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# $B_s$ Decays and Mixing

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Theoretical remarks are offered regarding recent hadron collider results on the mixing and decays of $B_s$ mesons. Topics covered include: (1) CP-violating mixing in $B_s(\overline{B}_s) \to J/\psi\phi$, (2) the D0 dimuon charge asymmetry, (3) information from triple products, (4) $B_s \to J/\psi f_0$, (5) new physics constraints, (6) some illustrative new physics scenarios.

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## 1. Introduction

Recent results on $B_s$ decays and mixing have been presented by the CDF and D0 Collaborations at the Fermilab Tevatron and the LHCb Collaboration at CERN. We begin by discussing CP-violating mixing in $B_s$ $(\overline{B}_s) \to J/\psi\phi$. Experiments at CDF and D0 suggested a mixing phase $\beta_s$ much larger than that in the Standard Model (SM). With such a large phase, we pointed out that time-dependent decays should display explicit time-dependence [1]. We update that analysis in Section 2.

The D0 Collaboration has presented evidence for a charge asymmetry in same-sign dimuons produced in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV [2]. We suggest in Section 3 a test of whether this asymmetry is due to decays of $b$ quarks, as claimed, or background sources such as kaons [3].

In Section 4 we discuss what triple products in $B_{(s)} \to V_1 V_2$ actually measure. The answer [4] is CP violation, but only under certain conditions. The study of $B_s \to J/\psi f_0$, mentioned in Section 5, avoids the angular analysis needed to interpret $B_s \to J/\psi\phi$. In Section 6, we note constraints on new physics, and comment in Section 7 on a couple of scenarios for consideration should any hints for physics beyond the SM be borne out by further tests. We conclude in Section 8.

## 2. CP violation in interference between $B_s$–$\overline{B}_s$ mixing and $B_s \to J/\psi\phi$ decay

For formalism we refer to [5]. $B_s$–$\overline{B}_s$ mixing is expected to be dominated by the top quark in box graphs. The observed values $\Delta m_s = (17.77 \pm 0.10 \pm 0.07)$ ps$^{-1}$ (CDF [6]) and $(17.63 \pm 0.11 \pm 0.04)$ ps$^{-1}$ (LHCb [7]) agree with SM predictions. Denoting

$$|B_{sL}\rangle = p|B_s\rangle + q|\overline{B}_s\rangle \ ; \ \ |B_{sH}\rangle = p|B_s\rangle - q|\overline{B}_s\rangle \ , \tag{2.1}$$

we expect for $\Delta\Gamma \ll \Delta m$, $q/p \simeq \exp(2i\beta_s)$, $\beta_s^{\rm SM} = -{\rm Arg}(-V_{ts}^* V_{tb}/V_{cs}^* V_{cb}) = (1.04 \pm 0.05)^\circ$ [5]. The SM $B_s \to J/\psi\phi$ CP asymmetry then should be governed by the small mixing phase $\phi_M = -2\beta_s^{\rm SM}$.

In 2008, CDF [8] and D0 [9] favored a mixing phase differing from $-2\beta_s^{\rm SM}$ by $\sim 2.2\sigma$ based on the decay $B_s \to J/\psi\phi$. At that time we pointed out that such a large mixing phase (the illustrative value was then $\phi_M = -44^\circ$ [8]) would imply detectable time-dependence of angular distribution coefficients, differing for tagged $B_s$ and $\overline{B}_s$ [1].

We review the discussion briefly. For a CP test, one tags the flavor at $t = 0$, denoting $\eta = \pm 1$ for a tagged $(B_s, \overline{B}_s)$. The coefficients of helicity amplitudes $|A_\parallel|^2$, $|A_\perp|^2$ describing different angular dependences are denoted by $\mathscr{T}_+$, $\mathscr{T}_-$, where

$$\mathscr{T}_\pm \equiv e^{-\Gamma t}[\cosh(\Delta\Gamma t)/2 \mp \cos(\phi_M)\sinh(\Delta\Gamma t)/2 \pm \eta\sin(\phi_M)\sin(\Delta m_s t)] \ . \tag{2.2}$$

