Search for new physics in B_s-mixing

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We present the current status of the search for new physics effects in the mixing quantities ΔM_s, $\Delta\Gamma_s$ and ϕ_s of the neutral B_s-system.

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1. Introduction

Despite the enormous success of the standard model there is still room for new physics to be detected at currently running experiments. Huge efforts have been made in recent years in the precision measurement and precision calculation of flavor physics observables at the B-factories and at TeVatron, see e.g. Ref. [1] for a review and references therein. The system of the neutral B_s mesons seems to be particular promising to find hints for new physics (for a recent review of B-mixing see Ref. [2]): the standard model contribution is suppressed strongly, so even small new physics contributions might be of comparable size and the hadronic uncertainties are under good control.

In the standard model the mixing of neutral B-meson ist described, by the box diagrams, see e.g. [3–8] for more details. The absorptive part Γ_{12} of the box diagrams is sensitive light internal particles and the dispersive part M_{12} is sensitive to heavy internal particles. The two complex quantities M_{12} and Γ_{12} can be related to the following physical quantities:

- The mass difference ΔM_s between the heavy and the light mass eigenstates of the neutral B mesons:

$$\Delta M_s = 2|M_{12}|\,. \tag{1}$$

- The decay rate difference $\Delta\Gamma_s$ between the heavy and the light mass eigenstates of the neutral B mesons:

$$\Delta\Gamma_s = 2|\Gamma_{12}| \cos(\phi_s) \tag{2}$$

with the weak phase $\phi_s :=\text{Arg}(-M_{12}/\Gamma_{12})$.

- The tiny CP asymmetries in semileptonic B-decays a_{sl}^s

$$a_{sl}^s = \frac{|\Gamma_{12}|}{|M_{12}|} \sin(\phi_s) \ . \tag{3}$$

For the weak phase ϕ_s different notations are used in the literature, which led already to some confusion. For more details on the definitions see the *Note added* in [7].
Recently there were several claims of possible new physics effects in the B_s-mixing system in the literature:

(1) End of 2006 a 2 σ-deviation was found,[9] if all mixing quantities in the B_s-system were combined.
(2) This was more or less confirmed in july 2007 by UT-Fit.[10]
(3) With new data available UT-fit[11] claimed in march 2008 a 3.7 σ-deviation from the standard model. Since from the experiments (D0 and CDF) the full information about the likelihoods was not available at that time, the combination of the data in Ref. [11] had to rely on some assumptions.
(4) This analysis is currently redone - with the missing experimental information - by CKM Fitter in collaboration with the authors of Ref. [9],[12] preliminary results[13] show a deviation of less than 3 σ.

The above claims are based on the following experimental data for the B_s mixing system, mostly from D0 and CDF:

- The mass difference ΔM_s was measuered at CDF[14] and at D0[15] and the numbers were combined from HFAG[16] to

$$\Delta M_s = 17.78 \pm 0.12 \,\text{ps}^{-1} \,. \tag{4}$$

- D0[17] and CDF[18] performed a tagged analysis of the decay $B_s \to J/\Psi\phi$ to determine the decay rate difference $\Delta\Gamma_s$ and the weak mixing angle ϕ_s. HFAG[16] combines the values to, see Fig. (1)

$$\Delta\Gamma_s = 0.154^{+0.054}_{-0.070} \,\text{ps}^{-1} \,, \tag{5}$$

$$\phi_s = -0.77^{+0.29}_{0.37} \,. \tag{6}$$

The result from CDF[18] is now superseeded by Ref. [19].

