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Radiative B decays and new physics searches at BABAR

Liang SUN[*][†]
University of Cincinnati
E-mail: sunl@slac.stanford.edu

In this talk, a number of recent results on radiative B decays from BABAR are covered. Based on the full BABAR dataset of 471 million $\Upsilon(4S) \to B\bar{B}$ events, the inclusive decays $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$, as well as the exclusive decays $B \to K\pi^+\pi^-\gamma$ are measured for new physics searches.

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1. Introduction

Both the $b \to s\gamma$ and $b \to s\ell^+\ell^-$ transitions are flavor-changing neutral-current processes, and forbidden at tree level in the Standard Model (SM). The Feymann diagrams representing these types of transitions must involve loops. In the effective field theory for $b \to s$ transitions, the effective Hamiltonian can be written conventionally as $H_{Eff} \propto \sum_{i=1}^{10} C_i \mathcal{O}_i$, which factorizes short-distance physics represented by the Wilson coefficients C_i from long-distance effects. New physics beyond the SM brings in new loops for $b \to s$ transitions, and may change the SM values of Wilson coefficients.

During its entire data-taking period from 1999 till 2008, the BaBar detector [1] collected ~471 million $B\bar{B}$ pairs at the $\Upsilon(4S)$ resonance with the $PEP-II$ asymmetric energy e^+e^- collider. Based on the full BaBar dataset, we present here the search for direct CP violation in $B \to X_s\gamma$ using a sum of exclusive final states, as well as the time-dependent analysis of $B^0 \to K_S^0\pi^+\pi^-\gamma$ and the study of the $K^+\pi^-\pi^+$ system in the decay $B^+ \to K^+\pi^-\pi^+\gamma$[1]. Finally we present the measurement of the $B \to X_s\ell^+\ell^-$ branching fraction (BF) and search for direct CP violation using a sum of exclusive final states. Here X_s represents any hadronic system with one unit of strangeness.

For all the BaBar analyses presented here, the major backgrounds are either from $e^+e^- \to q\bar{q}$ ($q = u,d,s,c$) continuum events or from combinatorial $B\bar{B}$ events. Different types of multivariate classifiers, such as a Fisher discriminant, boosted decision trees (BDTs), and random forests, are trained for the background suppression. Furthermore, We distinguish a fully reconstructed B candidate from backgrounds with energy-substituted mass $m_{\rm ES} = \sqrt{E_{\rm CM}^2/4 - p_B^{*2}}$, and the energy difference $\Delta E = E_B^* - E_{\rm CM}/2$, where p_B^* and E_B^* are the reconstructed B momentum and energy in the $\Upsilon(4S)$ center-of-mass(CM) frame, respectively, and $E_{\rm CM}$ is the total CM energy.

2. Search for direct *CP* violation in $B \to X_s\gamma$ using a sum of exclusive final states

The direct CP asymmetry (A_{CP}) for the sum of exclusive final states of $B \to X_s\gamma$ is measured by:

$$A_{CP}(B \to X_s\gamma) \equiv \frac{\Gamma_{\bar{B}^0/B^- \to X_s\gamma} - \Gamma_{B^0/B^+ \to X_{\bar{s}}\gamma}}{\Gamma_{\bar{B}^0/B^- \to X_s\gamma} + \Gamma_{B^0/B^+ \to X_{\bar{s}}\gamma}}. \tag{2.1}$$

In the SM, A_{CP} is expected to be small and within a range of $-0.6\% < A_{CP}^{SM} < 2.8\%$ [2]. Measuring the difference in A_{CP} in charged and neutral B mesons $\Delta A_{X_s\gamma} \equiv A_{B^\pm \to X_s\gamma} - A_{B^0/\bar{B}^0 \to X_s\gamma}$ is proposed to be another test of the SM. $\Delta A_{X_s\gamma}$ depends on two Wilson coefficients $C_{7\gamma}$ and C_{8g} representing the electromagnetic dipole and the chromo-magnetic dipole transitions, respectively, according to the relationship [2],

