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# Radiative and EWP $B$ decays at $B$-factories

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We report on the recent measurements related to the flavour-changing-neutral-current $b \to s$ quark-level transitions at the $B$-factories. The measurement of the decay $B \to K^{*}\gamma$, time-dependent $CP$ asymmetry in the decay $B^{0} \to K_{S}^{0}\eta\gamma$, and angular analysis of $B \to K^{*}\ell^{+}\ell^{-}$ are reviewed. We also report on the searches for the decays $B^{+} \to K^{+}\tau^{+}\tau^{-}$ and $B \to h\nu\nu$. All these analyses are performed on the data sample recorded by the Belle or BaBar detector at the $\Upsilon(4S)$ resonance.

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## 1. Introduction

Flavor changing neutral current (FCNC) involving quark level transition $b \to s$ are forbidden at tree level in the standard model (SM) and proceed at lowest order through penguin loop or box diagrams. These decays are sensitive probe for the new physics (NP) as heavy non-SM particles can also enter in the loop.

The $B$-factories, Belle and BaBar experiments, had a successful operational period with a total recorded data-sample over 1.5 ab$^{-1}$, containing more than $1.2 \times 10^9$ $B$-meson pairs. A very clean sample of quantum correlated $B$-meson pairs produced at the $B$-factories enables efficient reconstruction of neutrals and missing mass analyses straight-forward.

Recently $B$-factories provided notable results on the measurements of the decays involving radiative and electroweak penguin $B$ meson decays. We report some of those results herein; the following results are from Belle: the measurements of the decay $B \to K^*\gamma$ [1]; measurement of time-dependent $CP$ asymmetries in the decay $B^0 \to K_S^0\eta\gamma$ [2]; lepton-flavor dependent angular analysis of the decay $B \to K^*\ell\ell$ [3]; search for the decays $B \to h\nu\nu$ [4]. These aforementioned studies are based on the 711 fb$^{-1}$ data set recorded at the $\Upsilon(4S)$ resonance by the Belle detector at the KEKB energy-asymmetric collider. We also report a search for the decay $B^+ \to K^+\tau^+\tau^-$ [5] based on 424 fb$^{-1}$ of data recorded by the BABAR detector at the $e^+e^-$ PEP-II collider at the SLAC National Accelerator Laboratory.

## 2. Measurement of $\mathbf{B \to K^*\gamma}$

The decays $B \to K^*\gamma$ [6] involves the quark-level transition $b \to s\gamma$ and proceed dominantly via one-loop electromagnetic penguin diagrams at the lowest order in the SM. The SM prediction for BF of these decays has large uncertainity ($\sim 30\%$) due to form factor and gives a weak constraint on the NP [7, 8, 9, 10, 11, 12, 13]. However, these theory uncertainties cancel out in the BF ratios, like isospin ($\Delta_{0+}$) and direct $CP$ asymmetries ($A_{CP}$), and provide strong constraint on NP [11].

In the recent measurement by Belle [1], $B^0 \to K^{*0}\gamma$ and $B^+ \to K^{*+}\gamma$ decays [14] are reconstructed, where the $K^*$ is formed from seven combinations: $K_S^0\pi^0$, $K^+\pi^-$, $K^-\pi^+$, $K^+\pi^0$, $K^-\pi^0$, $K_S^0\pi^+$ and $K_S^0\pi^-$. The photon candidate is selected from isolated clusters consistent with electromagnetic shower shape. Further, vetoes are applied on the photon candidate to ensure it does not originate from a $\pi^0$ or an $\eta$ decay. The dominant background from the $e^+e^- \to q\bar{q}$ continuum events is suppressed by utilizing event shape variables in a multivariate analysis with a neural network. Then, a simultaneous fit is performed to all the seven $M_{\rm bc}$ distributions to extract the combined branching fractions (BFs), $A_{CP}$, $\Delta_{0+}$ and the difference of $A_{CP}$ between charged and neutral $B$ mesons ($\Delta A_{CP}$); these variables are defined in Ref. [1].

