Phenomenology of quark singlet models

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Abstract

Recent development in flavor physics is described. We show the elements of the quark mixing matrix, Cabibbo-Kobayashi-Maskawa (CKM) matrix [1,2]. In addition, we discuss the Bs physics, and then the phenomena appearing in quark singlet models.

1. Introduction

The CKM matrix in the Standard Model (SM) is given by a 3×3 unitary matrix,

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} . \tag{1.1}$$

This matrix may be written by using the Wolfeinstein parameterization [3] as

$$V_{CKM} = \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4) . \tag{1.2}$$

The unitarity constraints are represented by the six independent triangles as shown in Fig.1.

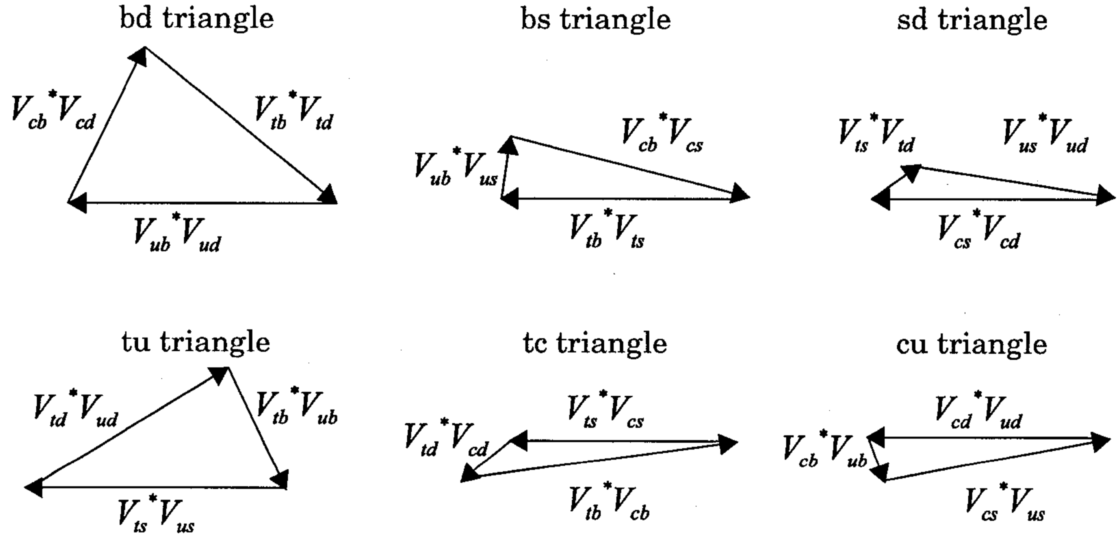


Fig.1. The CKM unitarity triangles.

Especially, the "bd triangle" has been investigated so far, and the corresponding elements are determined experimentally. Each result shows the success of the SM, but phenomena by New Physics (NP) may not be excluded. Now we are at the stage for precise measurement of this triangle at the B factories. For the Bs physics, the mass difference Δm_{B_s} is experimentally determined by CDF and D0, and the other parameters will be measured by LHCb in the near future.

This article is organized as follows. The experimentally determined values of the CKM matrix elements are reviewed in Sec. 2. Then, the experimental results and expectations for the Bs physics are described in Sec. 3. In Sec. 4, possible NP in quark singlet models is discussed. Sec. 5 is devoted to summary.

2. The CKM matrix elements

2-1. The sides

2-1-1. $|V_{ud}|$

The magnitude of V_{ud} is determined from the nuclear beta decays ($0^+ \to 0^+$) and semileptonic charged pion decay ($\pi^+ \to \pi^0 e^+ \nu$) as

$$|V_{ud}| = 0.97377 \pm 0.00027 \quad \text{(nuclear beta decays) [4,5],}$$
$$|V_{ud}| = 0.9728 \pm 0.0026 \quad \text{(pion decay) [6].} \qquad (2.1)$$

