NEW PHYSICS SEARCH IN HADRONIC PENGUINS AND LEPTONIC B DECAYS*

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In this presentation, I review some of the recent findings in hadronic penguin and leptonic decays of B mesons in regard to search for new physics beyond the Standard Model (SM). Several "tensions" and "puzzles" will be discussed that may indicate effects of new physics.

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1. Introduction

Since BaBar and Belle, the two asymmetric e^+e^- colliders running at $\sqrt{s} = 10.58$ GeV, so-called the "B-factories" started their operations in 1999, there have been enormous new results on the decays of B mesons as well as charm and τ systems. Perhaps, the most prominent recognition for the B-factory experiments was the 2008 Nobel physics prize, for which the B-factory results played critical roles in verifying the Kobayashi–Maskawa (KM) hypothesis [1] of CP violation.

Even with the amazing success and the subsequent recognition of the KM model, there still remain many open questions in flavor physics. A few of these questions are:

- What is the origin of elementary fermion flavors? Why do both leptons and quarks have 6 flavors, in three generations?
- Why do we have the mass and flavor-mixing patterns of the leptons and quarks?
- Why (and how) did the antimatter disappear?

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Even if SUSY or any other new physics is found at future experiments, these questions may remain unanswered. Nevertheless, step-by-step experimental approach in understanding the flavor sector of elementary particle physics is needed. In this presentation, I will review some of the recent findings in B decays in regard to search for new physics beyond the Standard Model (SM). In particular, I will talk about hadronic penguin and leptonic decays of B mesons.

2. Leptonic B decays

The decay widths of the purely leptonic $B^+ \to \ell^+\nu$ decays are cleanly calculated in the SM, except for the CKM element V_{ub} and the B decay constant f_B (Eq. (1)). Once these values are known from other measurements or calculations (*e.g.* lattice QCD), this mode can be used for a very sensitive test of physics beyond the SM. Figure 1 shows the decay processes of $B^+ \to \ell^+\nu$ both in the SM (Fig. 1(a)) and in a leptoquark model beyond SM (Fig. 1(b)). Moreover, a charged Higgs appearing in place of the virtual W can affect the branching fraction by a large factor.

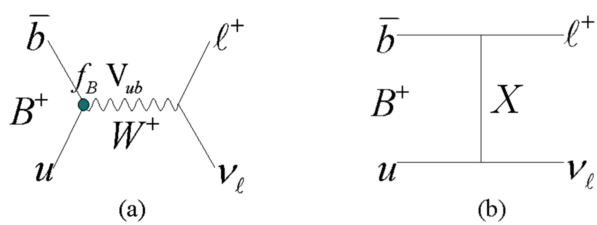

Fig. 1. Decay diagrams of $B^+ \to \ell^+\nu$: (a) a SM process via W annihilation; (b) a process mediated by a leptoquark from models beyond the SM.

The decay width in the SM is given by

$$\Gamma\left(B^+ \to \ell^+\nu\right) = \frac{G_{\mathrm{F}}^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \,. \quad (1)$$

The factor m_ℓ^2 in Eq. (1) indicates helicity-suppression. As a result, decays to light charged leptons ($\ell = e$ or μ) are highly suppressed in comparison to $B^+ \to \tau^+\nu$ in the SM.

2.1. $B^+ \to \tau^+\nu$

The first evidence for $B^+ \to \tau^+\nu$ was obtained by Belle with a full-reconstruction B-tagging method [2]. BaBar also reported a search for the decay using semileptonic B-tagging [3] as well as the fully reconstructed hadronic tagging method [4]. With 657×10^6 $B\overline{B}$ pairs, Belle updated the measurement using semileptonic tagging [5]. Figure 2(a) shows the Belle result with semileptonic tagging, where three τ decay modes ($e\nu\nu$, $\mu\nu\nu$, $\pi\nu$) are combined. The significance of the signal is 3.8σ and the measured branching fraction is $(1.65^{+0.38+0.35}_{-0.37-0.37}) \times 10^{-4}$. Figure 2(b) shows the BaBar result with hadronic tagging. In both figures, the displayed observable (called $E_{\rm ECL}$ for Belle) is the energy in the electromagnetic calorimeter that has been accounted for neither in tagging nor in signal reconstruction. In general, the signal modes are expected to have $E_{\rm ECL}$ near zero while the background events tend to have large $E_{\rm ECL}$. Combining the hadronic and semileptonic tagging results, BaBar obtained the branching fraction $\mathcal{B}(B^+ \to \tau^+\nu) = (1.8 \pm 0.6) \times 10^{-4}$.

