Penguin and rare decays in *BABAR*

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Abstract. We present recent results from the *BABAR* Collaboration on radiative decays. These include searches for new physics via measurements of the several observables such as the time-dependent *CP* asymmetry in $B^0 \to K_S^0\pi^-\pi^+\gamma$ exclusive decays, as well as direct *CP* asymmetries and branching fractions in $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$ inclusive decays.

1. Introduction

Until the end of 2007, the *BABAR* experiment recorded e^+e^- collisions at the $\Upsilon(4S)$ resonance with 471×10^6 $B\overline{B}$ pairs produced, corresponding to an integrated luminosity of $429\,\text{fb}^{-1}$. Seven years after the end of the data-taking period, *BABAR* is still producing many physics results. In the LHC era, *BABAR* is still competitive, especially for channels involving neutral particles such as π^0 or K_S^0. We present here a selection of recent results on radiative decays from the *BABAR* experiment. In the Standard Model (SM), both the $b \to s\gamma$ and $b \to s\ell^+\ell^-$ transitions are quark-level flavor-changing neutral current (FCNC) processes. Since all FCNC processes are forbidden at tree level in the SM, the lowest order diagrams representing these transitions must involve loops. In such processes, QCD corrections can typically be described using an effective Hamiltonian defined as $\text{H}_{\text{eff}} \propto \sum_{i=1}^{10} C_i\mathcal{O}_i$, where the C_i and $\mathcal{O}_i$ are, respectively, the short-distance Wilson coefficients and local long-distance operators. Contributions from New Physics (NP) in $b \to s$ transitions may modify the SM values of the Wilson coefficients, and change the values, predicted by the SM, of observables such as branching fractions and *CP* asymmetries.

2. Measurements of direct *CP* asymmetries in $B \to X_s\gamma$ decays using a sum of exclusive decays

In this analysis [1], the direct *CP* asymmetry, A_{CP}, given by Eq. 1, for the sum of exclusive final states is measured.

$$A_{CP} = \frac{\Gamma_{\overline{B}^0/B^-\to X_s\gamma} - \Gamma_{B^0/B^+\to X_{\bar{s}}\gamma}}{\Gamma_{\overline{B}^0/B^-\to X_s\gamma} + \Gamma_{B^0/B^+\to X_{\bar{s}}\gamma}} \,. \tag{1}$$

$$\Delta A_{CP} \simeq 0.12 \times \frac{\tilde{\Lambda}_{78}}{100\,\text{MeV}}\text{Im}\frac{C_{8g}}{C_{7\gamma}} \,. \tag{2}$$

The SM prediction for the asymmetry was found in a recent study to be in the range $-0.6\% < A_{CP}^{SM} < 2.8\%$ [2]. From Ref. [2], another test of the SM is proposed, via the measurement of the difference in A_{CP} in charged and neutral B mesons: $\Delta A_{CP} = A_{B^\pm\to X_s\gamma} - A_{B^0/\overline{B}^0\to X_s\gamma}$. As

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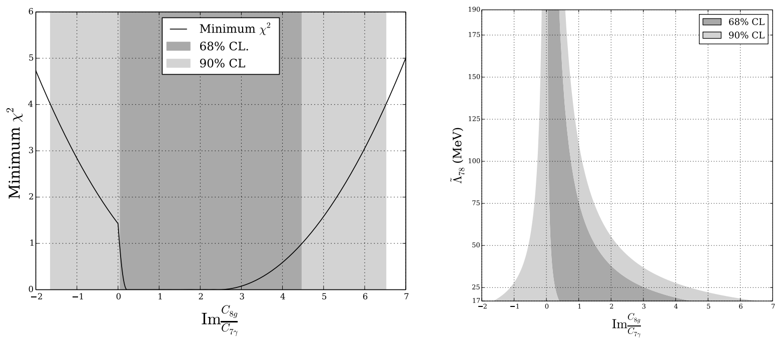

Figure 1. (left) The minimum χ^2 for given $\mathrm{Im}\frac{C_{8g}}{C_{7\gamma}}$ from all possible values of $\tilde{\Lambda}_{78}$. 68% and 90% confidence intervals are shown in dark gray and light gray, respectively. (right) The 68% and 90% confidence intervals for $\mathrm{Im}\frac{C_{8g}}{C_{7\gamma}}$ as a function of $\tilde{\Lambda}_{78}$.

shown by Eq. 2, the magnitude of ΔA_{CP} is proportional to $\mathrm{Im}\frac{C_{8g}}{C_{7\gamma}}$, where $C_{7\gamma}$ and C_{8g} are the Wilson coefficients corresponding to the electromagnetic dipole and the chromo-magnetic dipole transitions, respectively. Since in the SM, both $C_{7\gamma}$ and C_{8g} are real, ΔA_{CP} is expected to be zero.