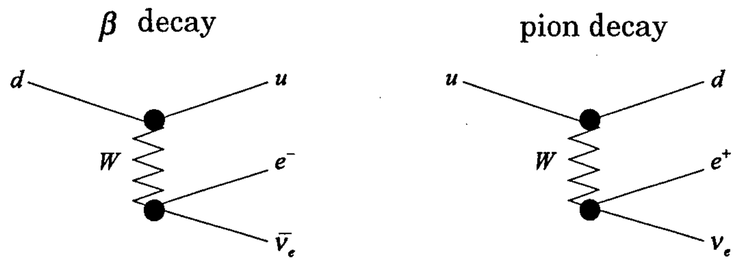


Fig.2. Nuclear beta decay and pion decay.

These results agree with each other in high accuracy. The effect of NP will be small.

2-1-2. $|V_{us}|$

The most traditional measurement of V_{us} is from the semileptonic kaon decay ($K^+ \to \pi^0 e^+ \nu$). It provides

$$|V_{us}| = 0.2257 \pm 0.0021 \text{ [7]}. \quad (2.2)$$

The other measurements are from the leptonic kaon decays ($K \to \mu\nu(\gamma)$), hyperon decays, and τ decays. From the kaon decays and hyperon decays, respectively, the ratio $|V_{us}/V_{ud}|$ is determined to provide

$$|V_{us}| = 0.2245^{+0.0012}_{-0.0031} \text{ (kaon decays) [8]},$$
$$|V_{us}| = 0.2250 \pm 0.0025 \text{ (hyperon decays) [9]}. \quad (2.3)$$

These results agree with each other in high accuracy. The effect of NP will be small.

2-1-3. $|V_{cd}|$

$|V_{cd}|$ can be extracted from the semileptonic charm decay ($D^0 \to \pi^- e^+ \nu$) with lattice QCD as

$$|V_{cd}| = 0.213 \pm 0.008 \pm 0.021 \text{ [10]}. \quad (2.4)$$

The difference of the ratios of the double-muon to single-muon productions by neutrino and antineutrino beams is proportional to

$$B_\mu |V_{cd}|^2 = (0.463 \pm 0.034) \times 10^{-2} \text{ [11].} \quad (2.5)$$

Then, using the next-to-leading-order QCD analysis, we obtain

$$|V_{cd}| = 0.230 \pm 0.011 \text{ [11].} \quad (2.6)$$

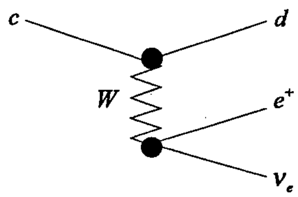


Fig.3. Semileptonic charm decay ($D_s^+ \to \ell^+ \nu$).

$$\nu_\mu + N \to \mu^- + c(\to \mu^+ + \nu_\mu) + X$$
$$\bar{\nu}_\mu + N \to \mu^+ + \bar{c}(\to \mu^- + \bar{\nu}_\mu) + X$$

Fig.4. Muon productions by neutrino and antineutrino beams.

2-1-4. $|V_{cs}|$

$|V_{cs}|$ is obtained from the on-shell $W^\pm$ decays ($W^+ \to c\bar{s}, W^- \to \bar{c}s$) as

$$|V_{cs}| = 0.94^{+0.32}_{-0.26} \pm 0.13 \text{ [12].} \quad (2.7)$$

Another determination is possible from leptonic the Ds decays ($D_s^+ \to \ell^+ \nu$) and semileptonic D decays ($D \to K\ell\nu, D \to \pi\ell\nu$) with lattice QCD calculation. It provides

$$|V_{cs}| = 0.957 \pm 0.017 \pm 0.093 \text{ [13].} \quad (2.8)$$

These results agree with each other, thus NP will not affect these processes.

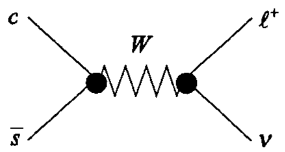


Fig.5. Leptonic Ds decay ($D_s^+ \to \ell^+ \nu$).

