

Study of $B \rightarrow K\pi\pi\gamma$ decays

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Abstract. In $b \rightarrow s\gamma$ transitions, the Standard Model predicts that B^0 (\bar{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 $B \rightarrow f_{CP}\gamma$ decays is expected to be small, thus being any sizeable observed asymmetries due to New Physics. In this analysis, we extract information about the $K\pi\pi$ resonant structures by means of an amplitude analysis of the $m_{K\pi\pi}$ and $m_{K\pi}$ spectra in $B^+ \rightarrow K^+\pi^-\pi^+\gamma$. The results are used, assuming isospin symmetry, to extract the mixing-induced CP parameters of the process $B^0 \rightarrow K_s^0\rho^0\gamma$ from the time-dependent analysis of $B^0 \rightarrow K_s^0\pi^+\pi^-\gamma$ decays without an explicit amplitude analysis of this mode.

1. Introduction

In $b \rightarrow s\gamma$ transitions, the Standard Model predicts that B^0 (\bar{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 $B \rightarrow f_{CP}\gamma$ decays, where f_{CP} is a CP eigenstate, is expected to be small (~ 0.03 [1]). This prediction may be altered by New Physics processes, which might emit a photon with both helicity states. Moreover, decays to $K\pi\pi\gamma$ can display an interesting hadronic structure: they have contributions from several kaon resonances decaying to $K\pi\pi$. In this analysis, we extract information about the $K\pi\pi$ resonant structures by means of an amplitude analysis of the $m_{K\pi\pi}$ and $m_{K\pi}$ spectra in the charged decay channel¹ $B^+ \rightarrow K^+\pi^-\pi^+\gamma$. The results are used, assuming isospin symmetry, to extract the mixing-induced CP parameters of the process $B^0 \rightarrow K_s^0\rho^0\gamma$ from the time-dependent analysis of $B^0 \rightarrow K_s^0\pi^+\pi^-\gamma$ decays without an explicit amplitude analysis of this mode.

Belle has previously reported a time-dependent CP asymmetry measurement of decays [2]. Similar measurements with $B^0 \rightarrow K_s^0\pi^0\gamma$ decays have been reported by BABAR [3] and Belle [4]. At this time the CP asymmetry parameters are compatible with SM predictions, and no evidence of NP has been observed. LHCb has recently observed the photon polarization in $B^+ \rightarrow K^+\pi^-\pi^-\gamma$ decay via the distribution of the angle of the photon with respect to plane defined by the final state hadrons [5]. Studies of the processes $B^+ \rightarrow K^+\pi^+\pi^-\gamma$ and $B^0 \rightarrow K_s^0\pi^-\pi^+\gamma$ including measurements of the branching fractions have been performed by both BABAR [6] and Belle [7]. The latter also finds the branching fraction of the resonant decay $B^+ \rightarrow K_1(1270)^+$.

2. Analysis strategy

The present study aims to perform a time-dependent analysis of $B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma$ decays to extract the direct and mixing-induced CP asymmetry parameters, $\mathcal{C}_{K_S^0 \rho \gamma}$ and $\mathcal{S}_{K_S^0 \rho \gamma}$, in the $B^0 \rightarrow K_S^0 \rho^0 \gamma$ mode. However, due to the large natural width of the $\rho^0(770)$, a non negligible amount of $B^0 \rightarrow K^{*\pm}(K_S^0 \pi^\pm) \pi^\mp \gamma$ events, which are not CP eigenstates and do not contribute to $\mathcal{S}_{K_S^0 \rho \gamma}$, are expected to lie under the $\rho^0(770)$ resonance and dilute $\mathcal{S}_{K_S^0 \rho \gamma}$. We can define a dilution factor $\mathcal{D}_{K_S^0 \rho \gamma}$ such as

$$\mathcal{D}_{K_S^0 \rho \gamma} = \frac{\mathcal{S}_{K_S^0 \pi^+ \pi^- \gamma}}{\mathcal{S}_{K_S^0 \rho \gamma}}, \quad (1)$$

where $\mathcal{S}_{K_S^0 \pi^+ \pi^- \gamma}$ is the effective value of the mixing-induced CP asymmetry measured for the whole $B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma$. This sample is expected to produce a small number of signal events, so that a proper amplitude analysis to discriminate $B^0 \rightarrow K^{*\pm}(K_S^0 \pi^\pm) \pi^\mp \gamma$ from $B^0 \rightarrow K_S^0 \rho^0(\pi^\mp \pi^\pm) \gamma$ is not feasible. Hence the dilution factor needs to be obtained in some other way. We decided to perform the amplitude analysis in the charged decay channel $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$, which has a richer statistics, and is related to $B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma$ by isospin symmetry. Assuming that the resonant amplitudes are the same in both modes, the dilution factor is calculated from those of $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$. Moreover, the amplitude analysis of

¹ Charge conjugation is implicit throughout the document.