$$\Delta A_{X_s\gamma} \simeq 0.12 \times \frac{\tilde{\Lambda}_{78}}{100 \text{ MeV}} \mathrm{Im}(C_{8g}/C_{7\gamma}), \tag{2.2}$$

where the interference amplitude $\tilde{\Lambda}_{78}$ is known to be within the range $17 \text{ MeV} < \tilde{\Lambda}_{78} < 190 \text{ MeV}$. In the SM, we expect $\Delta A_{X_s\gamma} = 0$ as the two Wilson coefficients C_{8g} and $C_{7\gamma}$ are real. Experimentally, C_{8g} is not as well constrained as $C_{7\gamma}$. Together with existing knowledge on $C_{7\gamma}$, a measurement on $\Delta A_{X_s\gamma}$ can place a constraint on C_{8g}.

[1] Charge conjugation is implied throughout unless explicitly noted.

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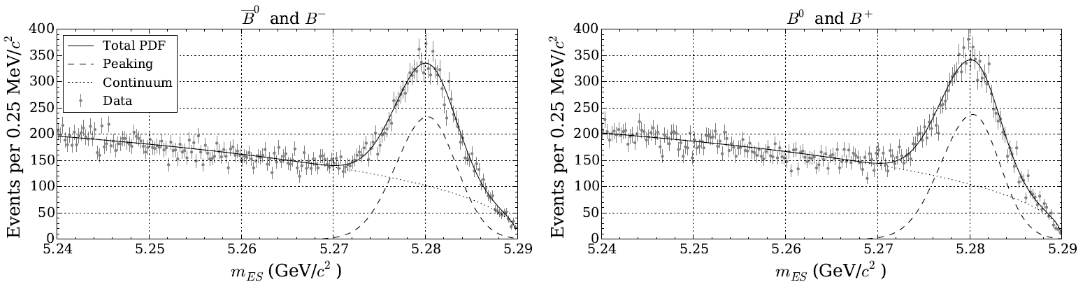

Figure 1: Fits to the $\bar{B}$ and B samples.

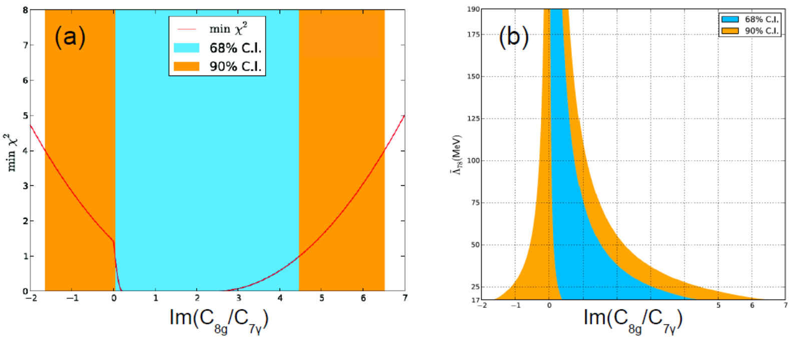

Figure 2: (a) The minimum χ^2 for given Im$\frac{C_{8g}}{C_{7\gamma}}$ from all possible values of $\tilde{\Lambda}_{78}$, also shown are the 68% and 90% confidence intervals for Im$\frac{C_{8g}}{C_{7\gamma}}$; (b) The 68% and 90% CLs for Im$\frac{C_{8g}}{C_{7\gamma}}$ as a function of $\tilde{\Lambda}_{78}$.

In this analysis [3], we fully reconstruct B meson decays in 16 self-tagging final states as listed in Ref. [3] where the B flavor can be determined from the final state particles.