The results are:

$$\begin{aligned}
\mathscr{B}(B^0 \to K^{*0}\gamma) &= (3.96 \pm 0.07 \pm 0.14) \times 10^{-5}, \\
\mathscr{B}(B^+ \to K^{*+}\gamma) &= (3.76 \pm 0.10 \pm 0.12) \times 10^{-5}, \\
A_{CP}(B^0 \to K^{*0}\gamma) &= (-1.3 \pm 1.7 \pm 0.4)\%, \\
A_{CP}(B^+ \to K^{*+}\gamma) &= (+1.1 \pm 2.3 \pm 0.3)\%, \\
A_{CP}(B \to K^{*}\gamma) &= (-0.4 \pm 1.4 \pm 0.3)\%, \\
\Delta_{0+} &= (+6.2 \pm 1.5 \pm 0.6 \pm 1.2)\%, \\
\Delta A_{CP} &= (+2.4 \pm 2.8 \pm 0.5)\%,
\end{aligned}$$

- Here, the first uncertainty is statistical, the second is systematic, and the third for $\Delta_{0+}$ is due to uncertainty in BF ratio for $\Upsilon(4S)$ to $B^+B^-$ and $B^0\bar{B}^0$.
- Isospin violation ($\Delta_{0+}$) is reported with a significance of $3.1\sigma$, which is consistent with the SM predictions [7, 11, 15, 16, 17, 18]. Dominant uncertainties for this measurement are statistical and due to uncertainty in BFs, $\Upsilon(4S) \to B^+B^-$ and $\Upsilon(4S) \to B^0\bar{B}^0$.
- The $A_{CP}$ and $\Delta A_{CP}$ measurements are consistent with zero.
- The BF ratio of $B^0 \to K^{*0}\gamma$ and $B_s^0 \to \phi\gamma$ is calculated and found to be $1.10 \pm 0.16 \pm 0.09 \pm 0.18$, which is also consistent with the previous measurement by LHCb [19] as well as with the SM predictions [12, 15]. For this measurement only the $K^{*0} \to K^+\pi^-$ mode is utilized to cancel common systematic uncertainties, while the BF for $B_s^0 \to \phi\gamma$ is taken from a previous Belle measurement from 121 $\text{fb}^{-1}$ data recorded at the $\Upsilon(5S)$ resonance [20].

## 3. Time-dependent CP Asymmetries in $\mathbf{B^0 \to K_S^0}\eta\gamma$

Photon polarization is an another important observable in the $b \to s\gamma$ processes. According to the SM, the photon is predominantly left-handed polarized; and the right-handed contribution can be enhanced in various NP models, such as supersymmetry, left-right symmetric models and extra-dimensions. Potential contributions from NP-associated right-handed currents could enhance the value of *CP* violation parameter, $\mathcal{S}$, in the $B^0 \to P_1^0 P_2^0 \gamma$ process where $P_1^0$ and $P_2^0$ are scalar or pseudoscalar mesons and the $P_1^0 P_2^0$ system is a *CP* eigenstate [21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32]. Belle reported the first measurement of time-dependent *CP* violation in $B^0 \to K_S^0 \eta\gamma$ [2], and the obtained *CP* violation parameters

$$\begin{aligned}
\mathcal{S} &= -1.32 \pm 0.77(\text{stat.}) \pm 0.36(\text{syst.}), \\
\mathcal{A} &= -0.48 \pm 0.41(\text{stat.}) \pm 0.07(\text{syst.})
\end{aligned}$$

and find that the central values are outside of the physical boundary defined by $\mathcal{S}^2 + \mathcal{A}^2 = 1$, shown in Fig 1. These results are consistent with the null-asymmetry hypothesis within 2 $\sigma$ as well as with the SM predictions [33, 34, 35, 36, 37, 38].

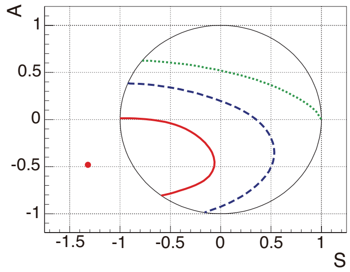


**Figure 1:** The solid red, dashed blue and dotted green curves show the $1\sigma$, $2\sigma$ and $3\sigma$ confidence contours, respectively. The red dot shows the fit result. The physical boundary $\mathcal{S}^2+\mathcal{A}^2=1$ is drawn with a thin solid black curve. The Belle result is consistent with a null asymmetry within $2\sigma$ [2].