The B meson decays are fully reconstructed in 16 self-tagging final states, which are listed in Ref. [1]. The raw asymmetry is extracted from a simultaneous fit to the *energy-substitued* B meson mass, m_{ES}, distributions of B and $\overline{B}$ tagged samples; $m_{\mathrm{ES}} \equiv \sqrt{(\sqrt{s}/2)^2 - (p^*_B)^2}$, where p^*_B is the momentum vector of the B in the e^+e^- center-of-mass (CM) frame and $\sqrt{s}$ is the total energy of the e^+e^- system. The direct *CP* asymmetry is obtained after correcting the raw asymmetry for detector effects. Possible dilution from the presence of peaking backgrounds in the m_{ES} distributions are taken into account as systematic uncertainties. The measured value is $A_{CP} = +(1.73 \pm 1.93 \pm 1.02)\%$, where the first quoted error is statistical and the second is systematic. This corresponds to the most precise to date measurement and is compatible with the SM. The first measurement of ΔA_{CP} is obtained by a simultaneous fit to the separate charge and neutral B samples, such as $\Delta A_{CP} = +(5.0 \pm 3.9 \pm 1.5)\%$, where the first quoted error is statistical and the second is systematic.

The interference amplitude, $\tilde{\Lambda}_{78}$, in Eq. 2 is only known as a range of possible values: $17\,\mathrm{MeV} < \tilde{\Lambda}_{78} < 190\,\mathrm{MeV}$. Using the measured values of ΔA_{CP}, a χ^2 minimization is performed for given $\mathrm{Im}\frac{C_{8g}}{C_{7\gamma}}$ from all possibles values of $\tilde{\Lambda}_{78}$, as shown in Fig. 1. The 68% and 90% confidence limits are then obtained from the ranges of $\mathrm{Im}(C_{8g}C_{7\gamma})$, which yield the minimum χ^2 less than 1 and 4, respectively, such as: $0.07 \leq \mathrm{Im}(C_{8g}/C_{7\gamma}) \leq 4.48$, at 68% CL and $-1.64 \leq \mathrm{Im}(C_{8g}/C_{7\gamma}) \leq 6.52$, at 90% CL.

3. Measurement of the $B \to X_s\,\ell^+\ell^-$ branching fraction and search for direct *CP* violation from a sum of exclusive final states

In the present analysis, the inclusive decay $B \to X_s\,\ell^+\ell^-$ is studied, where X_s is a hadronic system containing exactly one kaon, using a sum over 20 exclusive final states, where $\ell^+\ell^-$ is either e^+e^- or $\mu^+\mu^-$, as listed in Ref. [3].

The total branching fraction (BF), as well as partial BFs in five disjoint dilepton mass-squared $q^2 \equiv m^2_{\ell^+\ell^-}$ bins and four hadronic mass m_{X_s} bins, which are defined in Ref. [3]. Events with q^2 corresponding to signal-like charmonium backgrounds J/ψ and $\psi(2S)$ from B decays are rejected. After requiring the invariant mass of the hadronic system $m_{X_s} < 1.8\,\mathrm{GeV}/c^2$, the entire selection represents $\sim 70\%$ of the inclusive $B \to X_s\,\ell^+\ell^-$ rate. The missing hadronic final states, as well as states with $m_{X_s} > 1.8\,\mathrm{GeV}/c^2$ are accounted for using JETSET fragmentation [4] and theory predictions.

The signal yields are extracted, in each q^2 and m_{X_s} bins, from a simultaneous fit to $m_{\rm ES}$ and a likelihood ratio L_R, which is defined as $L_R \equiv \mathcal{P}_S/(\mathcal{P}_S + \mathcal{P}_B)$ with $\mathcal{P}_S$ ($\mathcal{P}_B$) the probability for a correctly-reconstructed signal ($B\overline{B}$ background) event calculated based on the response of boosted decision trees.