Taking $\phi_M = -44^\circ$, $\Delta\Gamma/\Gamma = 0.228$, and assuming the tagging $\eta$ to be diluted by a factor of 0.11, we concluded that wiggles should be distinguishable between the $B_s$-tagged and $\overline{B}_s$-tagged $\mathscr{T}_\pm$ distributions. We advocated making such a plot as evidence for CP violation in $B_s \to J/\psi\phi$ at a level beyond the SM. Here we update our estimate of $t$-dependence, finding the oscillations a bit smaller, but still visible. We take $\phi_M = (-39 \pm 17)^\circ$ based on an average between CDF [10, 11] and D0 [12] values, choose $\Delta\Gamma/\Gamma = 0.143$ based on an average between CDF $(0.075 \pm 0.035 \pm 0.010)$ and D0 $(0.15 \pm 0.06 \pm 0.01)$, and continue to assume a dilution factor of 11%. The resulting plot is shown in Fig. 1.

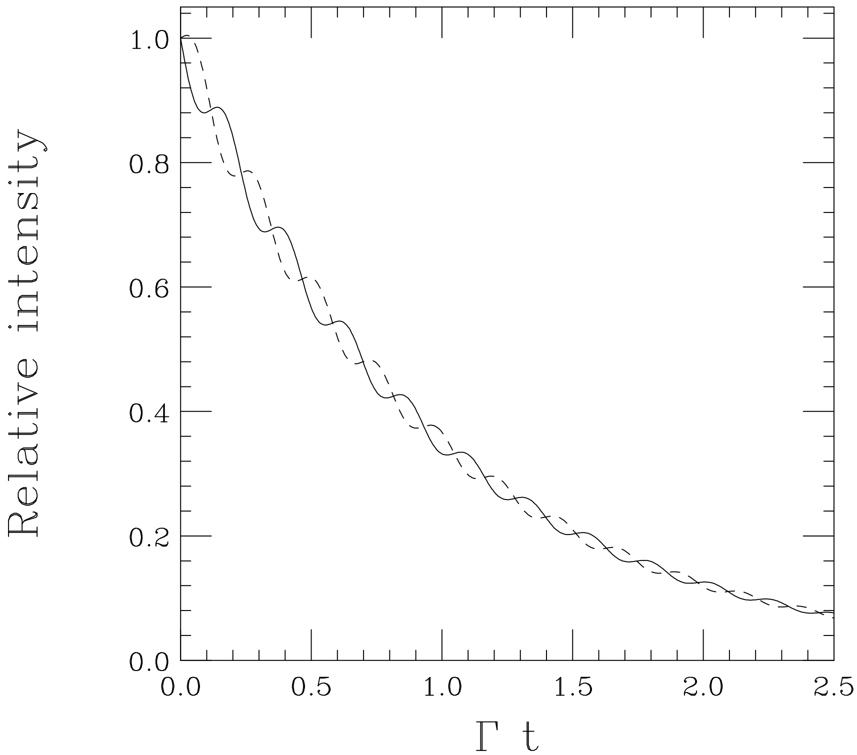


**Figure 1:** Relative intensities of $\mathscr{T}_+$ signals as functions of $\Gamma t$, for $B_s$ tags (solid) and $\overline{B}_s$ tags (dashed). This figure represents an update of a similar one in Ref. [1].

At this Conference, LHCb presented data restricting $\phi_M$ to the range $[-2.7, -0.5]$ [13] (68% c.l.), $1.2\sigma$ from the SM. We are eagerly awaiting data from ATLAS and CMS.

## 3. D0 dimuon asymmetry – Is it due to *b*'s? *K*'s?

The SM predicts a small asymmetry in the yield of same-sign muon pairs due to $b\bar{b}$ production followed by meson $\Leftrightarrow$ antimeson oscillation: $A^b_{sl} \equiv \frac{N^{++}-N^{--}}{N^{++}+N^{--}} = (-2.0 \pm 0.3) \times 10^{-4}$ [14]. The D0 Collaboration reports a much larger value, $A^b_{sl} = (-9.57 \pm 2.51 \pm 1.46) \times 10^{-3}$, nearly 50 times the SM value [2]. (CDF is not ready to report such a measurement but has quoted a new average mixing parameter $\bar{\chi}$ [15].)