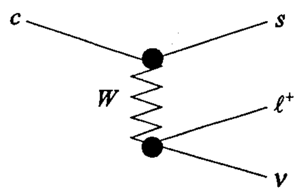


Fig.6. Semileptonic charm decay ($D \to K\ell\nu$).

2-1-5. $|V_{cb}|$

$|V_{cb}|$ is measured from the inclusive and exclusive decays of B mesons. The inclusive decays ($b \to c\ell\bar{\nu}, b \to s\gamma$) provide [14]

$$|V_{cb}| = (41.7 \pm 0.7) \times 10^{-3}, \tag{2.9}$$

while the exclusive decays ($B \to D^{*}\ell\nu$) provide

$$|V_{cb}| = (40.9 \pm 1.8) \times 10^{-3}. \tag{2.10}$$

The average is given as

$$|V_{cb}| = (41.6 \pm 0.6) \times 10^{-3}. \tag{2.11}$$

These results agree with each other. NP contribution will be negligible.

2-1-6. $|V_{ub}|$

$|V_{ub}|$ is not measured so precisely because it is hard to distinguish $b \to u$ from $b \to c$ transitions. This is due to the smallness of $|V_{ub}|$ compared with $|V_{ub}|$. Measurements of the inclusive decays ($b \to u\ell\bar{\nu}, b \to s\gamma$) and exclusive decays ($B \to \pi\ell\nu$) have been performed. These results are shown in Table 1-1 and 1-2 [15].

Table 1-1. $|V_{ub}|$ from the inclusive decays [HFAG winter 2006].

Group (analysis)	$\|V_{ub}\|$
CLEO (endpoint)	$4.09 \pm 0.48 \pm 0.36$
BELLE (endpoint)	$4.82 \pm 0.45 \pm 0.30$
BABAR (endpoint)	$4.41 \pm 0.29 \pm 0.31$
BABAR (E_e, q^2)	$4.10 \pm 0.27 \pm 0.36$
BELLE (m_x)	$4.06 \pm 0.27 \pm 0.24$
BELLE (m_x, q^2)	$4.37 \pm 0.46 \pm 0.29$
BABAR (m_x, q^2)	$4.75 \pm 0.35 \pm 0.32$
Average	$4.45 \pm 0.20 \pm 0.26$

Table 1-2. $|V_{ub}|$ from the exclusive decays [HFAG winter 2006].

Group (analysis)	$\|V_{ub}\|$
Ball-Zwicky ($q^2 < 16$)	$3.36 \pm 0.15 {}^{+0.55}_{-0.37}$
HPQCD ($q^2 < 16$)	$4.20 \pm 0.29 {}^{+0.63}_{-0.43}$
FNAL ($q^2 < 16$)	$3.75 \pm 0.26 {}^{+0.65}_{-0.43}$
APE ($q^2 < 16$)	$3.78 \pm 0.26 {}^{+1.45}_{-0.67}$

The annihilation process for $B^- \to \tau^- \bar{\nu}$ can be used to constrain $|V_{ub}|$ Due to the helicity suppression term, there is practically no possibility to perform branching fraction measurements of $B \to \mu(e)\nu$ at the B factories. The constraint is given as

$$B(B^- \to \tau^- \bar{\nu}) = \frac{G_F{}^2 m_B m_\tau{}^2}{8\pi}\left(1 - \frac{m_\tau{}^2}{m_B{}^2}\right) \times f_B{}^2 |V_{ub}|^2 \tau_B < 2.6 \times 10^{-4} \text{ [16]}. \quad (2.12)$$

The result of $|V_{ub}|$ measurement is not precise enough to confirm the SM prediction. There may be some room for NP in these processes.