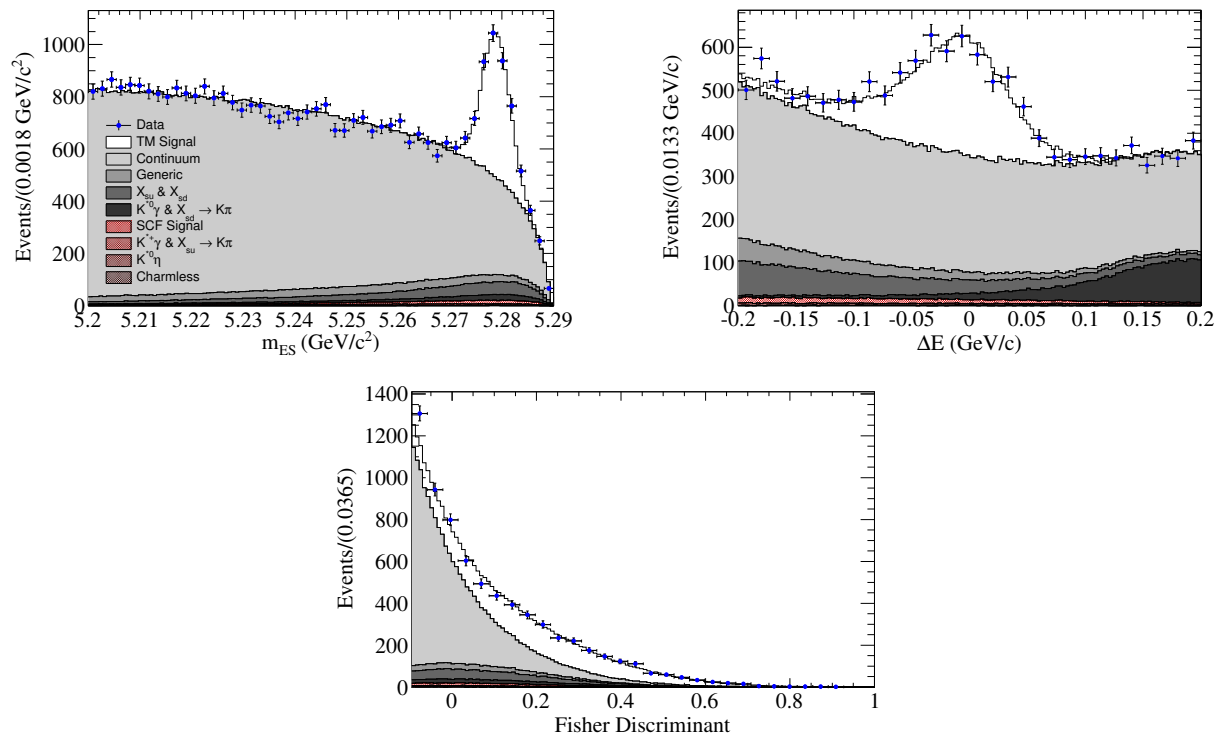


Figure 1. Distributions of m_{ES} (top left), ΔE (top right) and the Fisher-discriminant output (bottom) showing the fit results on the $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$ data sample. The distributions have their signal/background ratio enhanced by means of the following requirements: $-0.100 < \Delta E < 0.075$ GeV (m_{ES}), $m_{ES} > 5.27$ GeV/ c^2 (ΔE) and $m_{ES} > 5.27$ GeV/ c^2 ; $-0.100 < \Delta E < 0.075$ GeV (Fisher). Points with error bars give the data. The solid histogram shows the projection of the fit result, and the shaded areas represent the contributions from different backgrounds, as described in the legend. Some of the contributions are hardly visible due to their small fractions.

