PROCEEDINGS OF SCIENCE

Study of Radiative and Electroweak Penguin Decays at Belle

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The recent studies on radiative and electroweak penguin decays by the Belle experiment are reported. These new measurements are based on the Belle full data set of 772 $\times 10^6 B\bar{B}$. All the measurements of $B \to K^*\gamma$ are the most precise to date and provide the first evidence of isospin violation in $b \to s\gamma$ decay with a significance of 3.1σ. Lepton flavor dependent angular analysis of $B \to K^*\ell^+\ell^-$ decays, where ℓ is either e or μ, and results of search for lepton flavor violating process of $B^0 \to K^{*0}\mu e$ and the rare decays of $B \to h^{(*)}\nu\bar{\nu}$, are presented.

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1. Introduction

Loop (penguin) processes are good probe for physics beyond the Standard Model (BSM), since new heavy particles could contribute to the loops. A BSM effect may be observed as a deviation from the SM values. The radiative penguin and electroweak penguin are defined as a process where a charged particle emits an external real photon and an emitted virtual photon or Z^0 that produces a pair of leptons, respectively.

2. Evidence of Isospin violation in $B \to K^* \gamma$

$B \to K^* \gamma$ is experimentally the cleanest exclusive decay of $b \to s\gamma$ process. The branching fraction is $\sim 4 \times 10^{-5}$ and it is corresponding to 12% of inclusive $B \to X_s \gamma$ decays. The prediction of branching fraction suffers from large uncertainties in form factors, while the isospin (Δ_{0+}) and direct CP asymmetries (A_{CP}) are theoretically clean observables thanks to cancellation of these uncertainties [1]. The Δ_{0+} and A_{CP} are defined as

$$\Delta_{0+} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)}, \tag{2.1}$$

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{K^*}\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\bar{B} \to \bar{K^*}\gamma) + \Gamma(B \to K^*\gamma)} \tag{2.2}$$

where Γ denotes the partial width.

Direct CP asymmetry arises due to the interference of decay amplitudes with different weak and strong CP phases. The $b \to s\gamma$ process is also possible via annihilation diagram. However this amplitude is suppressed in the SM. Since only one major diagram contributes, A_{CP} of $B \to K^*\gamma$ is zero in the SM. If there are BSM contributions from annihilation diagram or due to the CP phase, A_{CP} could be detectable. Isospin asymmetry between the neutral and charged decays arises due to the contribution from weak annihilation diagrams. Predictions of the isospin asymmetry range from 2% to 8% with a typical uncertainty of 2% in the SM [1–4]. In the analysis of Ref. [5], $B^0 \to K^{*0}\gamma$ and $B^{*+} \to K^*\gamma$ are reconstructed, where K^* is formed from $K^+\pi^-, K_S^0\pi^0, K^+\pi^0$ or $K_S^0\pi^+$ combination. The signal yield is extracted from an unbinned maximum likelihood fitting to the beam energy constrained mass distribution (Figure 1), $M_{\rm bc} \equiv \sqrt{(E^*_{\rm beam}/c^2)^2 - (p^*_B/c)^2}$, where $E^*_{\rm beam}$ is the beam energy and p^*_B is the momentum of the B meson candidate in the c.m. frame is used. The results are

$$Br(B^0 \to K^{*0}\gamma) = (3.96 \pm 0.07 \pm 0.14) \times 10^{-5}, \tag{2.3}$$

$$Br(B^+ \to K^{*+}\gamma) = (3.76 \pm 0.10 \pm 0.12) \times 10^{-5}, \tag{2.4}$$