The raw asymmetry is extracted via fitting simultaneously to the $m_{\rm ES}$ distributions of B and $\bar{B}$ tagged samples, as demonstrated in Fig. 1, which is further corrected for detector related effects to get A_{CP}. We measure $A_{CP} = +(1.7 \pm 1.9[\text{stat.}] \pm 1.0[\text{syst.}])\%$, which is the most precise to date and agrees with the SM. Through fitting simultaneously to the separate charged and neutral B samples, we also provide the first measurement on $\Delta A_{X_s\gamma}$: $\Delta A_{X_s\gamma} = +(5.0 \pm 3.9[\text{stat.}] \pm 1.5[\text{syst.}])\%$, which is consistent with the SM expectation of zero. We compare the measured $\Delta A_{X_s\gamma}$ with the prediction based on the relationship in Eq. 2.2 for given $\text{Im}(C_{8g}/C_{7\gamma})$ and $\tilde{\Lambda}_{78}$ to calculate the minimum χ^2, as shown in Fig. 2(a). The ranges of $\text{Im}(C_{8g}/C_{7\gamma})$ and $\tilde{\Lambda}_{78}$ that yield the minimum χ^2 less than 1 and 4 are used to obtain the 68% and 90% confidence limits (CLs) shown in Fig. 2(b). Using the extremes in Fig. 2(b) for all permitted values of $\tilde{\Lambda}_{78}$, we conservatively set $\text{Im}(C_{8g}/C_{7\gamma})$: $0.07 \leq \text{Im}(C_{8g}/C_{7\gamma}) \leq 4.48$ @68% CL; $-1.64 \leq \text{Im}(C_{8g}/C_{7\gamma}) \leq 6.52$ @90% CL.

3. Studies of $B \to K\pi\pi\gamma$ decays

We measure *CP* asymmetry in the decay $B^0 \to K_S^0 \rho^0 \gamma$ as a function of B^0–$\bar{B}^0$ decay-time difference Δt, which is defined as:

$$A_{CP} \equiv \frac{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}\gamma) - \Gamma(B^0(\Delta t) \to f_{CP}\gamma)}{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}\gamma) + \Gamma(B^0(\Delta t) \to f_{CP}\gamma)} = \mathcal{S}_{K_S^0\rho^0\gamma} \sin(\Delta m_d \Delta t) - \mathcal{C}_{f_{K_S^0\rho^0\gamma}} \cos(\Delta m_d \Delta t),$$

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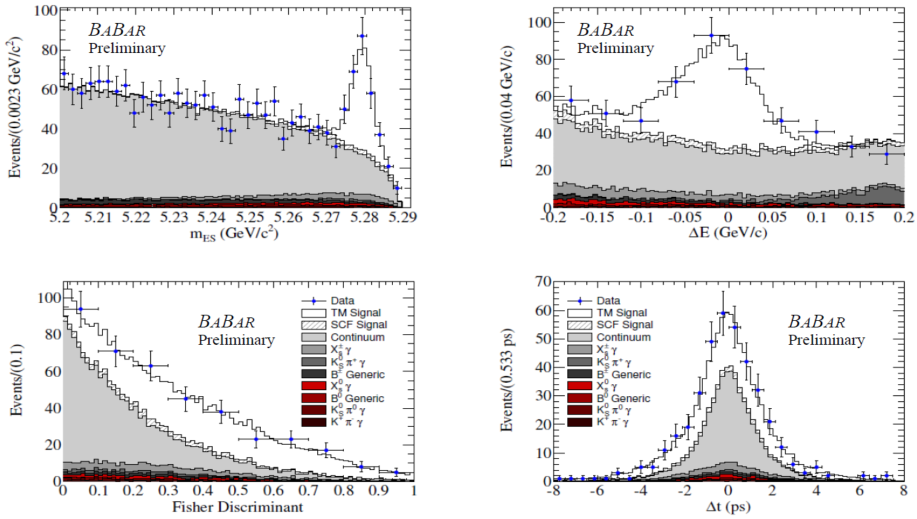

Figure 3: Fit to the distributions of $m_{\rm ES}$ (top left), ΔE (top right), and the Fisher-discriminant output (bottom left), and Δt (bottom right) from the $B^0 \to K^0_S \pi^+\pi^-\gamma$ data sample. The distributions have their signal/background ratios enhanced by means of the following requirements respectively: $-0.15 < \Delta E < 0.10$ GeV ($m_{\rm ES}$); $m_{\rm ES} > 5.27$ GeV$/c^2$ (ΔE); $m_{\rm ES} > 5.27$ GeV$/c^2$ and $-0.15 < \Delta E < 0.10$ GeV (Fisher and Δt).

where Δm_d is the $B^0\bar{B}^0$ oscillation frequency fixed to the measurement in Ref. [4], while $\mathcal{C}_{K^0_S\rho^0\gamma}$ and $\mathcal{S}_{K^0_S\rho^0\gamma}$ are the direct and mixing-induced *CP* asymmetry parameters, respectively.