## 4. Angular Analysis of $B \to K^*\ell\ell$

The decay $B \to K^*\ell\ell$ involves the FCNC transition $b \to s\ell\ell$, and is a rare process in the SM. Interestingly, in the recent years several measurements have shown possible deviations from the SM for this decay [39]. A global fit to $B$ decay results suggests lepton non-universality, where muon modes would have larger contributions from the NP than electron modes [40]. This motivates to check lepton-flavor dependent angular analysis. The observables $P_i'$, introduced in Ref. [41, 42], are considered to be largely free from form-factor uncertainties [43]. Any deviation from zero in the difference $Q_i = P_i^{\mu} - P_i^{e}$ would be a direct hint of NP [44]; here, $i = 4,5$ and $P_i^{\ell}$ refers to $P_{4,5}'$ in the corresponding lepton mode. The definition of $P_i'$ values follows the LHCb convention [45]. In total, four decay modes are reconstructed $B^0 \to K^{*0}\mu^+\mu^-$, $B^+ \to K^{*+}\mu^+\mu^-$, $B^0 \to K^{*0}e^+e^-$ , and $B^+ \to K^{*+}e^+e^-$; where $K^{*0}$ decays to $K^+\pi^-$ and $K^{*+}$ decays to $K^+\pi^0$ or $K_S^0\pi^+$. Signal yields are extracted with an unbinned extended maximum likelihood fit and in total, $127\pm15$ and $185\pm17$ signal candidates are obtained for the electron and muon channel, respectively. The analysis is performed in the four independent bins of $q^2$ (invariant mass squared of the two leptons). An additional $q^2 \in (1.0, 6.0)$ GeV$^2/c^2$ bin is considered, which is favored for theoretical predictions [41]. To maximize the potency of limited statistics, a data-transformation technique is utilized [46, 47]. Overall the result is in agreement with the SM value [48, 49]. The largest deviation is $2.6\sigma$, observed in $q^2 \in (4.0, 8.0)$ GeV$^2/c^2$ bin of $P_5'$ for the muon mode. This tension is coincidental to the $P_5'$ anomaly earlier reported by LHCb [45, 46]. In the same region the electron modes deviate by $1.3\sigma$ and the combination deviates by $2.5\sigma$. The observables $Q_4$ and $Q_5$ are presented in Figure 2, where they are compared with SM and NP scenario [44]. The results show no significant deviation from zero.

Global fits performed including these measurements [3] suggests for lepton-universality-violation [50].

## 5. Search for $\mathbf{B^+ \to K^+\tau^+\tau^-}$

The decay $B^+ \to K^+\tau^+\tau^-$ is special among $b \to s\ell\ell$ FCNC transitions, because it involves the heaviest lepton and thus can provide additional sensitivity to NP due to third-generation couplings [51]. BaBar experiment searched for the decay $B^+ \to K^+\tau^+\tau^-$ based on 424 fb$^{-1}$ data collected at $\Upsilon(4S)$ resonance [5]. In this study, hadronic $B$ meson tagging method is used, where

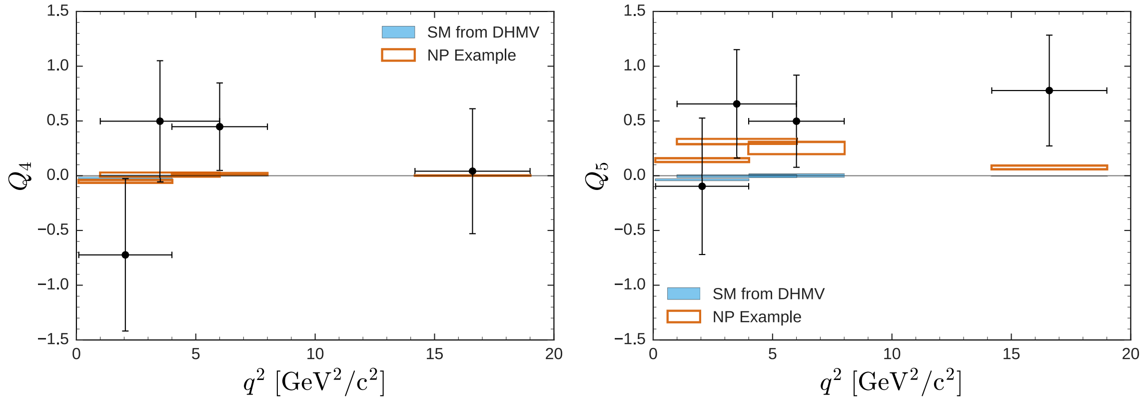


**Figure 2:** $Q_4$ (left) and $Q_5$ (right) observables compared with SM and NP scenario, respectively shown by the cyan filled and brown open boxes [3].