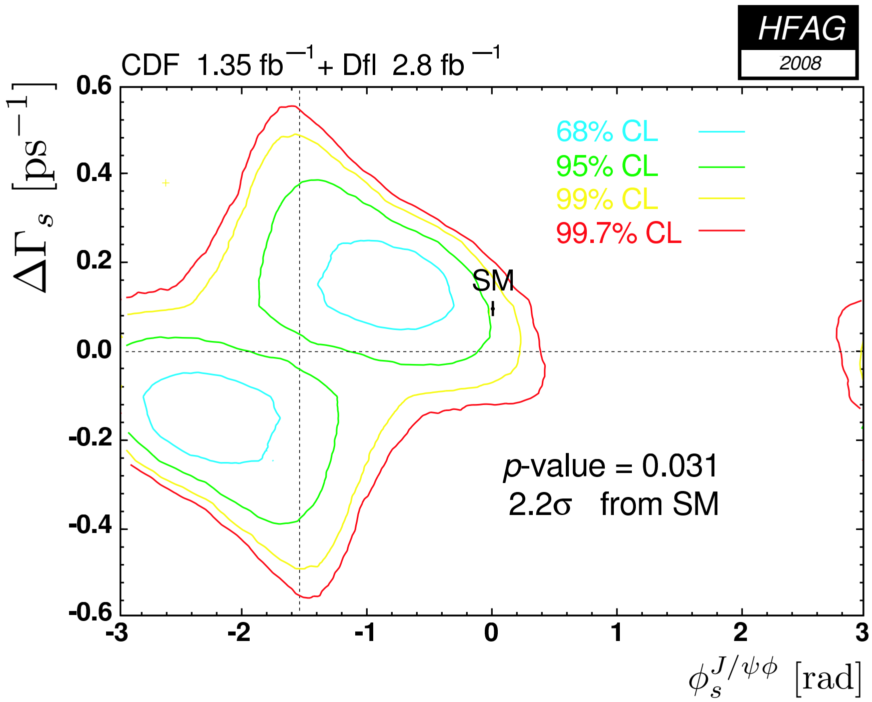

Fig. 1. The combined experimental values for $\Delta\Gamma_s$ and ϕ_s from the tagged analysis of the decay $B_s \to J/\Psi\phi$ from D0 and CDF.

- The semileptonic CP asymmetry can be obtained from the dimuon asymmetry (CDF,[20] D0[21]) or it can be measure directly (D0[22]). These numbers were combined from HFAG[16] to

$$a_{sl}^s = +0.0016 \pm 0.0085\,. \tag{7}$$

The untagged result from Ref. [[22]] is now superseeded by the new tagged result[23]

$$a_{sl}^s = -0.0024 \pm 0.0117^{+0.0015}_{-0.0024}\,. \tag{8}$$

There are numerous applications of new physics models to the B_s mixing sector, for some recent examples, see e.g. Refs. [24–42]. TeVatron is continuing to take data and we will get more precise data from the upcomming experiments at LHC[43] or possibly at a SuperB-factory[44] running also at the $\Upsilon(5s)$-resonance.

2. Strategy to search for new physics

In [9] we worked out a model independent analysis of new physics effects in B-mixing. Γ_{12} is due to real intermediate states, i.e. particles which are lighter than m_B. Any new physics contributions to Γ_{12} affects also tree-level B-decays. Since no evidence for sizeable new physics effects in tree-level B-decays has been found so far, it reasonable to assume that Γ_{12} is described by the standard model contributions alone. Deviations from that assumption are expected to be smaller than the hadronic unvertainties in the standard model prediction for Γ_{12}. M_{12}, however, might be affected by large new physics effects. We write therefore

$$M_{12}^s = M_{12}^{SM,s} \cdot \Delta = M_{12}^{SM,s} \cdot |\Delta| \cdot e^{i\phi_s^\Delta}\,, \tag{9}$$

$$\Gamma_{12}^s = \Gamma_{12}^{SM,s}\,, \tag{10}$$

where all new physics effects are parameterized by the complex number Δ. Now we can relate the experimental observables in the mixing system with the standard model predictions[9] and with Δ.

$$\begin{aligned}
\Delta M_s &= \Delta M_s^{\rm SM}\,|\Delta_s| \\
&= (19.30 \pm 6.74)\,{\rm ps}^{-1} \cdot |\Delta_s|\,, && (11)\\
\Delta\Gamma_s &= 2|\Gamma_{12}^s|\,\cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right) \\
&= (0.096 \pm 0.039)\,{\rm ps}^{-1} \cdot \cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)\,, && (12)\\
\frac{\Delta\Gamma_s}{\Delta M_s} &= \frac{|\Gamma_{12}^s|}{|M_{12}^{\rm SM,s}|} \cdot \frac{\cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)}{|\Delta_s|} \\
&= (4.97 \pm 0.94) \cdot 10^{-3} \cdot \frac{\cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)}{|\Delta_s|}\,, && (13)\\
a_{\rm fs}^s &= \frac{|\Gamma_{12}^s|}{|M_{12}^{\rm SM,s}|} \cdot \frac{\sin\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)}{|\Delta_s|} \\
&= (4.97 \pm 0.94) \cdot 10^{-3} \cdot \frac{\sin\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)}{|\Delta_s|}\,, && (14)\\
\text{with} \qquad \phi_s^{\rm SM} &= (4.2 \pm 1.4) \cdot 10^{-3}\,. && (15)
\end{aligned}$$