Experimentally, for the hadronic part of $B^0 \to K^0_S\pi^+\pi^-\gamma$ final state, as $\rho^0(770)$ possesses a large natural width, a large amount of irreducible background events from non-*CP* eigenstates ($K^{*\pm}\pi^\mp$) will lie underneath the $\rho^0(770)$ resonance from our $B \to K^0_S\rho^0(\to \pi^+\pi^-)\gamma$ signal decay, and thus dilute our *CP* parameter $\mathcal{S}_{K^0_S\rho^0\gamma}$. The dilution factor is defined as $\mathcal{D}_{K^0_S\rho^0\gamma} \equiv \frac{\mathcal{S}_{K^0_S\pi^+\pi^-\gamma}}{\mathcal{S}_{K^0_S\rho^0\gamma}}$, where $\mathcal{S}_{K^0_S\pi^+\pi^-\gamma}$ is the effective value of the mixing-induced *CP* asymmetry measured based on all $B^0 \to K^0_S\pi^+\pi^-\gamma$ data events. In order to measure $\mathcal{S}_{K^0_S\rho^0\gamma}$, an amplitude study on the hadronic system of $B^0 \to K^0_S\pi^+\pi^-\gamma$ events is needed here to extract $\mathcal{D}_{K^0_S\rho^0\gamma}$. However this turns out to be a rather difficult task due to limited statistics. We therefore turn to the statistically more abundant sample of charged decays $B^+ \to K^+\pi^-\pi^+\gamma$ for the determination of the dilution factor under the assumption of isospin symmetry.

The fits to $B^+ \to K^+\pi^-\pi^+\gamma$ events undergo in three steps: first we perform a three-dimensional fit using $m_{\rm ES}$, ΔE, and the Fisher discriminant output to unfold the signal distributions of invariant masses $m_{K\pi\pi}$ and $m_{K\pi}$. Then we fit to the $m_{K\pi\pi}$ distribution from the first step to determine the BFs of different kaonic resonances, such as $K_1(1270)^+$, $K_2^*(1430)^+$, etc. The final fit is to the $m_{K\pi}$ distribution to determine the amplitudes and BFs of the intermediate resonances ($K^{*0}(892)$, $\rho(770)^0$, etc.) decaying to $K^+\pi^-$ and $\pi^+\pi^-$. From the measured branching fractions in the last step of fit we compute the dilution factor as $\mathcal{D}_{K^0_S\rho^0\gamma} = 0.549^{+0.096}_{-0.094}$, where the uncertainties incorporate both statistical and systematic contributions.

As shown in Fig. 3, we perform a four-dimensional fit to the data from the neutral mode $B^0 \to K^0_S\pi^+\pi^-\gamma$, to extract the *CP* asymmetry parameters. With the measured dilution factor from the

