Addendum to: Implications of the measurements of $B_s$–$\bar{B}_s$ mixing on SUSY models

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This is an addendum to the previous publication, P. Ko and J.-h. Park, Phys. Rev. D80, 035019 (2009). The semileptonic charge asymmetry in $B_s$ decays is discussed in the context of general MSSM with gluino-mediated flavor and CP violation in light of the recent measurements at the Tevatron.

In this addendum to Ref. [1], we discuss the semileptonic charge asymmetry in the $B_s$ decays in general SUSY models with gluino-mediated flavor and CP violation, in light of the recent measurements of like-sign dimuon charge asymmetry by DØ Collaboration at the Tevatron. The model is described in Ref. [1], to which we refer for the details of the model and other phenomenological aspects related with $B_s$–$\bar{B}_s$ mixing, the branching ratio of and CP asymmetry in $B \rightarrow X_s \gamma$, $B_d \rightarrow \phi K_S$ and CP asymmetry in $B_s \rightarrow J/\psi \phi$.

One can define the semileptonic charge asymmetry in the decay of $B_s$ mesons as

$$a_{sl}^q \equiv \frac{ \Gamma(B^0_q(t) \rightarrow \mu^+ X) - \Gamma(B^\prime_0(t) \rightarrow \mu^- X) }{ \Gamma(B^0_q(t) \rightarrow \mu^+ X) + \Gamma(B^\prime_0(t) \rightarrow \mu^- X) },$$  \hspace{1cm} (1)

for $q = d, s$. In terms of the matrix elements of the effective Hamiltonian describing the damped oscillation between $B^0_q$ and $B^\prime_0$, the asymmetry $a_{sl}^q$ is given by

$$a_{sl}^q = \text{Im} \frac{ \Gamma_{12}^q }{ M_{12}^q } = \frac{ \Gamma_{12}^q }{ \sqrt{ M_{12}^q }^2 } \sin \phi_q,$$  \hspace{1cm} (2)

where $\phi_q \equiv \arg(-M_{12}^q/\Gamma_{12}^q)$. That is, this is another observable measuring CP violation in $B_s$–$\bar{B}_s$ mixing. We take the approximation, $\Gamma_{12}^q = \Gamma_{12}^{q,SM}$, since the leading contribution comes from the absorptive part of the box diagrams for $B_s$–$\bar{B}_s$ mixing and there is no new common final state into which both $B_s$ and $\bar{B}_s$ can decay in our scenario. The size of $M_{12}^q$ is fixed by the $\Delta M_q$ data up to hadronic uncertainties. Then, $a_{sl}^q$ can be regarded as a sine function of $\phi_q$, multiplied by the factor $|\Gamma_{12}^q|/|M_{12}^q|$. This curve is traversed as one allows for arbitrary supersymmetric contributions to $M_{12}^q$ obeying the $\Delta M_q$ constraint. Combining the SM predictions [2],

$$|\Gamma_{12}^{s,SM}|/|M_{12}^{s,SM}| = (49.7 \pm 9.4) \times 10^{-4},$$

$$\phi_s^{SM} = (4.2 \pm 1.4) \times 10^{-3},$$  \hspace{1cm} (3)

one finds the vanishingly small asymmetry $a_{sl}^{s,SM} \sim 2 \times 10^{-5}$.

Recently, the DØ collaboration reported a measurement of like-sign dimuon charge asymmetry [3]. They interpreted the result as coming from the mixing of neutral $B$ mesons and have found an evidence for an anomaly in the asymmetry,

$$A_{sl}^b = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}},$$  \hspace{1cm} (4)

where $N_b^{++}$ and $N_b^{--}$ are the number of events where decays of two $b$ hadrons yield two positive and two negative muons, respectively. Their result shows a discrepancy of 3.2σ from the SM expectation. This asymmetry consists of $a_{sl}^b$ coming from $B_d$ decays as well as $a_{sl}^s$ from $B_s$. One can extract the asymmetry relevant to the $B_s$ meson using the measured value of $a_{sl}^d$ and the result by DØ is

$$a_{sl}^s = -0.0146 \pm 0.0075.$$  \hspace{1cm} (5)

This is 1.9σ away from the SM prediction. We shall use this data in the following discussion.

This DØ result has drawn interest in new physics explanations [3–8]. (For earlier works, see e.g. Refs. [9–11].) Some of the works consider extra contributions to $\Gamma_{12}^q$ since the dimuon charge asymmetry depends on it as well as on $M_{12}^q$ [3–6]. This approach also has a possibility of altering $|\Delta M_s|$ even though its current experimental value is in agreement with the SM one, $2 |\Gamma_{12}^{s,SM} \cos \phi_s^{SM}|$ [2–12,13]. As we said, $\Gamma_{12}^q$ is fixed in the present work and we are left only with the option of modifying $M_{12}^q$. Therefore, $|\Delta M_s|$ shall become smaller than its SM prediction as $|\phi_s|$ grows up to $\mathcal{O}(1)$.