$$A_{CP}(B^0 \to K^{*0}\gamma) = (-1.3 \pm 1.7 \pm 0.4)\%, \tag{2.5}$$

$$A_{CP}(B^+ \to K^{*+}\gamma) = (+1.1 \pm 2.3 \pm 0.3)\%, \tag{2.6}$$

$$A_{CP}(B \to K^*\gamma) = (-0.4 \pm 1.4 \pm 0.3)\%, \tag{2.7}$$

$$\Delta_{0+} = (+6.2 \pm 1.5 \pm 0.6 \pm 1.2)\%, \tag{2.8}$$

$$\Delta A_{CP} = (+2.4 \pm 2.8 \pm 0.5)\% \tag{2.9}$$

where the first uncertainty is statistical, the second is systematic, and the third for Δ_{0+} is the uncertainty from f_{+-}/f_{00}, the ratio of the branching fraction $\Upsilon(4S) \to B^+B^-$ to that of $\Upsilon(4S) \to B^0\bar{B}^0$.

The first evidence of isospin violation in $b \to s\gamma$ decay is found with a significance of 3.1σ [6] . ΔA_{CP} is difference of A_{CP} between charged and neutral B mesons defined as $\Delta A_{CP} = A_{CP}(B^+ \to K^{*+}\gamma) - A_{CP}(B^0 \to K^{*0}\gamma)$. ΔA_{CP} is consistent with zero in the first measurement for $B \to K^*\gamma$. Figures 2 and 3 show a comparison with previous results and SM predictions for isospin and direct CP asymmetries, respectively. They are consistent with the previous results and prediction of the SM [1–4].

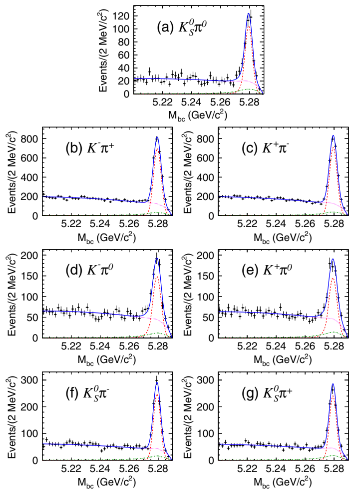

Figure 1: $M_{\rm bc}$ distributions for $K_S^0\pi^0$ (a), $K^-\pi^+$ (b), $K^+\pi^-$ (c), $K^-\pi^0$ (d), $K^+\pi^0$ (e), $K_S^0\pi^-$ (f) and $K_S^0\pi^+$ (g).

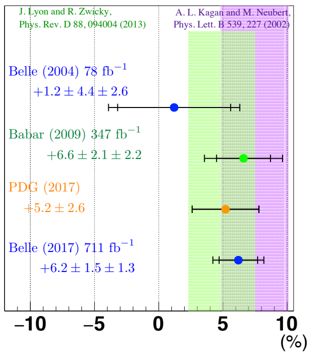

Figure 2: Comparison with previous results and SM predictions for isospin asymmetry.

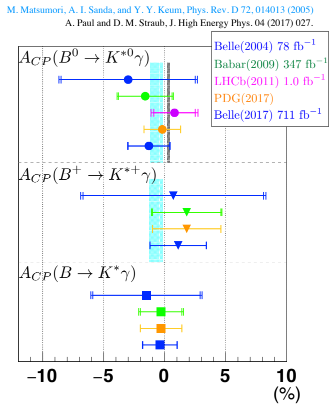

Figure 3: Comparison with previous results and SM predictions for direct CP asymmetry.

3. Lepton flavor dependent angular analysis

LHCb reported 3σ deviation in an angular observable P_5' from a full angular analysis of $B \to K^*\mu^+\mu^-$. They also reported anomaly in lepton flavor universality [7, 8]. An independent measurement is desired and lepton flavor dependence in angular analysis should also be checked. In the analysis of Ref. [9], angular observables are measured and a test of lepton flavor universality (LFU) is performed in the $B \to K^*\ell^+\ell^-$ decay, where $\ell = e, \mu$. Figure 4 shows the $M_{\rm bc}$ distribution of $B \to K^*\ell^+\ell^-$ candidates and P_5' and Q_5 observables for combined electron and muon modes. 2.6σ deviation is seen in P_5' of muon mode. The Q_5 observable is shown for the first time.