The total BF for $q^2 > 0.1\,{\rm GeV}^2/c^4$ is measured to be $\mathcal{B}(B \to X_s\,\ell^+\ell^-) = 6.73^{+0.70+0.34}_{-0.64-0.25} \pm 0.50 \times 10^{-6}$, which is less than 2σ above the SM prediction of $\mathcal{B}_{SM} = 4.6 \pm 0.8 \times 10^{-6}$ [5]. In the low mass range, for $1 < q^2 < 6\,{\rm GeV}^2/c^4$, the BF is measured to be $\mathcal{B}^{\rm low}(B \to X_s\,\ell^+\ell^-) = 1.60^{+0.41+0.17}_{-0.39-0.13} \pm 0.18 \times 10^{-6}$, which is in good agreement with the SM predictions of $\mathcal{B}^{\rm low}_{SM}(B \to X_s\,\mu^+\mu^-) = (1.59 \pm 0.11) \times 10^{-6}$ and $\mathcal{B}^{\rm low}_{SM}(B \to X_s\,e^+e^-) = (1.64 \pm 0.11) \times 10^{-6}$ [6]. In the high mass range, for $q^2 > 14.2\,{\rm GeV}^2/c^4$, the BF is measured to be $\mathcal{B}^{\rm high}(B \to X_s\,\ell^+\ell^-) = 0.57^{+0.16+0.03}_{-0.15-0.02} \pm 0.00 \times 10^{-6}$, which is about 2σ higher than the SM predictions for $q^2 > 14.4\,{\rm GeV}^2/c^4$ of $\mathcal{B}^{\rm high}(B \to X_s\,\mu^+\mu^-) = (0.24 \pm 0.07) \times 10^{-6}$ and $\mathcal{B}^{\rm high}(B \to X_s\,e^+e^-) = (0.21 \pm 0.07) \times 10^{-6}$ [6]. For each of the measured BF result listed above, the first uncertainties are statistical, the second experimental systematics and the third model-dependent systematics. The measured partial BFs results in bins of q^2 and m_{X_s} are detailed in Ref [3].

A search for the direct *CP* asymmetry in $B \to X_s\,\ell^+\ell^-$ decays, using the 14 self-tagging final states as listed in Ref. [3], is also performed. For $q^2 > 0.1\,{\rm GeV}^2/c^4$, the measured *CP* asymmetry, $A_{CP}(B \to X_s\,\ell^+\ell^-) = 0.04 \pm 0.11 \pm 0.01$, is consistent with the SM prediction, where it is expected to be suppressed well below the 1%.

4. Time-dependent analysis of $B^0 \to K^0_S\pi^+\pi^-\gamma$ and studies of the $K^+\pi^-\pi^+$ system in $B^+ \to K^+\pi^-\pi^+\gamma$ decays

In $b \to s\gamma$ transitions, the SM predicts that B^0 ($\overline{B}^0$) decays are related predominantly to the presence of right (left) handed photons in the final state. Therefore, the mixing-induced *CP* asymmetry in $B \to f_{CP}\gamma$ decays, where f_{CP} is a *CP* eigenstate, is expected to be small.

One of the goals of the present study is to perform a time-dependent analysis of $B^0 \to K^0_S\pi^+\pi^-\gamma$ decays to extract the direct and mixing-induced *CP* asymmetry parameters, $\mathcal{C}_{K^0_S\rho\gamma}$ and $\mathcal{S}_{K^0_S\rho\gamma}$, in the $B^0 \to K^0_S\rho^0\gamma$ mode. However, due to the large natural width of the $\rho^0(770)$, a non negligible amount of $B^0 \to K^{*\pm}(K^0_S\pi^\pm)\pi^\mp\gamma$ events, which do not contribute to $\mathcal{S}_{K^0_S\rho\gamma}$, are expected to lie under the $\rho^0(770)$ resonance and dilute $\mathcal{S}_{K^0_S\rho\gamma}$. We can define a dilution factor $\mathcal{D}_{K^0_S\rho\gamma}$ such as $\mathcal{D}_{K^0_S\rho\gamma} = \mathcal{S}_{K^0_S\pi^+\pi^-\gamma}/\mathcal{S}_{K^0_S\rho\gamma}$, where $\mathcal{S}_{K^0_S\pi^+\pi^-\gamma}$ is the effective value of the mixing-induced *CP* asymmetry measured for the whole $B^0 \to K^0_S\pi^+\pi^-\gamma$ dataset. Since a small number of signal events is expected in this sample, it is difficult to discriminate $B^0 \to K^{*\pm}(K^0_S\pi^\pm)\pi^\mp\gamma$ from $B^0 \to K^0_S\rho^0(\pi^\mp\pi^\pm)\gamma$ decays. Hence the dilution factor needs to be obtained by other means. To do that, the amplitudes of the different resonant modes are extracted in the charged decay channel[2] $B^+ \to K^+\pi^-\pi^+\gamma$, which has more signal events and is related to $B^0 \to K^0_S\pi^+\pi^-\gamma$ by isospin symmetry. Assuming that the resonant amplitudes are the same in both modes, the dilution factor is calculated from those of $B^+ \to K^+\pi^-\pi^+\gamma$. Moreover, the branching fractions of the different $B \to K_{\rm res}\gamma$ intermediate decay modes (where $K_{\rm res}$ designates a kaonic resonance decaying to $K\pi\pi$) are in general not well known. We also use the amplitude analysis of the charged decay mode $B^+ \to K^+\pi^-\pi^+\gamma$ to extract them.