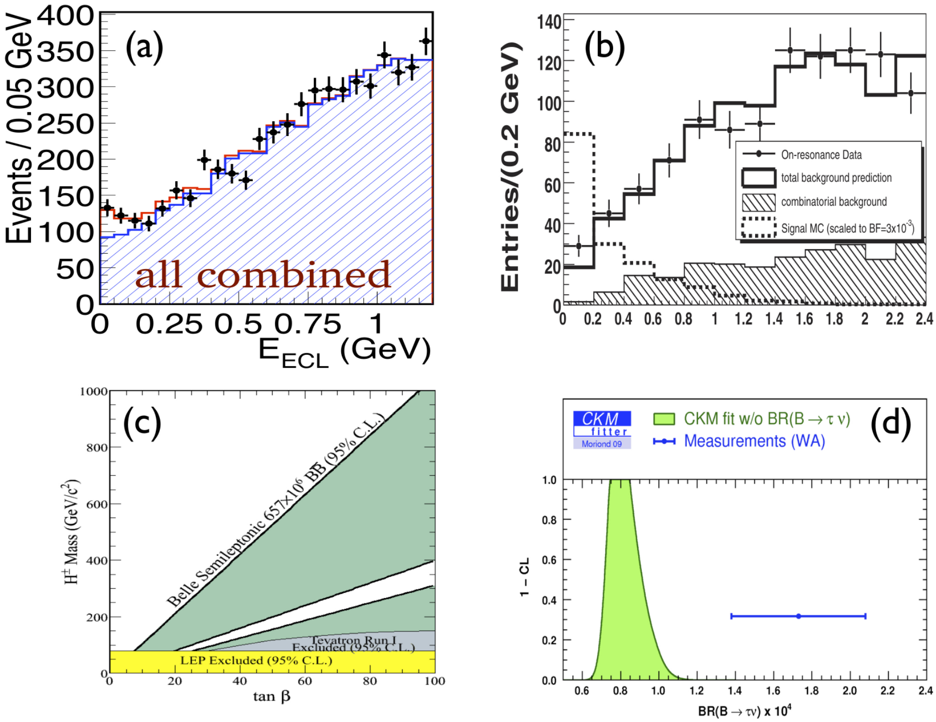

Fig. 2. Results and interpretations of $B^+ \to \tau^+\nu$: (a) the $E_{\rm ECL}$ distribution of semileptonic tagging analysis by Belle; (b) a similar distribution of hadronic tagging analysis by BaBar; (c) the region in m_{H^+} *vs.* $\tan\beta$ excluded by Belle's semileptonic tagging analysis; (d) comparison of $B^+ \to \tau^+\nu$ with the prediction from CKM-constrained fitting.

Within the two Higgs doublet model, the measured $\mathcal{B}(B^+ \to \tau^+\nu)$ can be used to constrain the allowed region of m_{H^+} *vs.* $\tan\beta$ parameter space [6]. Figure 2(c) shows the region excluded by the measurement of $B^+ \to \tau^+\nu$ by Belle's semileptonic tagging analysis. A substantial portion of the m_{H^+} *vs.* $\tan\beta$ space is excluded by the result.

Shown in Fig. 2(d) is a comparison of the world-average value of $\mathcal{B}(B^+ \to \tau^+\nu)$ to that inferred from the CKM constraints [7]. It seems that a "tension" of about 2σ exists between the two.

2.2. $B^+ \to \ell^+\nu$ *with* $\ell = e, \mu$

In comparison to $B^+ \to \tau^+\nu$, $B^+ \to \ell^+\nu$ decays with $\ell = e$ or μ are suppressed by the ratio m_ℓ^2/m_τ^2 ("helicity suppression"). On the other hand, with contributions from new physics beyond the SM, the helicity suppression may be avoided. Moreover, these modes have a very clean experimental signature of $p_\ell \approx m_B/2$ in the B rest frame.