$B^+ \rightarrow K^+\pi^-\pi^+\gamma$ provides also the branching fractions of $B \rightarrow K_{\text{res}}\gamma$ (where K_{res} designates a kaonic resonance decaying to $K\pi\pi$), which are in general not well known.

We use the full dataset collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector [8] at the PEP-II asymmetric-energy e^+e^- collider at the SLAC National Accelerator Laboratory. This corresponds to a total integrated luminosity of 429 fb^{-1} , and to $471 \times 10^6 B\bar{B}$ pairs produced.

3. The charged channel $B^+ \rightarrow K^+\pi^-\pi^+\gamma$

To select the charged mode candidates, we require the center-of-mass energy of the photon to be between 1.5 and 3.5 GeV. We also require $5.200 < m_{\text{ES}} < 5.292\text{ GeV}/c^2$ and $|\Delta E| < 200\text{ MeV}$. 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, while $m_{\text{ES}} = \sqrt{(s/2 - \mathbf{p}_B\mathbf{p}_0)^2/E_0^2 - \mathbf{p}_B^2}$, where (E_B, \mathbf{p}_B) and (E_0, \mathbf{p}_0) are the four-vectors of the B -candidate and of the CM frame, respectively. Charged particle identification is performed to assign the pion and kaon hypotheses. We also reject events where the γ comes from a π^0 or a η .

We first perform an unbinned extended maximum-likelihood fit to data to extract the yield of $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ signal events. The fit uses the variables ΔE , m_{ES} , and the Fisher-discriminant output to discriminate signal events from background. The Fisher-discriminant combine six discriminating variables related to the shape of the event. Using information from the maximum likelihood fit, the $m_{K\pi\pi}$, $m_{K\pi}$ and $m_{\pi\pi}$ spectra in signal events (where m_X is the invariant mass of the X particle system) are extracted using the *sPlot* technique [9]. The results are shown in Figure 1. A signal yield of $2441 \pm 91_{-57}^{+34}$ is observed.

We perform a fit to the signal *sPlot* of $m_{K\pi\pi}$ in order to extract from data the branching fractions of kaonic resonances decaying to $K^+\pi^-\pi^+$. We model the $m_{K\pi\pi}$ distribution as a coherent sum of five Relativistic Breit-Wigner (RBW) line shapes, with constant widths. Since helicity angles are not explicitly taken into account, the interference occurs between resonances with same J^P only. The result of the fit is shown in Figure 2, and the branching fractions obtained are given in Table 1.

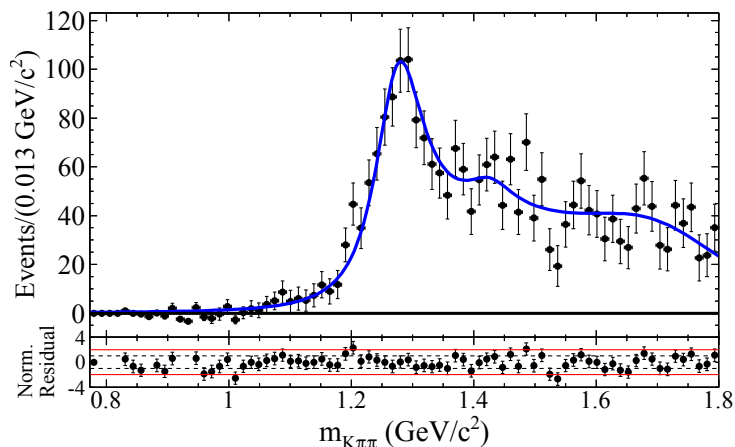


Figure 2. Distribution of $m_{K\pi\pi}$ for $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ signal events (*sPlot*), extracted from the maximum likelihood fit to m_{ES} , ΔE and the Fisher discriminant. Points with error bars give the sum of *sWeights*. The blue solid curve is the result of the fit performed directly to this $m_{K\pi\pi}$ distribution to extract the different contributions from kaonic resonances decaying to $K^+\pi^-\pi^+$. Below each bin are shown the residuals, normalized in error units. The parallel dotted and full lines mark the 1σ and 2σ levels, respectively.