4. Search for lepton flavor violating $B^0 \to K^{*0}\mu e$ decays

Violation of lepton universality is accompanied by lepton flavor violation (LFV) in many models of BSM. The $B^0 \to K^{*0}\mu^\pm e^\mp$ decay is a promising place to search for LFV. In the analysis of Ref. [13], $B^0 \to K^{*0}\mu^\pm e^\mp$ is studied using the Belle full data samples, which is more than three times larger than that of the previous results by *BABAR* [14]. Figure 5 shows the distribution of $M_{\rm bc}$ for the $B^0 \to K^{*0}\mu^+e^-$, $B^0 \to K^{*0}\mu^-e^+$ data, as well as for both decays combined. No statistically

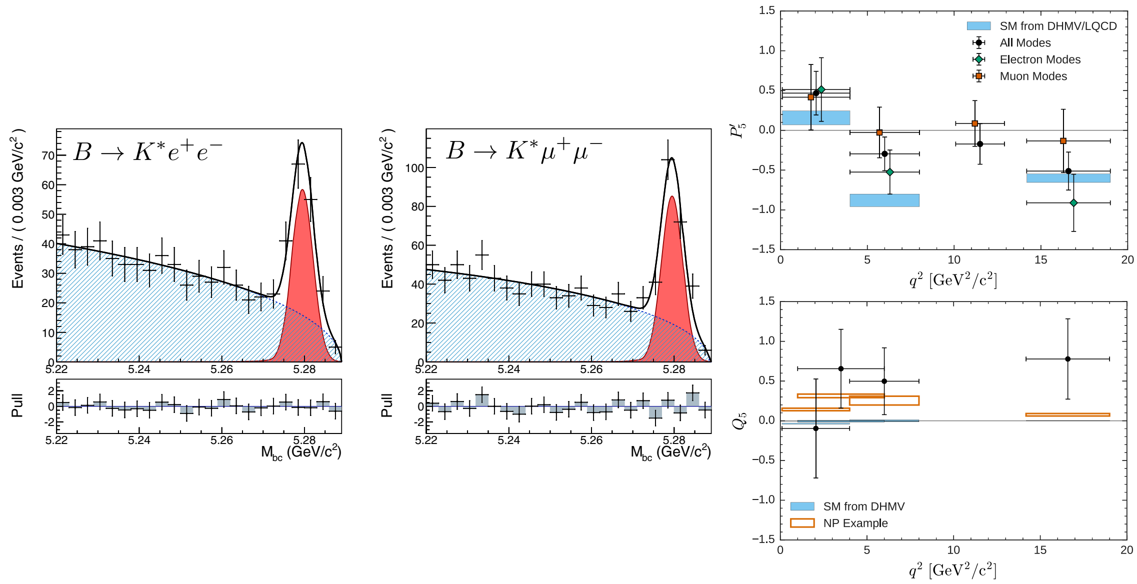

Figure 4: Distribution of the beam energy constrained mass for selected $B \to K^* e^+ e^-$ and $B \to K^* \mu^+ \mu^-$ candidates. P_5' and Q_5 observables for combined electron and muon modes. The SM predictions are provided by DHMC [10, 11] and lattice QCD [12] and displayed as boxes for the muon modes only. Favored NP "Scenario 1" from Ref. [10] for Q_5.

significant signals are seen and 90% confidence level upper limits on the branching fractions are

$$Br(B^0 \to K^{*0} \mu^+ e^-) \; < \; 1.2 \times 10^{-7}, \tag{4.1}$$

$$Br(B^0 \to K^{*0} \mu^- e^+) \; < \; 1.6 \times 10^{-7}, \tag{4.2}$$

$$Br(B^0 \to K^{*0} \mu^\pm e^\mp) \; < \; 1.8 \times 10^{-7}. \tag{4.3}$$

These results are the most stringent constraints on these LFV decays to date.