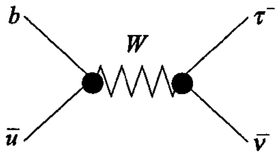


Fig.7. Annihilation prosess for $B^- \to \tau^- \bar{\nu}$

2-1-7. $|V_{td}|$

The magnitude of V_{td} is determined by the $B^0 \bar{B}^0$ oscillation frequency Δm_{B_s} measured at the B factories. The result is

$$\Delta m_{B_d} = 0.507 \pm 0.004 \quad \text{ps}^{-1} \text{ [17]}. \quad (2.13)$$

(Updated on 07/03/06 $\Delta m_{B_d} = 0.505 \pm 0.005$ ps^{-1}.) Then, one obtains

$$|V_{td}| = (7.4 \pm 0.8) \times 10^{-3}. \tag{2.14}$$

In the $B^0\bar{B}^0$ mixing, NP may contribute at the tree level up to 20% of the SM [18].

2-1-8. $|V_{ts}|$

The magnitude of V_{ts} is determined by the $B_s{}^0\bar{B}_s{}^0$ oscillation frequency Δm_{B_s}. The combined result from CDF and D0 measurements is

$$\Delta m_{B_s} = 17.33 {}^{+0.42}_{-0.21} \pm 0.07 \quad \text{ps}^{-1} \text{ [19]}. \tag{2.15}$$

This quantity, however, cannot be measured at the B factories. A constraint on $|V_{td}|/|V_{ts}|$ [$(|V_{td}|/|V_{ts}|)^2 \propto \Delta m_{B_d} / \Delta m_{B_s}$] is instead obtained from $B \to \rho(\omega)\gamma$ and $B \to K^*\gamma$ as

$$|V_{td}|/|V_{ts}| = 0.199 {}^{+0.026}_{-0.025}(\text{exp}) {}^{+0.018}_{-0.015}(\text{theo}) \quad \text{[Belle] [20]},$$

$$|V_{td}|/|V_{ts}| < 0.19 \qquad \text{[BABAR][21]}. \tag{2.16}$$

These results are consistent with the measurements of the above neutral B meson mixings. Possibility of NP in the neutral B meson mixings is, however, may not be excluded yet.

2-1-9. $|V_{tb}|$

There are two measurements to constrain $|V_{tb}|$. One is obtained from the measurement of $R = B(t \to Wb)/B(t \to Wq)$ by CDF and D0 as

$$|V_{tb}| > 0.78 \text{ [22]}. \tag{2.17}$$

The other is from the top-loop contribution to $\Gamma(Z \to b\bar{b})$ as

$$|V_{tb}| = 0.77 {}^{+0.48}_{-0.24} \text{ [23]}. \tag{2.18}$$

More precise measurements are expected to be performed in future.

2-2. The complex phases for CP violation

2-2-1. $\beta(\phi_1)$

Measurements of the angle β are separated into two classes. One is the class in which both tree and penguin diagrams exist for the decays ($b \to c\bar{c}s$) including a charmonium. The other is the one in which penguin diagrams are dominant for the decays ($b \to sq\bar{q}$) including a strange quark (no tree level contribution). The theoretically cleanest example of the former class is $B^0 \to J/\varphi K^0$ mode ($B^0 \to J/\varphi K_S$ and $B^0 \to J/\varphi K_L$). In this mode, we are not suffered from penguin pollution because the penguin weak phase is the same as the tree one. This is the so called "Gold plated mode", and precise determinations of $\sin 2\beta$ are performed at Belle and BABAR. These experimentally measured values of $\sin 2\beta$ agree with each other very well. The averaged value is given as

$$\sin 2\beta = 0.69 \pm 0.03 \ \text{[HFAG2006]}. \tag{2.19}$$

The penguin dominated decay $b \to sq\bar{q}$ involves the same CKM phase as the tree level decay $b \to c\bar{c}s$. There are a lot of modes through this decay to measure $\sin 2\beta$. In table 3, the values of $\sin 2\beta$ determined from these measurements are shown [24].