Mode	$\mathcal{B}(B^+ \rightarrow \text{Mode}) \times \mathcal{B}(K_{\text{res}} \rightarrow K^+ \pi^- \pi^+) \times 10^6$	$\mathcal{B}(B^+ \rightarrow \text{Mode}) \times 10^6$	PDG values ($\times 10^6$)
Inclusive $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$...	$27.2 \pm 1.0^{+1.1}_{-1.3}$	27.6 ± 2.2
$K_1(1270)^+ \gamma$	$14.5^{+2.0+1.1}_{-1.3-1.2}$	$44.0^{+6.0+3.5}_{-4.0-3.7} \pm 4.6$	43 ± 13
$K_1(1400)^+ \gamma$	$4.1^{+1.9+1.3}_{-1.2-0.8}$	$9.7^{+4.6+3.1}_{-2.9-1.8} \pm 0.6$	< 15
$K^*(1410)^+ \gamma$	$9.7^{+2.1+2.4}_{-1.9-0.7}$	$23.8^{+5.2+5.9}_{-4.6-1.4} \pm 2.4$	\emptyset
$K_2^*(1430)^+ \gamma$	$1.5^{+1.2+0.9}_{-1.0-1.4}$	$10.4^{+8.7+6.3}_{-7.0-9.9} \pm 0.5$	$< 14 \pm 4$
$K^*(1680)^+ \gamma$	$17.0^{+1.7+3.5}_{-1.4-3.0}$	$71.7^{+7.2+15}_{-5.7-13} \pm 5.8$	< 1900

Table 1. Branching fractions of the different K_{res} decaying into $K^+ \pi^- \pi^+$, extracted from the fit to the $m_{K\pi\pi}$ spectrum. The quoted numbers are obtained using the fit fraction of each component and the corresponding efficiency. To correct for the secondary branching fractions we use the values from PDG [10]. The upper limit reported are at 90% C.L.. The first uncertainty is statistical, the second is systematic, and the third, when present, is due to the uncertainties on the secondary branching fractions.

We then extract the intermediate resonances decaying into $K^+ \pi^-$ and $\pi^+ \pi^-$. The limited statistics does not allow to perform a full two-dimensional amplitude analysis, so we perform a binned maximum-likelihood project to the signal $sPlot$ of the projected $m_{K\pi}$ variable. The spectrum is modeled as the projection of two 1^- and one 0^+ components. The vector components are the $\rho^0(770)$ (described with a Gounaris-Sakurai lineshape), and the $K^{*0}(892)$ (described with a Relativistic Breit-Wigner). The scalar component is modeled by the LASS parametrization [11], which consists of the $K_0(1430)^0$ resonance together with an effective range non-resonant component. Both in the fit to the $m_{K\pi\pi}$ and the $m_{K\pi}$ spectra, we measure directly the magnitudes and phases of the different components of the corresponding signal model. The amplitudes of the different kaonic resonances extracted from the fit to $m_{K\pi\pi}$ are used to compute their fit fractions. These, in turn, are used to extract branching fractions of the different K_{res} contributions, that are used as inputs to the $m_{K\pi}$ fit model. The result of the fit is given in Figure 3, and gives the amplitudes of the three $K^+ \pi^-$ and $\pi^+ \pi^-$ intermediate states. In order to optimize the sensitivity on $\mathcal{S}_{K_s^0 \rho \gamma}$, to calculate the dilution factor, we apply the additional cuts $600 < m_{\pi\pi} < 900 \text{ MeV}/c^2$, in order to enhance the proportion of the $\rho^0(770)$, and we apply a veto on the $K^{*0}(892)$ requiring $m_{K\pi} < 845 \wedge m_{K\pi} > 945 \text{ MeV}/c^2$. We obtain the dilution factor:

$$\mathcal{D}_{K_s^0 \rho \gamma} = 0.549^{+0.096}_{-0.094}, \quad (2)$$

where the quoted uncertainties are sums in quadrature of statistical and systematic uncertainties. The branching fractions obtained are reported in Table 2.