5. Search for $B \to h^{(*)} \nu \bar{\nu}$ decays

The decay $B \to h \nu \bar{\nu}$ can proceed only via a penguin or a box diagram at leading order in the SM and is highly suppressed. These channels are theoretically clean since they are mediated only by the Z and W bosons, in contrast to $B \to K^{(*)} \ell\ell$ decays where photon contributes, and there is no charm loop as in $b \to s\ell\ell$. This decay is also experimentally challenging since there are multiple neutrinos in the final state. Detection of B decays to $h^{(*)}$ and *'nothing'* is required. $B \to h \nu \bar{\nu}$ decays have been studied previously by Belle with a hadronic tagging algorithm [15], and by *BABAR* with both hadoronic [16] and semileptonic tagging [17].

In the analysis of Ref. [18], the accompanying B meson ($B_{\rm tag}$) in the semileptonic decay channels $B \to D^{(*)} \ell \nu_\ell$ ($\ell = e, \mu$) is reconstructed. The neutral (charged) D candidates are reconstructed in 10 (7) different decay channels. Signal B daughter candidates are reconstructed through the decays $K^{*0} \to K^+ \pi^-$, $K^{*+} \to K^+ \pi^0$ and $K_S^0 \pi^+$, $\rho^+ \to \pi^+ \pi^0$, $\rho^0 \to \pi^+ \pi^-$, $K_S^0 \to \pi^+ \pi^-$, and $\pi^0 \to \gamma\gamma$. Figure 6 shows the extra energy ($E_{\rm ECL}$) distributions for all eight $B \to h \nu \bar{\nu}$ channels. $E_{\rm ECL}$ is the

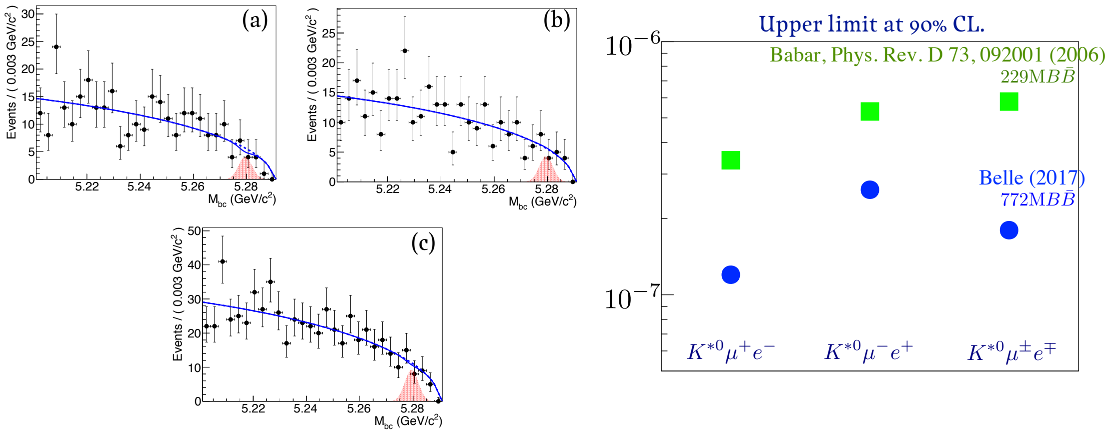

Figure 5: Distribution of the beam energy constrained mass for selected $B^0 \to K^{*0}\mu^+e^-$(a), $B^0 \to K^{*0}\mu^-e^+$(b), and also both decays combined(c). Dots with error bars are the data, and the blue solid curve is the result of the fit for the signal-plus-background hypothesis, where the blue dashed curve is the background component. The red shaded histogram represents the probability density function for signal with arbitrary normalization. Comparison with the previous results [14] for the upper limit at 90% confidence level.