D0 has interpreted its result as $3.2\sigma$ evidence for CP violation in neutral $B$ mixing. They have performed 16 systematic checks for which their results are found consistent with their nominal ones. Estimating the correct kaon decay backgrounds is crucial.

We have suggested a test [3] to see if a smaller asymmetry is obtained in a sample depleted in $b\bar{b}$ pairs. If one reduces the maximum allowed impact parameter of muon tracks, the signal should vanish more rapidly than background. The effect of our suggestion, an impact parameter cut of $b < 100\mu$m, is not yet known to us.

We denote quantities in the $B$ rest frame with an asterisk (*) and those in the lab frame with none. The lab energy of the $B$ is $E_B = \gamma m_B = m_B/\sqrt{1-\beta^2}$. Muon angles with respect to the $B$

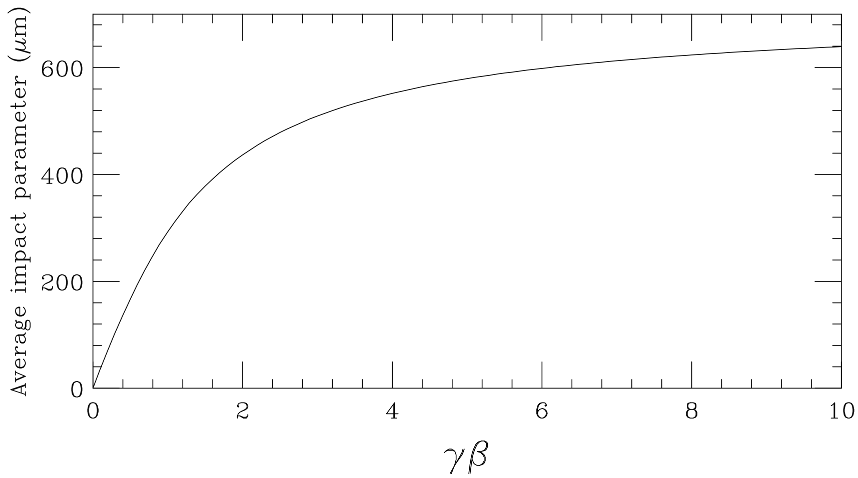


**Figure 2:** Dependence of $\langle b \rangle$ on $\gamma\beta$ [3].

**Table 1:** Fraction of events remaining for a given $\langle b \rangle$ when events with $b > b_0$ are discarded [3].

| $b_0$ ($\mu$m)<br>$\langle b \rangle$ ($\mu$m) | 100 | 200 | 300 | 400 | 500 |
|---|---|---|---|---|---|
| 150 | 0.237 | 0.542 | 0.748 | 0.866 | 0.930 |
| 300 | 0.080 | 0.237 | 0.400 | 0.542 | 0.658 |
| 450 | 0.040 | 0.129 | 0.237 | 0.347 | 0.450 |

boost are denoted by $\theta^*$ in the $B$ rest frame and $\theta$ in the lab. The transformation between them is $\sin\theta = \sin\theta^*/[\gamma(1+\beta\cos\theta^*)]$. The isotropy of muon emission in $\cos\theta^*$ can be used to calculate the average values of $\sin\theta$ and $b = \gamma\beta\sin\theta c\tau$, where $c\tau = 450\mu$m and

$$\langle \sin\theta \rangle = \frac{1}{2}\int_0^\pi \frac{\sin^2\theta^* d\theta^*}{\gamma(1+\beta\cos\theta^*)} = \frac{\pi}{2}\frac{1}{1+\gamma} \ . \qquad (3.1)$$

The dependence of $\langle b \rangle$ on $\gamma\beta$ is shown in Fig. 2.

An eyeball fit to the CDF $b$ distribution [16] gives $\langle b \rangle = 350$ $\mu$m. Table 1 denotes the effect of discarding events with $b$ exceeding various values of $b_0$.