Currently, the most stringent limit on the $B^+ \to e^+\nu$ is obtained by Belle, $\mathcal{B}(B^+ \to e^+\nu) < 1.0 \times 10^{-6}$ [8], while BaBar obtains the most stringent limit on $\mathcal{B}(B^+ \to \mu^+\nu) < 1.0 \times 10^{-6}$ [9]. The limit on $B^+ \to \mu^+\nu$ mode is still an order of magnitude larger than the SM expectation.

2.3. $B \to \overline{D}^{(*)}\tau^+\nu$

The semileptonic $B \to \overline{D}^{(*)}\tau^+\nu$ decays are similar to the well-measured $B \to \overline{D}^{(*)}\mu/e\ \nu$, but they share many features in common with purely leptonic $B^+ \to \tau^+\nu$ decays, both experimentally and theoretically. Compared to $B \to \overline{D}^{(*)}\mu/e\ \nu$, they are suppressed because of large τ mass. On the other hand, the large τ mass makes them sensitive to interaction with charged Higgs, where H^+ may replace the virtual W, thereby affecting the branching fraction. Therefore, this mode provides a very good opportunity to search for indirect evidence of charged Higgs or other new physics hypotheses. Moreover, we can have access to more dynamical information by measuring τ polarization. On the experimental aspect, however, it is very difficult to measure this mode because of multiple neutrinos in the final state, which causes large background contamination.

The $B \to \overline{D}^*\tau^+\nu$ decay was first observed by Belle, by loosely reconstructing the accompanying B to apply tighter kinematic constraints for improved background suppression [10]. Figure 3(a) shows the distribution of $M_{\rm tag}$ which is the beam-constrained invariant mass of the tagging-side B meson. A clear signal excess around m_B is observed. The branching fraction is $\mathcal{B}(B \to \overline{D}^*\tau^+\nu) = (2.02^{+0.40}_{-0.37} \pm 0.37)\%$. BaBar uses full reconstruction of the accompanying B in the hadronic modes to observe $B \to \overline{D}\tau^+\nu$ and confirm $B \to \overline{D}^*\tau^+\nu$ [11]. Figures 3(b) and 3(c) show the

q^2 distributions measured by BaBar in the $\overline{D}^{*0}\tau^+\nu$ and $\overline{D}^0\tau^+\nu$ modes, respectively. Various background components as well as the signal excess are indicated as cumulated histograms. The branching fractions are measured as $\mathcal{B}(B \to \overline{D}\tau^+\nu) = (0.86 \pm 0.24 \pm 0.11 \pm 0.06)\%$ and $\mathcal{B}(B \to \overline{D}^{(*)}\tau^+\nu) = (1.62 \pm 0.31 \pm 0.10 \pm 0.05)\%$. In the course of this analysis, BaBar measures the distributions of key kinematic variables q^2 and $|p^*_\ell|$ for each mode. In a new analysis, Belle applies a full reconstruction of the accompanying B to obtain the branching fractions separately for B^0 and B^+ decays [12].

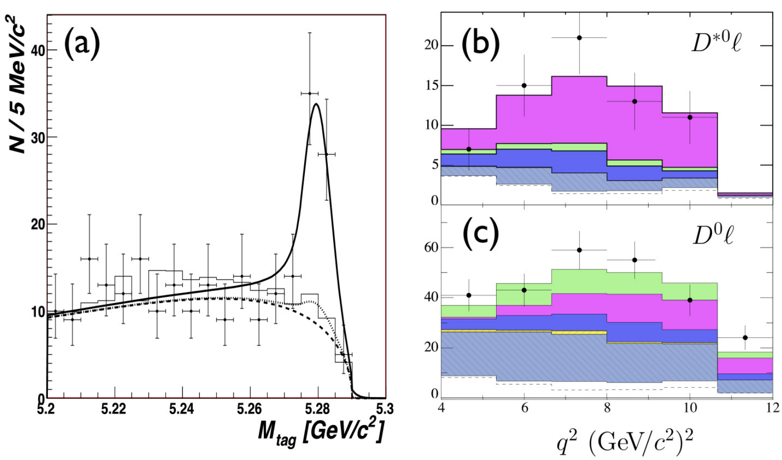

Fig. 3. Results of $B \to \overline{D}^{(*)}\tau^+\nu$: (a) first observation of $B \to \overline{D}^*\tau^+\nu$ from Belle; the q^2 distributions for (b) $B^+ \to \overline{D}^{*0}\tau^+\nu$ and (c) $B^+ \to \overline{D}^0\tau^+\nu$ from BaBar.