We perform the numerical analysis in the same way as in the main article [1]. The crucial ingredient for evaluating $a_{sl}^s$ is the range of $\phi_s$ to be used. Following the latest reports from DØ [3] and CDF [14], there have been a couple of attempts to make a global fit of $B_s$–$\bar{B}_s$ mixing parameters including $\phi_s$ [4–6]. However, the official combination is not available yet. Partly because of this reason and partly for the sake of coherent presentation, we keep using the range used in Refs. [1,15].

$$\phi_s \in [-1.10, -0.36] \cup [-2.77, -2.07].$$  \hspace{1cm} (6)

As a matter of fact, this range is not very different from the 2σ interval found in Ref. [3]. As for $\Gamma_{12}^{s,SM}/M_{12}^{s,SM}$, we take its central value from Eqs. (3). Considering the error in this ratio could add 20% more of uncertainty to the thickness of the $a_{sl}^s$ band in the following figures.

We show $a_{sl}^s$ as a function of $\phi_s$ for $\tan \beta = 3$ in Figs. 1. The four plots are for the LL, the RR, the $LL = RR$, and
FIG. 1. Plots of $a_{s1}$ as a function of $\phi_s$ for the four different cases with $\tan \beta = 3$. The hatched region is excluded by the $B \to X_s \gamma$ constraint. The hatched gray region leads to the lightest squark mass $< 100 \text{ GeV}$. The hatched region is allowed both by $\Delta M_s$ and $\phi_s$. The black square is the SM point. The dashed and solid lines (both red online) mark the 1$\sigma$ and 2$\sigma$ ranges of $a_{s1}$, respectively.

\[ LL = -RR \] cases, respectively. One can immediately notice the aforementioned sinusoidal dependence of $a_{s1}$ on $\phi_s$, coming from Eq. (2) and the $\Delta M_s$ constraint. This feature is not only true of all the cases shown here but also of any new physics model that does not affect $\Gamma_{12}$. The nonzero thickness of the band arises from the uncertainty in $\Delta M_s$. The difference between $a_{s1}$ and its central value is at least about 1.0$\sigma$. This discrepancy becomes worse but only slightly after $\phi_s$ is restricted inside its preferred ranges (colored in blue). If one incorporates the $B \to X_s \gamma$ constraint, substantial part of the blue regions is excluded, in particular in the upper two cases with one insertion. Even then, however, the lowest possible value of $a_{s1} \approx -0.006$ within the blue region does not change. In the lower two cases with two insertions, $B \to X_s \gamma$ does not play an important role since the supersymmetric effect on $B_s - \bar{B}_s$ mixing is enhanced.

Plots for $\tan \beta = 10$ are displayed in Figs. 2. The model-independent characteristics dictated by Eq. (2) remain exactly the same as in the previous set of figures. The only difference is the stronger $B \to X_s \gamma$ constraint due to higher $\tan \beta$. Here, it excludes more part of the blue regions. Again, this is particularly true of the upper two cases in which $a_{s1}$ is restricted closer to its SM value. In Fig. 2(a), $\Delta M_s$, $\phi_s$, and $B \to X_s \gamma$, together allow $a_{s1}$ to be as low as $-0.003$. In Fig. 2(b), there is no solution satisfying all the three constraints. One could get $a_{s1} \approx -0.0006$ if $\phi_s$ were not limited. In the lower two cases, the lowest $a_{s1}$, compatible with $\Delta M_s$ and $\phi_s$, is almost the same as in Figs. 1.

We summarize. We have examined how $a_{s1}$ is influenced by the $LL$ and/or $RR$ mass insertions. For $\tan \beta = 3$, one can reduce the discrepancy between $a_{s1}$ and its SM expectation from 1.9$\sigma$ down to 1.0$\sigma$ in each
of the $LL$, $RR$, $LL = RR$, and $LL = -RR$ cases, obeying the $\Delta M_s$, $B \rightarrow X_s \gamma$, and $\phi_s$ constraints. This amounts to reduction of the $A_{t \ell}^0$ tension from $3.2\sigma$ down to $2.2\sigma$ if one assumes no new physics in the $b \rightarrow d$ transition. For $\tan\beta = 10$, it becomes difficult for the $LL$ and $RR$ cases whereas the $LL = RR$ and $LL = -RR$ cases are less limited by $B \rightarrow X_s \gamma$.

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NOTE ADDED

While we were waiting for the approval for submission, a paper by J. K. Parry appeared on the e-print archive that employs a related model [8]. However, the flavor structure of the squark mass matrix therein is different from any of those here. As far as squarks are concerned, he considers only one case where $(\delta_{23})_{RR}$ is a variable parameter and $(\delta_{23})_{LL}$ is fixed to a value that comes from renormalization group running. This way of parameter scan is not covered in this work. He does not display the $B \rightarrow X_s \gamma$ constraint on his plots, but it may not be very restrictive in his case depending on $\mu$ and $\tan\beta$. (See e.g. Fig. 4 in Ref. [16].)

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