In $B^0 \to \phi K^0$ at BABAR, $B^0 \to \pi^0 K_S$ at BABAR, $B^0 \to \omega K_S$ at BABAR, $B^0 \to f_0 K_S$ at Belle, $B^0 \to \pi^0\pi^0 K_S$ at both, and $B^0 \to K^+K^-K^0$ at BABAR, significant derivations from the result of the charm decay are seen.

Especially in $B^0 \to \pi^0\pi^0 K_S$ mode, a large derivation exists.

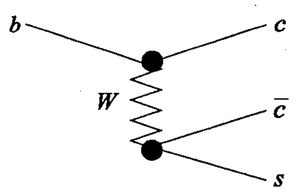


Fig.8. Tree diagram for b→s ($b \to c\bar{c}s$).

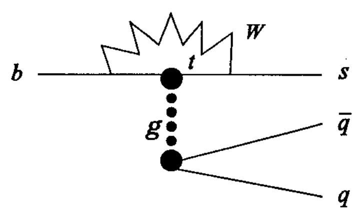


Fig.9. Penguin diagram for b→s ($b \to sq\bar{q}$).

Table 3. The $\sin 2\beta$ from the penguin decays [HFAG2006].

Mode	Group	$\sin 2\beta$
Cf. $b \to c\bar{c}s$ tree mode $B^0 \to J/\varphi K^0$	World average	0.69 ± 0.03
$B^0 \to \phi K^0$	BABAR Belle	$0.50 \pm 0.25 {}^{+0.07}_{-0.04}$ $0.44 \pm 0.27 \pm 0.05$
$B^0 \to \eta' K^0$	BABAR Belle	$0.36 \pm 0.13 \pm 0.03$ $0.62 \pm 0.12 \pm 0.04$
$B^0 \to f_0 K_S$ through this decay	BABAR Belle	$0.95 {}^{+0.23}_{-0.32} \pm 0.10$ $0.47 \pm 0.36 \pm 0.08$
$B^0 \to \pi^0 K_S$	BABAR Belle	$0.35 {}^{+0.30}_{-0.33} \pm 0.04$ $0.22 \pm 0.47 \pm 0.08$
$B^0 \to \pi^0 \pi^0 K_S$	BABAR	$-0.84 \pm 0.71 \pm 0.08$
$B^0 \to \omega K_S$	BABAR Belle	$0.50 {}^{+0.34}_{-0.38} \pm 0.02$ $0.95 \pm 0.53 {}^{+0.12}_{-0.15}$
$B^0 \to \rho^0 K_S$	BABAR	$0.17 \pm 0.52 \pm 0.26$
$B^0 \to K^+ K^- K^0$	BABAR Belle	$0.41 \pm 0.18 \pm 0.07 \pm 0.11$ $0.60 \pm 0.18 \pm 0.04 {}^{+0.19}_{-0.12}$
$B^0 \to K_S K_S K_S$	BABAR Belle	$0.63 {}^{+0.28}_{-0.32} \pm 0.04$ $0.58 \pm 0.36 \pm 0.08$
Cf. $b \to sq\bar{q}$ penguin mode	Naive average	0.50 ± 0.06

2-2-2. $\alpha(\phi_2)$

The decay mode $B^0 \to J/\varphi K^0$ is dominated by the amplitude with one weak phase because the penguin diagram involves the same weak phase as the tree diagram. In contrast, the tree and penguin diagrams provide comparable contributions with different weak phases in $B \to \pi\pi$ decays.

The angle α is extracted from $B^0 \to \pi^+\pi^-$, $B^0 \to \pi^0\pi^0$ and $B^+ \to \pi^+\pi^0$ by using isospin analysis. A constraint is obtained as

$$0^\circ < \alpha < 17^\circ,\ 73^\circ < \alpha < 180^\circ \quad [25]. \tag{2.20}$$

