ_s. The CP–conserving piece of the angular distribution depends on $\cos(\delta_2 - \delta_1)$, so that the experimental error on $\cos(\delta_2 - \delta_1)$ is smaller than the error on $\cos\delta_1$ and $\cos\delta_2$, which appear in the CP–violating piece proportional to $\sin(\phi_s^\Delta - 2\beta_s)$. The DØ result for $\delta_2 - \delta_1 = \pm(2.6 \pm 0.4)$[26] is in good agreement with theoretical model calculations predicting $\delta_1 \sim \pi$ and $\delta_2 \sim 0$[29]. In our analysis we have fixed $\cos\delta_1 < 0$ and $\cos\delta_2 > 0$, which reduces the four–fold ambiguity in ϕ_s^Δ to a two–fold one. DØ finds[26]

$$\begin{aligned} \Delta\Gamma_s = &\ \ 0.17 \pm 0.09_{(\text{stat})} \pm 0.03_{(\text{syst})}\ \text{ps}^{-1} \\ &\text{and} \quad \phi_s^\Delta - 2\beta_s = -0.79 \pm 0.56_{(\text{stat})} \pm 0.01_{(\text{syst})} \end{aligned} \tag{32}$$

$$\begin{aligned} \text{or} \qquad \Delta\Gamma_s = &-0.17 \pm 0.09_{(\text{stat})} \pm 0.03_{(\text{syst})}\ \text{ps}^{-1} \\ &\text{and} \quad \phi_s^\Delta - 2\beta_s = -0.79 \pm 0.56_{(\text{stat})} \pm 0.01_{(\text{syst})} + \pi\,. \end{aligned} \tag{33}$$

The second solution deviates from the Standard Model by several standard deviations. In order to assess the compatibility of the measurement with the Standard Model we only need to consider the first solution in Eq. (32).

The same–sign di–muon asymmetry a_{sl} in Eq. (31) involves both a_{sl}^s and a_{sl}^d. In order to translate the DØ measurement[28] of

$$a_{\text{sl}} = \left(-2.8 \pm 1.3_{(\text{stat})} \pm 0.9_{(\text{syst})}\right) \cdot 10^{-3} \tag{34}$$

into a number for a_{sl}^s we have used our theory prediction for a_{sl}^d[22,5]. Combining the result with the measurement of a_{sl}^s[27] gives

$$a_{\text{sl}}^s = \left(-5.2 \pm 3.2_{(\text{stat})} \pm 2.2_{(\text{syst})}\right) \cdot 10^{-3}\,. \tag{35}$$

Fig. 1 shows the combination of all measurements. It indicates a deviation from the Standard Model value $\Delta_s = 1$ by 2σ.

For this conclusion it is crucial that we use the theoretical value for a_{fs}^d[5], which is much more precise than the current measurement of this quantity (see Ref. [14] of Ref. [30]):

$$a_{\text{fs}}^{d,\text{th}} = \left(-4.8^{+1.0}_{-1.2}\right) \cdot 10^{-4}, \qquad a_{\text{fs}}^{d,\text{exp}} = (-47 \pm 46) \cdot 10^{-4}. \tag{36}$$

This assumes, of course, that no new physics enters a_{fs}^d. Another combined analysis of the DØ data of Refs. [26,27,28] has been performed in Ref. [30]. This analysis has used the experimental value $a_{\text{fs}}^{d,\text{exp}}$ in Eq. (31), which leads to a significantly weaker constraint from the same–sign di–muon asymmetry. Also no theory input on $2|\Gamma_{12}^s|$ has been used in the analysis of Ref. [30]. The final result for ϕ_s is therefore more conservative than ours and implies a deviation from the Standard Model by only 1.5σ.

5. Conclusions

I presented an improved theoretical prediction of Γ_{12}^s, which permits more accurate predictions of the width difference $\Delta\Gamma_s$ and of the CP asymmetry in flavor-specific decays, a_{fs}^s, in scenarios of physics beyond the Standard Model. Applying the new formulae to DØ data we find that the $\text{B}_\text{s} - \overline{\text{B}}_\text{s}$ mixing phase deviates from the

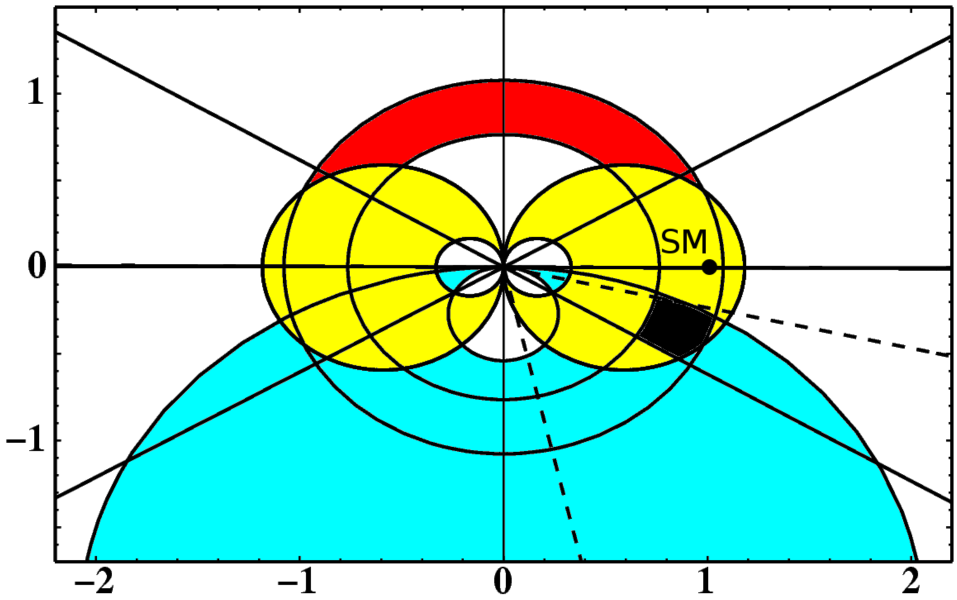

Fig. 1. Current experimental bounds in the complex Δ_s-plane. The bound from ΔM_s is the red (dark-grey) annulus around the origin. The bound from $|\Delta\Gamma_s|/\Delta M_s$ corresponds to the yellow (light-grey) region and the bound from $a_{\rm fs}^s$ is given by the light-blue (grey) region. The angle ϕ_s^Δ can be extracted from $|\Delta\Gamma_s|$ (solid lines) with a four–fold ambiguity — each of the four regions is bounded by a solid ray and the x-axis — or from the angular analysis in $B_s^0 \to J/\psi\phi$ (dashed line). (No mirror solutions from discrete ambiguities are shown for the latter.) The current experimental situation shows a 2σ deviation from the Standard Model case $\Delta_s = 1$.

Standard Model value by 2σ. We conclude that current experiments are reaching the sensitivity to probe new physics in the $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing phase.

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