The D0 Collaboration defines a transverse impact parameter $b_\perp$ relative to the closest primary vertex and a longitudinal distance $b_\parallel$ from the point of closest approach to this vertex. They choose $b_\perp < 3000$ $\mu$m and $b_\parallel < 5000$ $\mu$m. These are related to $b$ as follows. The transverse and longitudinal components of muon momentum in the lab are $p_\perp^\mu = p^\mu \sin\psi$, $p_\parallel^\mu = p^\mu \cos\psi$. The distance $d$ of a point along the $\mu$ trajectory from the vertex is $d^2 = b_\perp^2 + (s\sin\psi)^2 + (s\cos\psi - b_\parallel)^2$, where $s =$ is the distance along the $\mu$ trajectory from the transverse point of closest approach. The minimum of $d$ is $b = d_{\rm min} = [b_\perp^2 + (b_\parallel \sin\psi)^2]^{1/2}$. Little signal reduction is seen with $b_\perp < 500$ $\mu$m, $b_\parallel < 500$ $\mu$m [2], but we advocate a tighter cut. The key question remains with regard to D0 muons:

are they really from $b$ decays? This question should be answered by imposing an upper bound of $b_0 < 100\mu$m on the impact parameter $b_0$.

## 4. What do triple products in $B_{(s)} \to V_1 V_2$ measure?

A spinless particle decaying to four spinless particles gives rise to three independent momenta in its rest frame. One can form a T-odd expectation value out of (e.g.) $\mathbf{p_1} \times \mathbf{p_2} \cdot \mathbf{p_3}$ [4, 17]. A famous example is the asymmetry of $(13.6 \pm 1.4 \pm 1.5)\%$ in $K_L \to \pi^+\pi^- e^+ e^-$ reported by the KTeV Collaboration [18]. However, what if two or more of the final-state particles are identical?

Consider the double-Dalitz decay of a CP-mixture (like $K_L$) to $e^+e^-e^+e^-$. (see, e.g., [19]). For low $M(e^+e^-)$ this process is like $K_L \to \gamma\gamma$, with photons having relative linear polarizations $(\|, \perp)$ for CP = $(+,-)$. Interference between CP-even and -odd decays can give a non-vanishing value of $\langle \sin\phi \cos\phi \rangle$, where $\phi$ is the angle between normals to the $e^+e^-$ planes.

Now consider the case of $B \to V_1 V_2$, with each $V$ decaying to two pseudoscalar mesons $P$. (For an extensive discussion of the formalism, see [20].) One extracts triple products (TPs) from angular analyses:

$$A_T \equiv \frac{\Gamma(\mathrm{TP} > 0) - \Gamma(\mathrm{TP} < 0)}{\Gamma(\mathrm{TP} > 0) + \Gamma(\mathrm{TP} < 0)}~;~~\mathrm{TP} \equiv p_1 \cdot (p_2 \times p_3)~; \tag{4.1}$$

they are tiny in the SM. A true T-violation is signified by

$$\mathscr{A}_T^{\mathrm{true}} \equiv \frac{\Gamma(\mathrm{TP} > 0) + \bar{\Gamma}(\mathrm{TP} > 0) - \Gamma(\mathrm{TP} < 0) - \bar{\Gamma}(\mathrm{TP} < 0)}{\Gamma(\mathrm{TP} > 0) + \bar{\Gamma}(\mathrm{TP} > 0) + \Gamma(\mathrm{TP} < 0) + \bar{\Gamma}(\mathrm{TP} < 0)}~. \tag{4.2}$$

The matrix element for $B(p) \to V_1(k_1, \varepsilon_1) + V_2(k_2, \varepsilon_2)$ can be written

$$M = a\varepsilon_1^* \cdot \varepsilon_2^* + \frac{b}{m_B^2}(p \cdot \varepsilon_1)(p \cdot \varepsilon_2) + i\frac{c}{m_B^2}\varepsilon_{\mu\nu\rho\sigma} p^\mu q^\nu \varepsilon^{*\rho} \varepsilon^{*\sigma}~;~~q \equiv k_1 - k_2 \tag{4.3}$$