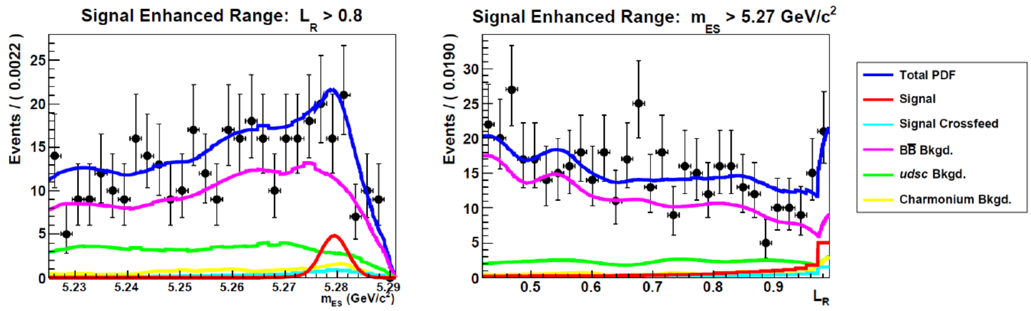

Figure 4: Fits to the distributions of m_{ES} (left) and L_R (right) for $B \to X_s e^+e^-$ events in the range $2.0 < q^2 < 4.3\ \mathrm{GeV}^2/c^4$.

charged mode, we find for the $B^0 \to K^0_S \rho^0 \gamma$ decay $\mathcal{S}_{K^0_S\rho^0\gamma} = \frac{\mathcal{S}_{K^0_S\pi^+\pi^-\gamma}}{\mathcal{D}_{K^0_S\rho^0\gamma}} = 0.249 \pm 0.455[\mathrm{stat.}]^{+0.076}_{-0.060}[\mathrm{syst.}]$, which is compatible with the SM expectation of $\sim$0.03[5].

4. Branching fractions and direct *CP* asymmetry in $B \to X_s \ell^+\ell^-$ using a sum of exclusive final states

In this analysis[6], the inclusive decay $B \to X_s \ell^+\ell^-$ is studied in 20 exclusive final states each comprises one kaon and at most two pions, $\ell^+\ell^-$ is either e^+e^- or $\mu^+\mu^-$, as listed in Ref. [6]. We reject events with dilepton mass squared $q^2 \equiv m^2_{\ell\ell}$ within a range of $6.8 < q^2 < 10.1\,\mathrm{GeV}^2/c^4$ ($12.9 < q^2 < 14.2\,\mathrm{GeV}^2/c^4$) to suppress signal-like charmonium backgrounds with J/ψ ($\psi(2S)$) from B decays. The entire event selection criteria represent $\sim$70% of the inclusive $B \to X_s \ell^+\ell^-$ rate with the invariant mass of the hadronic system $m_{X_s} < 1.8\ \mathrm{GeV}/c^2$, accounting for K^0_L modes, $K^0_S \to \pi^0\pi^0$, and π^0 Dalitz decays in our signal reconstruction efficiencies. We also extrapolate for the missing final states, and those with $m_{X_s} > 1.8\ \mathrm{GeV}/c^2$, using JETSET fragmentation [7] and theory predictions.

We measure the total BF and partial BFs in different ranges of q^2 or $m_{X_s}$by performing a two-dimensional fit to the distributions of m_{ES} and likelihood ratio L_R, which is defined as $L_R \equiv \mathcal{P}_S/(\mathcal{P}_S + P_B)$ with $\mathcal{P}_S$ ($\mathcal{P}_B$) as the probability for a correctly-reconstructed signal ($B\bar{B}$ background) event calculated based on the response of $B\bar{B}$ BDT. The L_R distributions for signal and $B\bar{B}$ background events peak around one and zero, respectively. A fit example is shown in Fig. 4 for $B \to X_s e^+e^-$ events with $2.0 < q^2 < 4.3\ \mathrm{GeV}^2/c^4$.