In the charged B-meson decay mode, we first perform a fit to data to extract the yield of $B^+ \to K^+\pi^-\pi^+\gamma$ signal events. The fit uses the knowledge of three discriminating variables, $m_{\rm ES}$, ΔE and a Fisher discriminant output, to discriminate signal events from backgrounds. ΔE is defined as the difference between the expected and reconstructed B meson energy, $\Delta E \equiv E^*_B - \sqrt{s}/2$, where E^*_B is the reconstructed energy of the B in the e^+e^- CM frame. Using information from the maximum likelihood fit, the $K\pi\pi$, $K\pi$ and $\pi\pi$ invariant mass spectra

[2] Charge conjugation is implicit throughout the document.

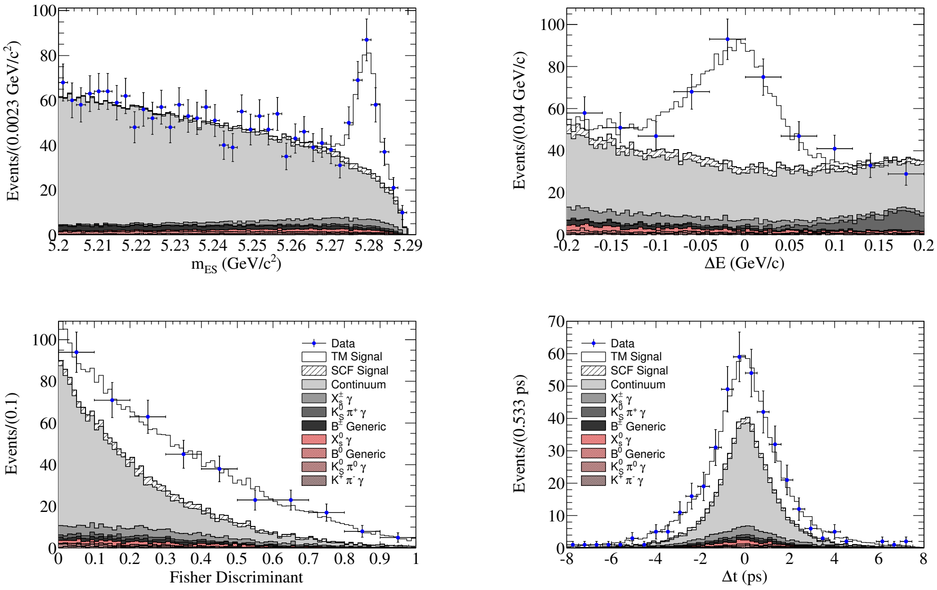

Figure 2. Distributions of $m_{\rm ES}$ (top left), ΔE (top right), the Fisher-discriminant output (bottom left), and Δt (bottom right), showing the fit results on the $B^0 \to K^0_S\pi^+\pi^-\gamma$ data sample. The distributions have their signal/background ratio enhanced by means of the following requirements: $-0.15 \leq \Delta E \leq 0.10\,{\rm GeV}/c$ ($m_{\rm ES}$), $m_{\rm ES} > 5.27\,{\rm GeV}/c^2$ (ΔE) and $m_{\rm ES} > 5.27\,{\rm GeV}/c^2$; $-0.15 \leq \Delta E \leq 0.10\,{\rm GeV}/c$ (Fisher and Δt).

in signal events are extracted using the ${}_s\mathcal{P}lot$ technique [7]. Then fitting the $m_{K\pi\pi}$ and $m_{K\pi}$ spectra, the amplitudes and BFs of the kaonic resonances and the intermediate state resonances, respectively, are extracted, allowing to compute the dilution factor, such as $\mathcal{D}_{K^0_S\rho\gamma} = 0.549^{+0.096}_{-0.094}$, where the quoted uncertainties are sums in quadrature of statistical and systematic uncertainties.

In the neutral B-meson decay mode, we perform a fit to data to extract the effective CP asymmetry parameters, using four discriminating variables, $m_{\rm ES}$, ΔE and a Fisher discriminant output and the proper-time difference Δt. Figure 2 shows the fit projections. We obtain the CP-violating parameters $\mathcal{S}_{K^0_S\pi^+\pi^-\gamma} = 0.137 \pm 0.249^{+0.042}_{-0.033}$ and $\mathcal{C}_{K^0_S\pi^+\pi^-\gamma} = -0.390 \pm 0.204^{+0.045}_{-0.050}$, where the first quoted errors are statistical and the second are systematic. Using the dilution factor, extracted from the charged mode analysis, we extract the time-dependent CP asymmetry related to the hadronic CP eigenstate $\rho^0 K^0_S$ and obtain $\mathcal{S}_{K^0_S\rho\gamma} = 0.249 \pm 0.455^{+0.076}_{-0.060}$, which is compatible with the SM expectation of ~ 0.03 [8].

5. Conclusions

The *BABAR* Collaboration, seven years after the shutdown of the experiment, is still producing competitive results. Three recent analyses have been presented, for which all the results are in agreement with the SM predictions.

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