The transversity amplitudes depend on $a, b, c$ as $A_\|(a)$, $A_0(a,b)$, and $A_\perp(c)$. Under CP conjugation, $a \to \bar{a}$, $b \to \bar{b}$, $ic \to -i\bar{c}$. Angular distributions depend on the angle $\phi$ and polar angles $\theta_1$, $\theta_2$, each in the rest frame of the decaying $V_1$ or $V_2$:

$$\begin{aligned}\frac{d\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} &\sim |A_0|^2 \cos^2\theta_1 \cos^2\theta_2 + (1/2)|A_\perp|^2 \sin^2\theta_1 \sin^2\theta_2 \sin^2\phi \\ &+ (1/2)|A_\||^2 \sin^2\theta_1 \sin^2\theta_2 \cos^2\phi + (1/2\sqrt{2})\mathrm{Re}(A_0 A_\|^*) \sin 2\theta_1 \sin 2\theta_2 \cos\phi \\ &- (1/2\sqrt{2})\mathrm{Im}(A_\perp A_0^*) \sin 2\theta_1 \sin 2\theta_2 \sin\phi - (1/2)\mathrm{Im}(A_\perp A_\|^*) \sin^2\theta_1 \sin^2\theta_2 \sin 2\phi~.\end{aligned} \tag{4.4}$$

The last two terms are T-odd and of two distinct types.

The interfering amplitudes are characterized by a weak phase difference $\phi_w$ and a strong phase difference $\delta$. In addition to the "true" TP $\mathscr{A}_T^{\mathrm{true}}$ defined above, one can define [4] a "fake" TP:

$$\mathscr{A}_T^{\mathrm{fake}} = \frac{\Gamma(\mathrm{TP} > 0) - \bar{\Gamma}(\mathrm{TP} > 0) - \Gamma(\mathrm{TP} < 0) + \bar{\Gamma}(\mathrm{TP} < 0)}{\Gamma(\mathrm{TP} > 0) + \Gamma(\mathrm{TP} > 0) + \Gamma(\mathrm{TP} < 0) + \Gamma(\mathrm{TP} < 0)}~, \tag{4.5}$$

**Table 2:** Longitudinal and transverse fractions $f_L$ and $f_T$ for some $b \to s$-penguin $B \to VV$ processes.

| | $B_s \to \phi\phi$ [22] | $B^+ \to \phi K^{*+}$ [23] | $B^+ \to \rho^0 K^{*+}$ [24] | $B^0 \to \rho^0 K^{*0}$ [24] |
|---|---|---|---|---|
| $f_L$ | 0.348±0.041±0.021 | 0.49±0.05±0.03 | 0.52±0.10±0.04 | 0.57±0.09±0.08 |
| $f_T$ | 0.652±0.041±0.021 | 0.51±0.05±0.03 | 0.48±0.10±0.04 | 0.43±0.09±0.08 |

where $\mathrm{TP_{true}} \propto \sin\phi_w \cos\delta$, $\mathrm{TP_{fake}} \propto \cos\phi_w \sin\delta$. The two T-odd observables are

$$A_T^{(1)} \equiv \frac{\mathrm{Im}(A_\perp A_0^*)}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2} \ , \ \ A_T^{(2)} \equiv \frac{\mathrm{Im}(A_\perp A_\parallel^*)}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2} \ . \tag{4.6}$$

For CP conjugates, one has similar definitions with barred amplitudes and a minus sign from complex conjugation of the imaginary coefficient of $c$. The TP asymmetries $\mathscr{A}_T$ then satisfy

$$\mathscr{A}_T^{\rm true} \propto \mathrm{Im}(A_\perp A_i^* - \bar{A}_\perp \bar{A}_i^*) \ , \ \ \mathscr{A}_T^{\rm fake} \propto \mathrm{Im}(A_\perp A_i^* + \bar{A}_\perp \bar{A}_i^*) \ , \ \ (i = 0, \|) \ . \tag{4.7}$$

The observables $A_T^{(1,2)}$ are related to those in Dorigo's talk [21] by "$u$" $\leftrightarrow A_T^{(2)}$; "$v$" $\leftrightarrow A_T^{(1)}$; he reports on their measurement in $B_s \to \phi\phi$.

The decays $B \to \phi K^*$ and $B_s \to \phi\phi$ are both dominated by the $b \to s$ penguin diagram. Factorization predicts dominant longitudinal polarization of the vector mesons, in contrast to observations [22, 23, 24] (Table 2). By contrast, the tree-dominated decay $B^0 \to \rho^+\rho^-$ has $f_L = 0.992 \pm 0.024^{+0.026}_{-0.013}$ [25], or nearly 1 as predicted. There is no reason to trust factorization for the penguin amplitude, which may be due to rescattering from charm-anticharm intermediate states.