Our measured partial BF results are shown in Fig. 5. We find the total BF for $q^2 > 0.1\ \mathrm{GeV}^2/c^4$ to be $\mathcal{B}(B \to X_s \ell^+\ell^-) = (6.73^{+0.70+0.34}_{-0.63-0.25} \pm 0.50) \times 10^{-6}$, which is less than 2σ above the SM prediction of $\mathcal{B}_{\mathrm{SM}}(B \to X_s \ell^+\ell^-) = (4.6 \pm 0.8) \times 10^{-6}$ [8]. In the low mass range with $1 < q^2 < 6\ \mathrm{GeV}^2/c^4$, we have $\mathcal{B}^{\mathrm{low}}(B \to X_s \ell^+\ell^-) = (1.60^{+0.41+0.17}_{-0.39-0.13} \pm 0.18) \times 10^{-6}$, which is in good agreement with the SM predictions of $\mathcal{B}^{\mathrm{low}}_{\mathrm{SM}}(B \to X_s e^+e^-) = (1.64 \pm 0.11) \times 10^{-6}$ and $\mathcal{B}^{\mathrm{low}}_{\mathrm{SM}}(B \to X_s \mu^+\mu^-) = (1.59 \pm 0.11) \times 10^{-6}$ [9]. And in the high mass range with $q^2 > 14.2\ \mathrm{GeV}^2/c^4$, our result of $\mathcal{B}^{\mathrm{high}}(B \to X_s \ell^+\ell^-) = (0.57^{+0.16+0.03}_{-0.15-0.02} \pm 0.00) \times 10^{-6}$ is about 2σ higher than the SM predictions of $\mathcal{B}^{\mathrm{high}}_{\mathrm{SM}}(B \to X_s e^+e^-) = (0.21 \pm 0.07) \times 10^{-6}$ and $\mathcal{B}^{\mathrm{high}}_{\mathrm{SM}}(B \to X_s \mu^+\mu^-) = (0.24 \pm 0.07) \times 10^{-6}$ [9]. In all the three results listed above, the first uncertainties are statistical, the second experimental systematics and the third model-dependent systematics.

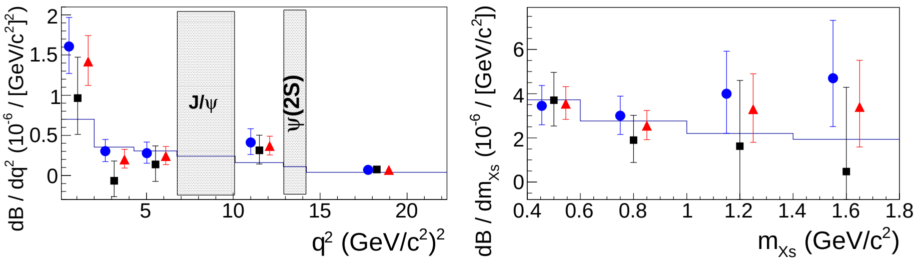

Figure 5: Differential BF as a function of q^2 (left) or m_{X_s} (right) for $X_s e^+e^-$ (●), $X_s\mu^+\mu^-$ (■), and lepton-flavor-averaged final states (▲). The errors correspond to the total uncertainties. The histogram shows the SM expectation, which has uncertainties of approximately 10-30% in different q^2 or m_{X_s} regions. The shaded boxes in the left plot denote the vetoed charmonium regions.

In 14 self-tagging final states as listed in Ref. [6], we search for the direct *CP* asymmetry in $B \to X_s\ell^+\ell^-$ which is defined in the same manner as $A_{CP}(B \to X_s\gamma)$ in Eq. 2.1. $A_{CP}(B \to X_s\ell^+\ell^-)$ is expected to be well below 1% in the SM [10]. We find the total A_{CP} for $q^2 > 0.1$ GeV$^2/c^4$ to be $A_{CP}(B \to X_s\ell^+\ell^-) = 0.04 \pm 0.11[\text{stat.}] \pm 0.01[\text{syst.}]$. We also measure A_{CP} in different q^2 regions, and find all the results to be consistent with zero as expected in the SM.

5. Summary

With the full *BABAR* dataset of 471 million $B\bar{B}$ pairs, we perform a series of interesting measurements in radiative B decays recently. Our direct $A_{CP}(B \to X_s\gamma)$ result is the most precise result to date and agree with the SM. The measured mixing-induced *CP* parameter for $B^0 \to K_S^0\rho^0\gamma$ is found to be compatible with the SM expectation. Our $\mathcal{B}(B \to X_s\ell^+\ell^-)$ and direct $A_{CP}(B \to X_s\ell^+\ell^-)$ results are generally consistent with the SM predictions, however some tensions exist for the total BF and partial BF in the region of $q^2 > 14.2$ GeV$^2/c^4$.

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