one of the two $B$ mesons is reconstructed exclusively in its hadronic decay modes. The remaining tracks, clusters, and the missing energy in the event is attributed to the signal $B$ meson. Only leptonic decays of the $\tau$ are considered, which results in three signal decay topologies with a $K^+$, multiple missing neutrinos, and either $e^+e^-$, $\mu^+\mu^-$, or $e^+\mu^-$. The neutrinos are accounted for the missing energy and any other neutral activity is discarded. Event shape variables are utilized to suppress continuum events. At this stage remaining background mostly arise from the $B\bar{B}$ events, which are suppressed using a neural network (NN) with several input variables related to signal decay kinematics. After applying the requirement on the output of the NN, the upper limit at 90% confidence level (CL) on the BF[$B^+ \to K^+\tau^+\tau^-$] $< 2.25 \times 10^{-3}$ .

## 6. Search for $B \to h\nu\nu$

The decays $B \to h\nu\nu$ (where $h$ refers to $K^+$, $K_s^0$, $K^{*+}$, $K^{*0}$, $\pi^+$, $\pi^0$, $\rho^+$ or $\rho^0$) are theoretically clean due to the exchange of a $Z$ boson alone, in comparison to other $b \to s$ transitions where the virtual photon also contributes [52].

Previously, the decays $B \to h\nu\nu$ have been searched in Belle utilizing the hadronic tag method [53] and in BaBar using both hadronic [54] and semi-leptonic tag [55]. The recent Belle analysis [4] is based on a more efficient semi-leptonic tagging method. The 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 $\pi^0 \to \gamma\gamma$. Event shape variables are utilized to suppress continuum events. Signal events are identified from extra energy in the electromagnetic calorimeter ($E_{ECL}$), which is calculated by removing all the associated $ECL$ energy from tag and signal $B$ mesons. The largest signal contribution is observed in the decay $B \to K^{*+}\nu\nu$ with a significance of $2.3\sigma$. In the absence of a significant signal in any of the modes, upper limits on the BFs are measured with 90% CL. The result is shown in Figure 3 along with expected values and previous measurements.

These decays can be observed with Belle II [56], assuming the SM prediction holds. Belle II will be able to provide a measurement with uncertainties of similar size as the current theoretical uncertainties [57].

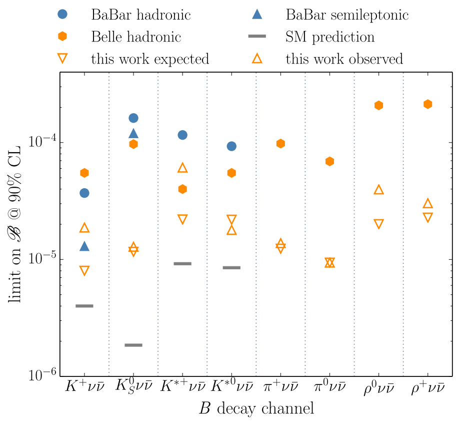


**Figure 3:** Observed upper limits along-with the expected values and previous measurement. SM predictions are also shown for the $K^{(*)}$ modes [4].

## 7. Summary

Decays involving $b \to s$ quark level transitions are forbidden at tree level in the SM, and these decays proceed via penguin loop or box diagrams in which various NP particles may also contribute. Recently, the first evidence of isospin violation is reported by Belle experiment in the $B \to K^*\gamma$ decay [1]; also first measurement of the difference of $CP$ asymmetries, between charged and neutral $B$ meson in performed in the same analysis. Belle measurement of $CP$ violation parameters in $B^0 \to K_S^0\eta\gamma$ [2] is consistent with the null-asymmetry hypothesis within 2 $\sigma$. Lepton-flavor dependent angular analysis for the decay $B \to K^*\ell\ell$ is performed [3] for the first time; and results are consistent with both SM values and NP scenarios. The decay $B^+ \to K^+\tau^+\tau^-$ is searched by BaBar experiment and an upper limit on its BF is derived at 90% CL. Also, Belle set the most stringent upper limits on the BFs for the decay $B \to h\nu\nu$ [4]. The upper limits are close to SM predictions [52] for the $K^{(*)}$ modes and Belle II has brighter prospects to observe these decays.

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