From $B^0 \to \phi K^{*0}$ amplitudes quoted by [4] we estimate

$$A_T^{(1)} = -0.260 \pm 0.048; \ \bar{A}_T^{(1)} = 0.203 \pm 0.050; \ A_T^{(2)} = 0.005 \pm 0.070; \ \bar{A}_T^{(2)} = 0.010 \pm 0.064. \tag{4.8}$$

These values imply a large fake $A_T^{(1)}$ (since $A_T^{(1)} - \bar{A}_T^{(1)} \neq 0$); no true $A_T^{(1)}$ (since $A_T^{(1)} + \bar{A}_T^{(1)}$ is consistent with zero); and no fake *or* true $A_T^{(2)}$ (since both $A_T^{(2)}$ and $\bar{A}_T^{(2)}$ are consistent with zero). The large fake $A_T^{(1)}$ simply reflects the importance of strong final-state phases.

## 5. $B_s \to J/\psi\phi$ vs. $B_s \to J/\psi f_0$

Helicity or transversity analysis for $B_s \to J/\psi\phi$ (S-, P-, D-wave) is avoided for $B_s \to J/\psi f_0$ (pure P-wave). As CP($J/\psi$) = CP($f_0$) = +, the overall final state is CP odd. An estimate of the rate for this process [26] is

$$R_{f_0/\phi} \equiv \frac{\Gamma(B_s \to J/\psi f_0, \ f_0 \to \pi^+\pi^-)}{\Gamma(B_s \to J/\psi\phi, \ \phi \to K^+K^-)} \simeq 20\% \ , \tag{5.1}$$

to be compared with experimental values $0.252^{+0.046+0.027}_{-0.032-0.033}$ [27], $\simeq 0.18$ ($\sim$ 30% stat. error) [28], and $0.292 \pm 0.020 \pm 0.017$ [21]. The CKM structure for this process is the same as for $B_s \to J/\psi\phi$. Although $f_0$ decays mainly to $\pi\pi$, it seems to be "fed" mainly from $s\bar{s}$: Comparing $J/\psi \to \phi\pi\pi$ and $J/\psi \to \omega\pi\pi$ [29], one sees a $\pi\pi$ peak at $M(f_0) \simeq 980$ MeV in $\phi\pi\pi$, not $\omega\pi\pi$.

## 6. New physics constraints

Two (of $\sim 100$) theoretical analyses [30, 31] emphasize the correlation between $a^q_{sl}$, $\Delta m_q$, $\Delta\Gamma_q$, and the mixing angle $\phi_q$, where $A^b_{sl} = (0.506 \pm 0.043)a^d_{sl} + (0.494 \pm 0.043)a^s_{sl}$. The questions of whether $\beta_s$ or $a^q_{sl}$ are nonstandard are separate; they are related by $a^q_{sl} = (|\Delta\Gamma_q|/\Delta m_s)\tan\phi_q$. If the D0 dimuon asymmetry is mainly from $a^s_{sl}$, Ref. [31] finds $a^s_{sl} = (-12.5 \pm 4.8) \times 10^{-3}$ by combining with the D0 measurement $(-1.7 \pm 9.1) \times 10^{-3}$. Using in this formula the (CDF, LHCb) average $\Delta m_s = (17.70 \pm 0.08)$ ps$^{-1}$ and the (CDF, D0) average $\Delta\Gamma_s = 0.094 \pm 0.031$ ps$^{-1}$, one expects $\phi_s = (-67^{+18}_{-7})^\circ$. Comparing with $\phi^s_M = (-39 \pm 17)^\circ$, this would favor slightly larger $\Delta\Gamma_s$ or a nonstandard value of $a^d_{sl}$. In Ref. [5] it is noted that one must respect the SM prediction of $\Delta m_q$. New physics must affect mainly *phases* of mixing amplitudes.