By comparing experiment and theory, we can give bounds in the complex Δ-plane [a]. If nature would be such, that Δ has the values:

$$|\Delta| = 0.9\,, \qquad \phi_s^\Delta = \frac{\pi}{4}\,, \tag{16}$$

[a]The bounds in the complex Δ-plane are much more descriptive than in the $|\Delta|$-ϕ_s^Δ-plane, which is used also in the literature.

one would get the bounds shown in Fig. (2).

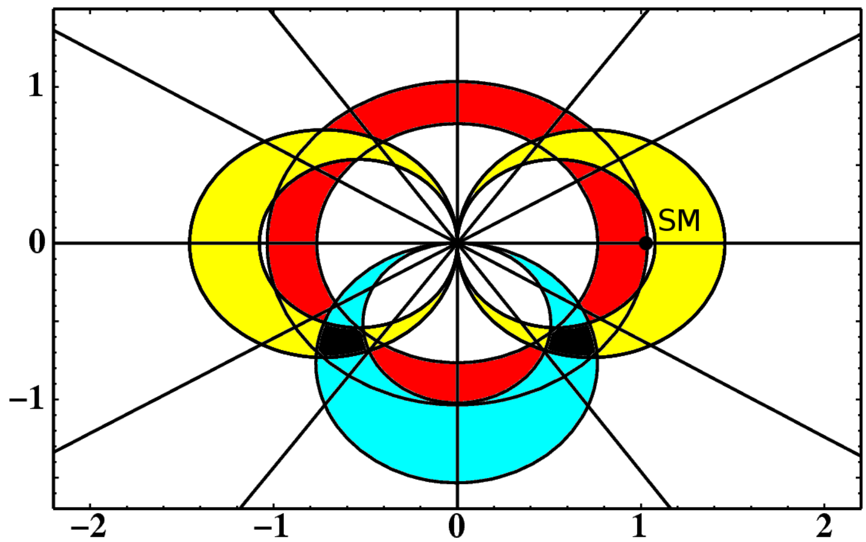

Fig. 2. The bounds in the complex Δ-plane, obtained by comparing experiment and theory for the mixing quantities. The red circle comes from ΔM_s, the yellow band from $\Delta\Gamma_s/\Delta M_s$, the light blue range from the semileptonic CP asymmetries and the rays through the origin from a direct determination of ϕ_s.

- ΔM_s gives a bound on the absolute value of Δ (c.f. Eq. (11)), which is represented by the red band in Fig. (2).
- ϕ_s^Δ can be obtained directly from the angular analysis of the decay $B_s \to J/\Psi\phi$. With a considerably worse accuracy this phase can also be obtained from $\Delta\Gamma_s$ (c.f. Eq. (12)).
- $\Delta\Gamma_s/\Delta M_s$ gives a bound on $\cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)/|\Delta|$ (c.f. Eq. (13)), which is represented by the yellow band in Fig. (2).
- $a_{\rm fs}^s$ gives a bound on $\sin\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)/|\Delta|$ (c.f. Eq. (14)), which is represented by the light blue band in Fig. (2).

The overlap of all these bounds gives the values for Re(Δ) and Im(Δ). Within the standard model one has Re(Δ)=1 and Im(Δ)=0.

3. Theoretical framework and uncertainties

In order to fulfill the above described program it is mandatory to have sufficient control over the theoretical uncertainities in the standard model predictions.