sum of the energies of all clusters in the electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) which are not used in reconstruction of the $\Upsilon(4S)$. No statistically significant signal is seen and 90% confidence level upper limits on the branching fractions are

$$Br(B \to K\nu\bar{\nu}) < 1.6 \times 10^{-5}, \quad (5.1)$$

$$Br(B \to K^*\nu\bar{\nu}) < 2.7 \times 10^{-5}, \quad (5.2)$$

$$Br(B \to \pi\nu\bar{\nu}) < 0.8 \times 10^{-5}, \quad (5.3)$$

$$Br(B \to \rho\nu\bar{\nu}) < 2.8 \times 10^{-5}. \quad (5.4)$$

The limits on the branching fraction for the $B^0 \to K_S^0\nu\bar{\nu}$, $B^0 \to K^{*0}\nu\bar{\nu}$, $B^+ \to \pi^+\nu\bar{\nu}$, $B^0 \to \pi^0\nu\bar{\nu}$, $B^+ \to \rho^+\nu\bar{\nu}$ and $B^0 \to \rho^0\nu\bar{\nu}$ channels are the most stringent to date.

6. Summary

New measurements for radiative and electroweak penguin are performed with the Belle full data set of 772 $\times 10^6 B\bar{B}$. All the measurements of $B \to K^*\gamma$ are the most precise to date and the first evidence of isospin violation in $b \to s\gamma$ decay is detected with a significance of 3.1σ. The first measurement of ΔA_{CP} for $B \to K^*\gamma$ is performed. A 2.6σ deviation is seen in P_5' of muon mode in the lepton flavor dependent angular analysis of $B \to K^*\ell\ell$. The most stringent constraints on LFV in B decays are obtained by a search for LFV $B \to K^*\mu e$. Upper limits on $B \to h^*\nu\bar{\nu}$ channels are also obtained.

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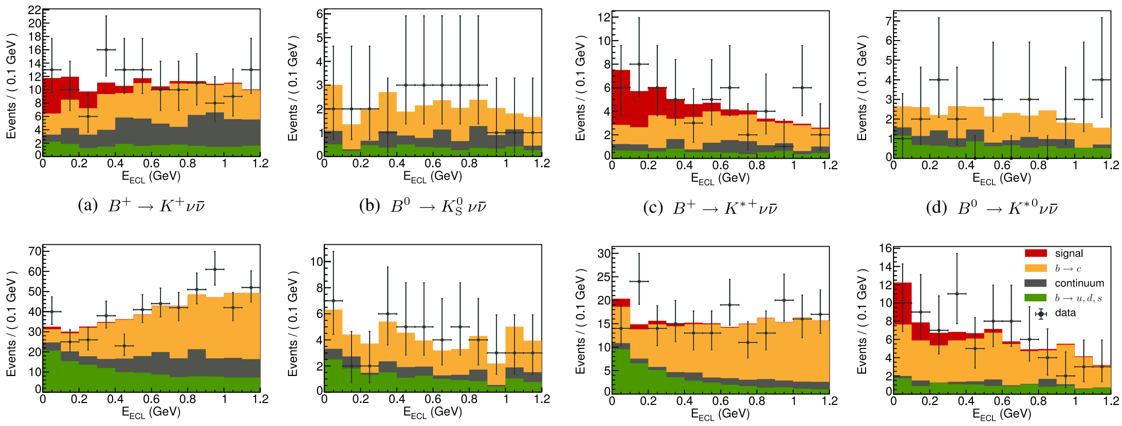

(a) $B^+ \to K^+\nu\bar{\nu}$ (b) $B^0 \to K_S^0\,\nu\bar{\nu}$ (c) $B^+ \to K^{*+}\nu\bar{\nu}$ (d) $B^0 \to K^{*0}\nu\bar{\nu}$

(e) $B^+ \to \pi^+\nu\bar{\nu}$ (f) $B^0 \to \pi^0\nu\bar{\nu}$ (g) $B^+ \to \rho^+\nu\bar{\nu}$ (h) $B^0 \to \rho^0\nu\bar{\nu}$

Figure 6: $E_{\rm ECL}$ distributions for all eight $B \to h\nu\bar{\nu}$ channels.

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