## 7. A cursory look at new physics scenarios

Supersymmetry has generic flavor-changing (but controllable) effects [32]. Randall-Sundrum [33] scenarios in which different quarks lie at different points along a fifth dimension offer a language for understanding quark mixings; but there is no predictive scheme yet. Theories with an extra (flavor-changing) $Z$ can induce mixing as desired. In Ref. [31] a contribution to $\Delta\Gamma$ is introduced through a new light pseudoscalar (an on-shell state in $B_s \leftrightarrow \overline{B}_s$). These are just some examples of a wealth of models on the market. Some of them predict other observable consequences but there are too many to enumerate exhaustively. Two of my current favorites are (1) a fourth generation, and (2) a hidden sector.

Lunghi and Soni [34] note the tension between $\sin 2\beta = \sin 2\phi_3 = 0.668 \pm 0.023$ (measured in $B$ decays) and that $(0.867 \pm 0.048)$ in (their) CKM fit. They note effects of new physics on both $\Delta$Flavor $= 1$ (penguin) and $\Delta$Flavor $= 2$ (box) amplitudes but give no specifics on $\beta_s$ or $a^s_{sl}$.

In a "hidden sector" let an extended gauge sector $G$ describe dark matter, and let there be particles $Y$ with charges in both the SM and in $G$, and particles $X$ with charges only in $G$. A box diagram describing $B_s$–$\overline{B}_s$ mixing in this scenario is shown in Fig. 3. Table 3 gives examples of ordinary, mixed, and "shadow" matter. There are clearly many opportunities in such a scenario for new contributions to penguin and box diagrams.

**Table 3:** Types of matter and their SM and hidden charges.

| Type of matter | Std. Model | G | Example(s) |
|---|---|---|---|
| Ordinary | Charged | Uncharged | Quarks, leptons |
| Mixed ($Y$) | Charged | Charged | Superpartners |
| Shadow ($X$) | Uncharged | Charged | $E'_8$ of $E_8 \otimes E'_8$ |

## 8. Summary

$B_s$ decays and mixing provide potential mirrors of new physics. While the phase $\beta_s$ has moved toward its Standard Model value, even the currently measured value of $\beta_s$ should be manifested in

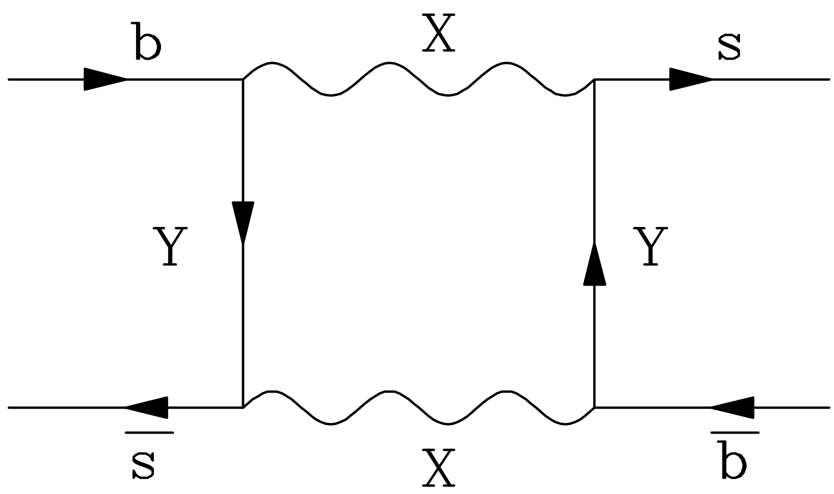


**Figure 3:** Diagram utilizing a hidden sector describing $B_s$–$\overline{B}_s$ mixing.

time-dependent quantities.

The D0 collaboration [2] claims a dimuon charge asymmetry. At this conference [15] CDF has reported a remeasurement of $\bar{\chi}$ and we look forward to their further progress on dimuons. The signal requires subtraction of a big kaon background. Is what's left really due to $b$ quark decays? We have proposed an impact parameter cut of $b < 100$ $\mu$m to find out [3].

Using triple products in four-body decays, one can construct T-odd observables providing strong and weak phase information. There is interest in what new physics one can learn from $B_s \to \phi\phi$ [21].

As for whether there is new physics in any of the above hints, I urge you to have your favorite model ready; there are enough to go around.

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PoS(BEAUTY 2011)045