3. Hadronic penguin B decays and the "puzzles"

Since the SM provides a very good approximation to reality for most processes in elementary particle physics, we need to look where the amplitude of SM is suppressed or zero, in order to search for effects of new physics beyond the SM. The flavor-changing neutral-current processes, so-called the "penguin" processes are in general good places to search for new physics, because penguin amplitudes are loop-suppressed in the SM. In this section, we review the current status of several "puzzles" related with hadronic penguin decays of B.

3.1. Time-dependent CP violations and the ΔS puzzle

Time-dependent analyses of CP asymmetry in B decays provide information about mixing-induced CP violation. In the SM, it is due to the KM mechanism. But in many new physics models, new CP-violating phases can contribute to the process, hence resulting in different measurements of CP-violating parameters.

The golden-mode of time-dependent CP analysis in B system is $B \to J/\psi K_S^0$ and related cousins of quark-level $b \to c\bar{c}s$ decays. In the SM, these are known to have very little CP violation other than that due to the $B\overline{B}$ mixing. Since the decays are dominated by a tree-level contribution, they are not sensitive to loop-level contributions from physics beyond the SM. Accurate measurement of $\sin 2\phi_1$ from the B-factories using $b \to c\bar{c}s$ decays is important as it becomes an anchor with which all the other time-dependent CP asymmetry values from B decays shall be compared. The current world-average is $\sin 2\phi_1 = 0.672 \pm 0.023$. The fractional error is about 3% and still mostly statistical. The precision will certainly improve with the LHCb experiment where orders-of-magnitude increase in statistics is anticipated.

Time-dependent CP asymmetry in the quark-level $b \to q\bar{q}s$ $(q = d,\ s)$ penguin decays are sensitive to new physics effects as the new CP-violating phases might enter into the decay through loop diagrams. Figure 4 summarizes the results from $b \to q\bar{q}s$ penguin modes in comparison to $b \to c\bar{c}s$. There are still a few modes which are positioned slightly away from the

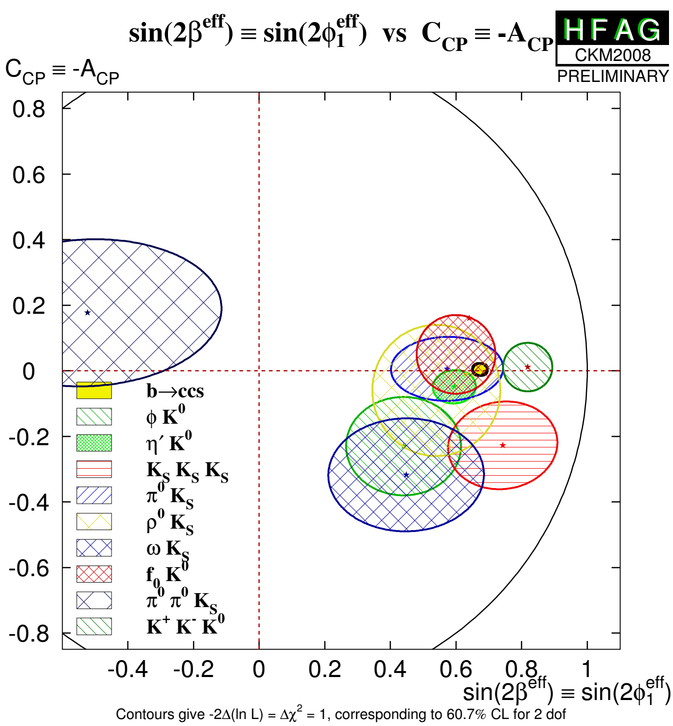

Fig. 4. Measurements of CP-violating parameters S and A in $b \to q\bar{q}s$ penguin decays. The result from the $b \to c\bar{c}s$ tree-diagram modes is shown as a small circle at (0.672,0.004).