In spite of the smallness of amplitude, $B^0 \to \rho^+\rho^-$ provides the best precision to determine α. From $B^0 \to \rho^+\rho^-$, $B^0 \to \rho^0\rho^0$ and $B^+ \to \rho^+\rho^0$ one obtains with isospin analysis

$$\alpha = 96^\circ \pm 13^\circ \ [25]. \tag{2.21}$$

From $B^0 \to \rho^+\pi^-$ with $B^0 \to \rho^0\pi^0$ and $B^0 \to \rho^-\pi^+$ one also obtains with isospin analysis

$$\alpha = 113^\circ {}^{+27^\circ}_{-17^\circ} \pm 6^\circ \ [25]. \tag{2.22}$$

By combining the above measurements, the angle α is determined as [25]

$$\alpha = 99^\circ {}^{+12^\circ}_{-9^\circ}. \tag{2.23}$$

2-2-3. $\gamma(\phi_3)$

The angle γ can be measured directly in the tree-level B decays, which is unlikely to be affected by NP. From the interference terms in $B^\pm \to D^0K^\pm$ and $B^\pm \to \bar{D}^0K^\pm$ it is extracted as [25],

$$\gamma = 68^\circ {}^{+14^\circ}_{-15^\circ} \pm 13^\circ \pm 11^\circ \ [\text{Belle}],$$
$$\gamma = 67^\circ \pm 28^\circ \pm 13^\circ \pm 11^\circ [\text{BABAR}]. \tag{2.24}$$

The decays $B^\pm \to D^{0*}K^{\pm*}$ and $B^\pm \to \bar{D}^{0*}K^{\pm*}$ also provide

$$\gamma = 63^\circ {}^{+15^\circ}_{-12^\circ} \ [25]. \tag{2.25}$$

3. Bs physics

3-1. Δm_{B_s}

While the $B_s^0\bar{B}_s^0$ oscillation cannot be measured in the B factories at LEP and SLAC, it is measured by CDF and D0 at Tevatoron. The result is given as

$$\Delta m_{B_s} = 17.33 \pm 0.10 \pm 0.07 \ \ \text{ps}^{-1}[17]. \tag{3.1}$$

On the other hand, owing to the CKM unitarity in the SM, Δm_{B_s} is estimated as

$$\Delta m_{B_s} = 17.9^{+3.6}_{-1.4} \ \ \text{ps}^{-1}[26]. \tag{3.2}$$

A more precise measurement may be done in $B_s^0 \to D_s^+ K^-$ and $B_s^0 \to \bar{D}_s^+ K^-$ decays observed at LHCb. The estimated statistical precision may be ~ 0.01 ps^{-1}[27]. Then, if the measurement result of Δm_{B_s} is inconsistent with the prediction of the SM, we will expect to see an effect of NP in this mixing.

3-2. $B_s^0 \to J/\varphi\phi$

In the SM, the phase ϕ_s of the $B_s^0\bar{B}_s^0$ mixing is expected to be very small as

$$\phi_s \simeq \arg \frac{V_{tb}^* V_{ts}}{V_{cb}^* V_{cs}} \simeq 0.04 \sim 0 . \tag{3.3}$$

Then this phase is sensitive to NP. At LHCb $\sin\phi_s$ will be measured with sensitivity up to 0.013 after first five years of running.

3-3. γ

$B_s^0 \to D_s K$ decays are not sensitive to NP because they occur at the tree level in the SM. By measuring these decays the phase $\gamma + \phi_s$ is extracted. In the SM, because $\phi_s = 0$, the phase $\gamma + \phi_s$ simply corresponds to γ. $B_s^{\pm} \to D_s K^{\pm}$ is also dominated by the same tree diagram as $B_s^0 \to D^0{}_s K^0$. This decay provides a clean measurement of γ.

$B_s^0 \to K^+K^-$ is dominated by a penguin diagram. The measurement of γ with this decay is thus sensitive to NP.

3-4. $B_s^0 \to \mu^+\mu^-$

In the SM, $BR(B_s^0 \to \mu^+\mu^-)$ is estimated to be very small as

$$(3.5 \pm 0.1)\times 10^{-9} \text{ [28].} \tag{3.4}$$

The best upper limit on the branching ratio at present comes from the experiments at Tevatron, reaching few$\times 10^{-7}$. More precise experiments will be performed at LHCb.