4. The neutral channel $B^0 \rightarrow K_s^0 \pi^+ \pi^- \gamma$

In the neutral decay mode, the event are selected with the same criteria as the charged mode. The K^+ is replaced with a $K_s^0 \rightarrow \pi^+ \pi^-$ candidate, which is required to have a mass within $11 \text{ MeV}/c^2$ from the nominal value, and a lifetime significance $> 5\sigma$, to ensure the decay vertices of the B^0 and K_s^0 to be well separated. In addition, we require the cosine of the angle between the K_s^0 flight direction and the vector connecting the B -daughter pions and the K_s^0 vertex to be > 0.995 , to suppress combinatorial background. The time difference Δt is obtained from the measured distance between the decay vertices positions of the fully reconstructed B^0 candidate (B_{rec}^0) and of the other one (B_{tag}^0). The distance is transformed to Δt using the known boost

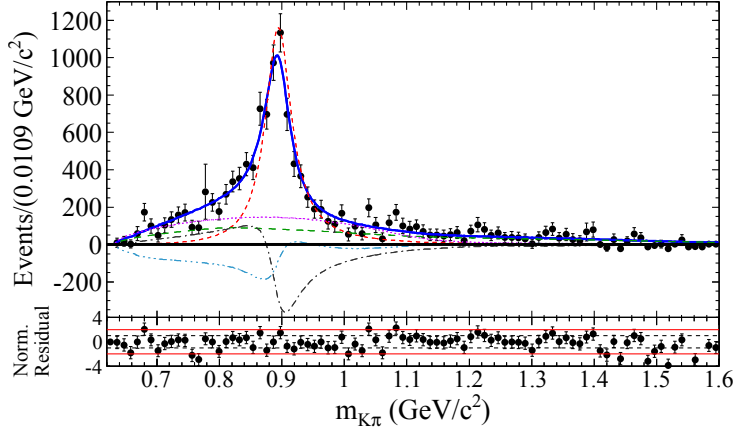


Figure 3. Distribution of $m_{K\pi}$ for $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ signal events ($sPlot$), extracted from the maximum likelihood fit to m_{ES} , ΔE , and the Fisher discriminant. Points with error bars give the sum of $sWeights$. The blue solid curve is the result of the fit performed directly to this $m_{K\pi}$ distribution to extract the different contributions from $K\pi$ and $\pi\pi$ intermediate states. The small-dashed red, medium-dashed green and dotted magenta curves correspond to the $K^{*0}(892)$, $\rho^0(770)$ and $(K\pi)$ S -wave contributions, respectively. The dashed-dotted gray curve corresponds to the interferences between the two P -wave components, *i.e.* the $K^{*0}(892)$ and the $\rho^0(770)$, while the dashed-triple-dotted light blue curve corresponds to the interferences between the $(K\pi)$ S -wave and the $\rho^0(770)$.

Mode	$\mathcal{B}(B^+ \rightarrow \text{Mode}) \times \mathcal{B}(R \rightarrow hh) \times 10^6$	$\mathcal{B}(B^+ \rightarrow \text{Mode}) \times 10^6$	PDG values ($\times 10^6$)
Inclusive $B^+ \rightarrow K^+\pi^-\pi^+\gamma$...	$27.2 \pm 1.0^{+1.1}_{-1.3}$	27.6 ± 2.2
$K^{*0}(892)\pi^+\gamma$	$17.3 \pm 0.9^{+1.2}_{-1.1}$	$26.0^{+1.4}_{-1.3} \pm 1.8$	20^{+7}_{-6}
$K^+\rho^0(770)\gamma$	$9.1^{+0.8}_{-0.7} \pm 1.3$	$9.2^{+0.8}_{-0.7} \pm 1.3 \pm 0.02$	< 20
$(K\pi)_0^{*0}\pi^+\gamma$	$11.3 \pm 1.5^{+2.0}_{-2.6}$...	\emptyset
$(K\pi)_0^0\pi^+\gamma$ (NR)	...	$10.8^{+1.4+1.9}_{-1.5-2.5}$	< 9.2
$K_0^*(1430)^0\pi^+\gamma$	$0.51 \pm 0.07^{+0.09}_{-0.12}$	$0.82 \pm 0.11^{+0.15}_{-0.19} \pm 0.08$	\emptyset

Table 2. Branching fractions of the different resonances decaying to $K\pi$ and $\pi\pi$, extracted from the fit to the $K^+\pi^-$ spectrum. The quoted numbers are obtained using the fit fraction of each component and the corresponding efficiency. R denotes an intermediate resonant state and h stands for the final state K, π . To correct for the secondary branching fractions we used the values from PDG [10] and $\mathcal{B}(K^{*0}(892) \rightarrow K^+\pi^-) = \frac{2}{3}$. The first uncertainty is statistical, the second is systematic, and the third, when applicable, is due to the uncertainties on the secondary branching fractions. The last two rows of the table are obtained by separating the contributions from the resonant and the non-resonant part of the LASS parametrization.