$b \to c\bar{c}s$ result. With an increased statistics by one or two orders of magnitude from the next-generation e^+e^- B-factories as well as that from LHCb, it can be a compelling test, looking for new CP phases in the individual $b \to q\bar{q}s$ penguin decay modes.

3.2. Direct CP violations in $B \to K\pi$ and the $K\pi$ puzzle

Time-integrated measurement of decay asymmetry between B and $\overline{B}$ reveals direct CP violation through interferences of two or more amplitudes for a given decay mode. The CP asymmetry $A^0_{K^-\pi^+}$ for $\overline{B}^0 \to K^-\pi^+$ decays is defined as:

$$A^0_{K^-\pi^+} \equiv \frac{N\left(\overline{B}^0 \to K^-\pi^+\right) - N\left(B^0 \to K^+\pi^-\right)}{N\left(\overline{B}^0 \to K^-\pi^+\right) + N\left(B^0 \to K^+\pi^-\right)}\,.$$

Recently, both Belle and BaBar measured that the direct CP violations in $B \to K^+\pi$ decays show difference for B^0 and B^+ decays [13]. For B^0, the asymmetry $A^0_{K\pi}$ is measured as $-0.107 \pm 0.016^{+0.006}_{-0.004}$ (BaBar) and $-0.094 \pm 0.018 \pm 0.008$ (Belle). On the other hand, for B^+, the corresponding CP asymmetry $A^+_{K\pi}$ (defined in a similar manner to $A^0_{K\pi}$) is measured as $-0.029 \pm 0.039 \pm 0.010$ (BaBar) and $0.03 \pm 0.03 \pm 0.01$ (Belle). Combining the results from Belle, BaBar and CDF [14], the difference $\Delta A \equiv A^0_{K\pi} - A^+_{K\pi} = -0.147 \pm 0.028$ is away from zero by more than 5 standard deviations.

This deviation (so-called the "$K\pi$ puzzle") is not easily accommodated within the SM. The color-suppressed tree diagram contribution can be enhanced in the B^+ modes, hence making the CP-violating phase different from that of B^0. But, it is highly unlikely that its contribution can be bigger or even comparable to that of color-allowed tree in the SM. Another possible source of deviation is due to electroweak penguin amplitudes. Since, however, their CP-violating phases are negligible in the SM, they cannot affect ΔA by much. All these speculations lead us to suspect that there might be a new CP-violating phase beyond the SM at work here.

One important information to understand the $K\pi$ puzzle is the CP asymmetry in $B^0 \to K^0\pi^0$. Figure 5 shows the signal yields of (a) $B^0 \to K^0_S\pi^0$ and (b) $B^0 \to K^0_L\pi^0$ measured by Belle [15]. By performing time-dependent analysis with flavor-tagging, a CP asymmetry is also measured.

All the CP asymmetries of various $B \to K\pi$ decay modes can be compared with the isospin sum rule [16]:

$$\begin{aligned}
&\mathcal{A}_{\rm CP}\left(K^+\pi^-\right) + \mathcal{A}_{\rm CP}\left(K^0\pi^+\right)\frac{\mathcal{B}\left(K^0\pi^+\right)}{\mathcal{B}\left(K^+\pi^-\right)}\frac{\tau_0}{\tau^+} \\
&= \mathcal{A}_{\rm CP}\left(K^+\pi^0\right)\frac{2\mathcal{B}\left(K^+\pi^0\right)}{\mathcal{B}\left(K^+\pi^-\right)}\frac{\tau_0}{\tau^+} + \mathcal{A}_{\rm CP}\left(K^0\pi^0\right)\frac{2\mathcal{B}\left(K^0\pi^0\right)}{\mathcal{B}\left(K^+\pi^-\right)}\,.
\end{aligned}$$