Inclusive decays can be described by the Heavy Quark Expansion (HQE),[45–52] for some recent examples see [53–55]. According to the HQE an inclusive decay rate can be expanded in inverse powers of the heavy b-quark mass

$$\Gamma = \Gamma_0 + \left(\frac{\Lambda_{QCD}}{m_b}\right)^2 \Gamma_2 + \left(\frac{\Lambda_{QCD}}{m_b}\right)^3 \Gamma_3 + \left(\frac{\Lambda_{QCD}}{m_b}\right)^4 \Gamma_4 + \dots . \quad (17)$$

In order to estimate the theoretical accuracy for the mixing quantities Γ_{12} and M_{12}, one first has to investigate the general validity of the expansion in Eq.(17). This was done many times in the literature under the name of *violations of quark-hadron duality*, see e.g. [56] and references therein. We follow a pragmatic strategy, as described in more detail in [5]: the calculation of the mixing quantities Γ_{12} is identical to the ones of the lifetimes, which are also known to NLO-QCD.[57,58] Since experiment and the HQE predicition agree very well,[5] we see no room for sizeable violations of quark-hadron duality.

All Γ_is in Eq.(17) are products of perturbatively calculable Wilson coefficients and of non-perturbative matrix elements. To be sure to achieve a reasonable theoretical accuracy we have to calculate up to a sufficient order in the HQE and in QCD (each Γ_i can be expanded as $\Gamma_i^{(0)} + \frac{\alpha_s}{\pi}\Gamma_i^{(1)} + ...$). In addition to the leading term $\Gamma_3^{(0)}$ the following corrections we done in the literature for Γ_{12}:

- 1996: Power corrections ($\Gamma_4^{(0)}$)[59] turned out to be sizable.
- 1998: NLO-QCD corrections ($\Gamma_3^{(1)}$)[60] to the leading term are also sizeable and of conceptual importance.
- 2000: In 1998 no lattice data for all arising matrix elements of four quark operators were available, the numerical update of [60] with lattice values was given in [61].
- 2003: NLO-QCD corrections ($\Gamma_3^{(1)}$) to all CKM structures were calculated in [62] and [63]. This was a relativeley small correction for $\Delta\Gamma$, but the dominant contribution to the semileptonic CP-asymmetries.
- 2004: At that time all corrections to the leading term of $\Delta\Gamma$ seemed to be unnatural large, this bad behaviour was summarized in [64].
- 2006: A reanalysis[9] of the theoretical determination of Γ_{12}, showed that

the above shortcommings were due to the use of an unproper operator basis with large unphysical cancellations, the use of the pole b-quark mass and the neglect of subleading CKM structures. Taking all this into account the theoretical uncertainty in Γ_{12}/M_{12} could be reduced by a facor of almost three.

- 2007: Higher power corrections $(\Gamma_5^{(0)})$[65] were estimated to be negligible.

Despite considerable efforts in the non-perturbative determination of the matrix elements of four-quark operators entering Γ_3, see [66] for a recent review, we still have a relatively limited knowledge of the decay constants, see e.g.[5] for more details, wich results in large uncertainties in ΔM_s and $\Delta\Gamma_s$ [b]. In Ref. [9] we used the conservative estimate $f_{B_s} = 240 \pm 40$ MeV, while [66] obtains the lattice average $f_{B_s} = 245 \pm 25$ MeV, which is very close to the most recent QCD sum rule estimate[67] $f_{B_s} = 244 \pm 21$ MeV. In Γ_{12}/M_{12} the decay constants cancel, and therefore $\Delta\Gamma_s/\Delta M_s$ and the semileptonic CP-asymmetries are theoretical well under control.
Summarizing we can state for the theoretical uncertainties in the B_s mixing quantities: $\Delta\Gamma_s$ and ΔM_s are completely dominated by the uncertainty in the decay constant f_{B_s}, while for $\Delta\Gamma_s/\Delta M_s$ and the semileptonic CP-asymmetries conservative error estimates yield errors of about $\pm 20\%$.[9]

4. Conclusions

The system of the neutral B_s mesons is ideally suited for the search for new physics effects. In particular the standard model predicts an almost vanishing mixing phase ϕ_s, while we have currently some experimental 2-3σ hints for a sizeable value of this phase. If this hints will be confirmed, then we have an unambiguous proof for new physics in flavor physics. Depending on the actual size of Δ a confirmation of the hints might already be possible at TeVatron or at an extended $\Upsilon(5s)$ run of Belle. Precision data on Δ will be available from LHC and from a Super-B factory.

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[b] ΔM_s and $\Delta\Gamma_s$ depend quadratically on f_{B_s}.

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