$\beta\gamma = 0.56$ of the e^+e^- system. The candidates are rejected when $|\Delta t| > 20$ ps, or if the error on Δt is higher than 2.5 ps. To determine the flavor of B_{tag}^0 , we use the B flavor-tagging algorithm described in Ref. [12].

We perform an unbinned extended maximum-likelihood fit to data to extract the yield of $B^0 \rightarrow K_S^0\pi^+\pi^-\gamma$ signal events. We consider also the additional selection cuts on $m_{\pi\pi}$ and $m_{K\pi}$ considered when computed $\mathcal{D}_{K_S^0\rho\gamma}$. The fit uses the variables ΔE , m_{ES} , and the Fisher-discriminant. The including of time-dependence in the fit allows the determination of mixing-

induced CP violation and provides additional continuum background rejection. The signal time-dependent decay rate is given by

$$\mathcal{P}(\Delta t, \sigma_{\Delta t}) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times \left[1 + q_{\text{tag}} \frac{\Delta D^c}{2} - q_{\text{tag}} \langle D \rangle^c \mathcal{C} \cos(\Delta m_d \Delta t) + q_{\text{tag}} \langle D \rangle^c \mathcal{S} \sin(\Delta m_d \Delta t) \right] \otimes \mathcal{R}^c(\Delta t, \sigma_{\Delta t}), \quad (3)$$

where q_{tag} is the flavor-tag of the event: $q_{\text{tag}} = -1$ for $B_{\text{rec}} = B^0$, and $+1$ for $B_{\text{rec}} = \bar{B}^0$, τ_{B^0} is the B^0 lifetime and Δm_d is the $B^0 \bar{B}^0$ oscillation frequency, fixed to the measurement from Ref. [12]. The parameters $\langle D \rangle^c$ and ΔD^c are related to the mistag probability, and to the performance difference for the two tags, respectively. The resolution function \mathcal{R} , takes into account the imperfect measurement of Δt . The coefficients \mathcal{S} and \mathcal{C} are the parameters associated with mixing-induced CP violation and direct CP violation, respectively.

The maximum-likelihood fit to data yields $245 \pm 24_{-16}^{+13}$ signal events, which results in an inclusive branching fraction of

$$\mathcal{B}(B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma) = (23.9 \pm 2.4_{-1.9}^{+1.6}) \times 10^{-6}. \quad (4)$$

In both cases, the first quoted uncertainty is statistical and the second is systematic. Figure 4 shows signal-enhanced distributions of the four discriminating variables in the fit. The result of the fit to data for the time-dependent CP violation parameters in signal events is

$$\mathcal{S}_{K_S^0 \pi^+ \pi^- \gamma} = +0.14 \pm 0.25_{-0.03}^{+0.04}, \quad (5)$$

$$\mathcal{C}_{K_S^0 \pi^+ \pi^- \gamma} = -0.39 \pm 0.20 \pm 0.05. \quad (6)$$

We finally obtain $\mathcal{S}_{K_S^0 \rho \gamma}$ dividing $\mathcal{S}_{K_S^0 \pi^+ \pi^- \gamma}$ by the $\mathcal{D}_{K_S^0 \rho \gamma}$ given in Eq. (2):

$$\mathcal{S}_{K_S^0 \rho \gamma} = 0.249 \pm 0.455_{-0.060}^{+0.076}, \quad (7)$$

which is compatible with the SM expectation of ~ 0.03 [1].

5. Systematic uncertainties

In the analysis of $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$ decays, we considered different sources of systematic uncertainties affecting the amplitudes in the $m_{K\pi\pi}$ and $m_{K\pi}$ spectra. These have been propagated to the dilution factor $\mathcal{D}_{K_S^0 \rho \gamma}$ and to the branching fractions calculated from the amplitudes. As for the K_{res} amplitudes, we account for effects from the fixed parameters in the maximum-likelihood fit, the fixed line-shape parameters of the kaonic resonances in the fit model, the effects of adding other resonances at high masses to the fit model, the procedure of the $m_{K\pi\pi}$ *sPlot* extraction, as well as the binning in the fitted distribution. The dominant systematic uncertainty originates from the fixed line-shape parameters of the resonances. The amplitudes extracted from the $m_{K\pi}$ spectrum are affected mostly by the weights of the kaonic resonances obtained in the $m_{K\pi\pi}$ fit. Specific sources of systematic uncertainties are also taken into account for the extraction of branching fractions, like the uncertainties on the number of $B\bar{B}$ pairs recorded in the full *BABAR* dataset, the input branching fractions, and other detector-related systematics. Similarly, for the neutral $B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma$ channel, systematics due to the fixed parameters in the maximum likelihood fit have been considered.