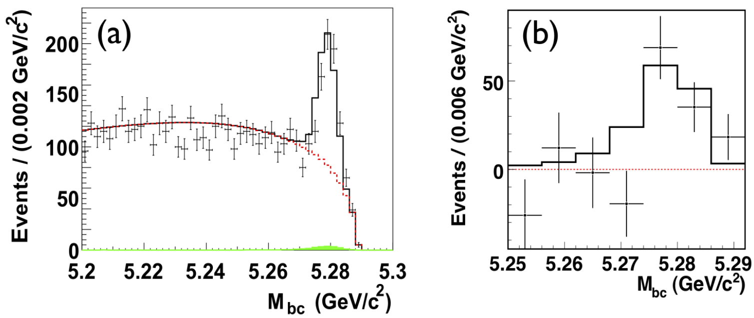

Fig. 5. Signal yields of (a) $B^0 \to K^0_S \pi^0$ and (b) $B^0 \to K^0_L \pi^0$ from Belle.

Figure 6 shows the measured asymmetries in $B^0 \to K^0\pi^0$ and $B^+ \to K^0\pi^+$ modes. Also shown in the figure is the region predicted by the sum rule above. There is a 1.9σ deviation. Although it is too early to draw any conclusion from this, it will be an interesting test with increased data sample in the next-generation experiments.

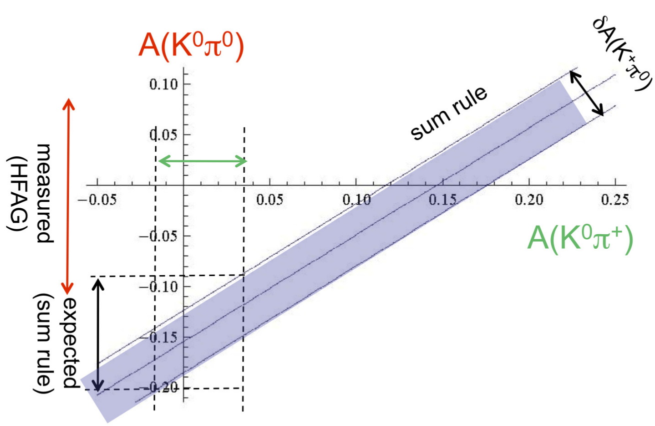

Fig. 6. Comparison of the measured CP asymmetries in $B^0 \to K^0\pi^0$ and $B^+ \to K^0\pi^+$ with respect to the isospin sum rule prediction.

3.3. VV polarization puzzle

In regard to the afore-mentioned $K\pi$ puzzle, it has been suggested [17] that vector–vector (VV) final states with the same quark combinations, *e.g.* $B \to \rho K^*$ may give insights to the puzzle, as any difference between $K\pi$ and their VV counterparts will be mainly hadronic. In addition, charmless B decays to VV final states show intriguing results in the final-state polarizations.

B decays to VV final states consist of three separate polarizations states. According to naive arguments based on helicity conservation, longitudinal polarization is expected to be dominant in $B \to VV$ decays, with $f_L \sim 1 - m_V^2/m_B^2$. The decays $B \to \phi K^*$ and $B \to \rho K^*$, both occurring mostly via the $b \to s$ penguin process, are found to have large transverse polarizations [18–20], in contrast to the expectation from factorization. On the other hand, $B^{+(0)} \to \rho^+\rho^{0(-)}$, which is mostly a $b \to uW^*$ tree-diagram process, is almost fully polarized longitudinally [21].

Although this VV polarization puzzle has not been completely solved yet, there have been progresses in theoretical understanding of the related phenomena. For example, with enhanced annihilation diagram and other non-factorizable contributions, Beneke *et al.* [22] as well as Cheng and Yang [23] were able to explain the measured values of polarizations in various VV modes.

It is worth mentioning that BaBar also measured the polarizations of B decays to vector plus tensor final states. For $B \to \omega K_2(1430)^*$, f_L is measured to be around 0.5 [25]. On the other hand, f_L for $B \to \phi K_2(1430)^*$ is measured to be around 0.8 ± 0.1 [24]. At this point, there is no theoretical study regarding the expected polarizations of such states.

4. Summary and outlook

We have gone through several "tensions" and "puzzles" in leptonic as well as hadronic penguin decays of B mesons. None of these is conclusive. With the next-generation flavor factories such as Belle-II, Super-B or LHCb, we will have an opportunity to look into such puzzles in much greater details and thus explore the new physics beyond the SM in the flavor physics.

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