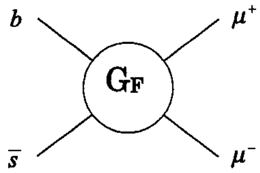
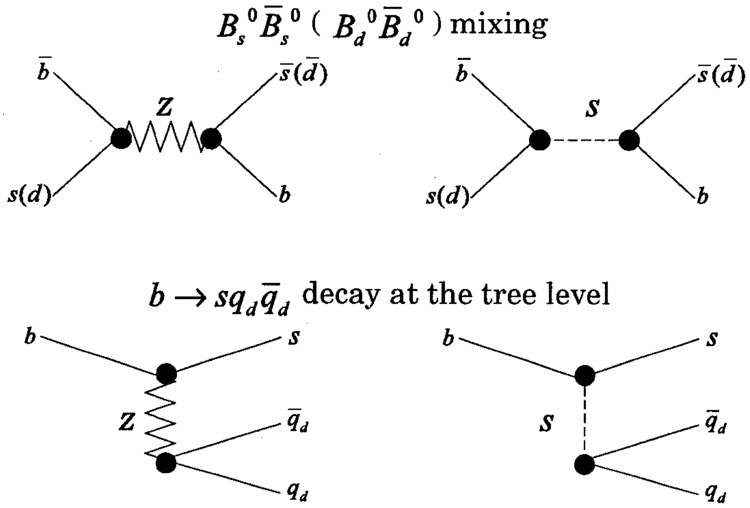


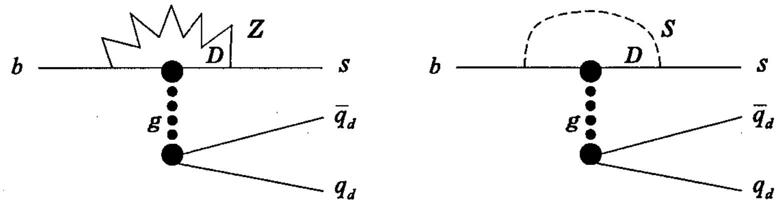
Fig.10. Leptonic decay $B_s^0 \to \mu^+\mu^-$.

4. Quark singlet models

Flavor changing neutral currents (FCNC's) at the tree level are present in quark singlet models [29], while they are absent in the SM. In this sort of models the 3×3 submatrix of quark mixing corresponding to the CKM matrix in the SM is no longer unitary. Then Z mediated and neutral scalar mediated FCNC's are present at the tree level. Typical diagrams with the FCNC's relevant for the B and Bs physics are shown in Fig.11.



$b \to s q_d \bar{q}_d$ decay via penguin diagrams



$B_s^0 \to \mu^+ \mu^-$ leptonic decay at the tree level

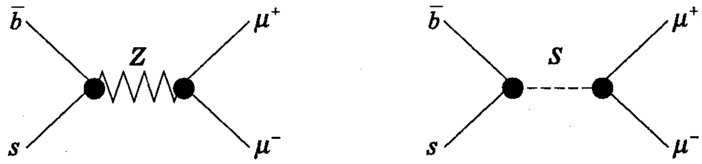


Fig.11. FCNC's in quark singlet models

5. Summary

We have described the experimental status concerning the flavor physics with quark mixing. The CKM elements, unitarity triangles and Bs physics are considered specifically. We see that the possibility of NP is not excluded in the measurements of $|V_{ub}|$ and $B_s^0 \bar{B}_s^0$ oscillation. The decays $B^- \to \tau^- \bar{\nu}$, $B_s^0 \to J/\varphi\phi$, $B_s^0 \to D_s^0 K^0$, $B_s^0 \to K^+ K^-$, $B_s^0 \to \mu^+ \mu^-$ and are sensitive to NP. In quark singlets models, Z mediated and neutral scalar mediated FCNC's are really present, contributing to these B meson decays as NP.

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