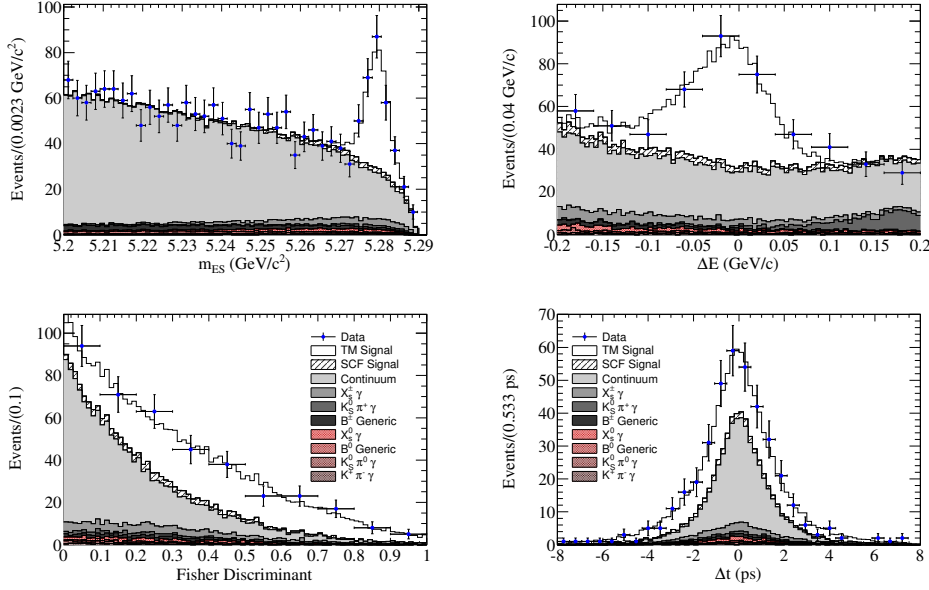


Figure 4. Distributions of m_{ES} (top left), ΔE (top right), the Fisher-discriminant output (bottom left), and Δt (bottom right), showing the fit results on the $B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma$ data sample. The distributions have their signal/background ratio enhanced by means of the following requirements: $-0.15 \leq \Delta E \leq 0.10$ GeV (m_{ES}), $m_{ES} > 5.27$ GeV/ c^2 (ΔE) and $m_{ES} > 5.27$ GeV/ c^2 ; $-0.15 \leq \Delta E \leq 0.10$ GeV (Fisher and Δt).

6. Conclusions

The *BABAR* Collaboration, seven years after the shutdown of the experiment, is still producing competitive results. We have presented a measurement of the time-dependent CP asymmetry in the radiative-penguin decay $B^0 \rightarrow K_S^0 \rho^0 \gamma$, using the full *BABAR* dataset recorded at the $\Upsilon(4S)$ peak. We obtain the CP -violating parameters $\mathcal{S}_{K_S^0 \pi^+ \pi^- \gamma} = +0.14 \pm 0.25^{+0.04}_{-0.03}$, and $\mathcal{C}_{K_S^0 \pi^+ \pi^- \gamma} = -0.39 \pm 0.20 \pm 0.05$, where the first quoted errors are statistical and the second are systematic. We extract from this measurement the time-dependent CP asymmetry related to the hadronic CP eigenstate $\rho^0 K_S^0$ and obtain $\mathcal{S}_{K_S^0 \rho^0 \gamma} = 0.25 \pm 0.46^{+0.08}_{-0.06}$. This observable is related to the photon polarization of the underlying $b \rightarrow s \gamma$ transition. The dilution factor has been extracted from the higher statistics charged mode $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$, assuming isospin symmetry, via the study of the resonant structures. Moreover, the branching fractions of the different $K_{res} \rightarrow K \pi \pi$ states and the overall branching fractions of the $\rho^0 K^+$, $K^{*0} \pi^+$, and $(K\pi)_{S\text{-wave}} \pi^+$ are also measured.

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