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Time-dependent CP Violation in $B^0 \to \eta' K_S^0$ decays at Belle - a sensitivity study

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We present a sensitivity study for a measurement of CP asymmetry parameters in $B^0 \to \eta' K_S^0$ decays, based on the final Belle data sample. The Belle detector, operating at the KEKB asymmetric-energy e^+e^- collider, has during its operation collected ~ 772 M $B\bar{B}$ pairs, making it the world largest sample. We give a motivation for studying CP asymmetry in $B^0 \to \eta' K_S^0$ decays and present the principle of the measurement, along with results from simulated events. Finally, we estimate the measurement sensitivity by studying simulated events, and compare it with Belle's previous measurement from 2006.

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1. Introduction

Measuring CP asymmetry in the decays of neutral B mesons provides a variety of methods to measure the angles of the CKM unitary triangle and gave strong motivation for the construction of the two so-called B factories (KEKB and PEP-II). Measurements of $\sin 2\phi_1$ (ϕ_1 being one of the unitary triangle angles) from CP asymmetry in $B^0 \to c\bar{c}K^0$ decays by Belle[1] and BaBar[2] collaborations have established CP violation (CPV) in the B^0 system that is consistent with the Standard Model expectations, confirming the Kobayashi-Maskawa mechanism as the dominant source of CPV. However, decays of this type ($b \to c\bar{c}s$) are dominated by a tree level diagram and as such not very sensitive to possible contributions of new CPV phases arising from physics beyond Standard Model (SM). From this point of view, decays that proceed primarily via $b \to s\bar{q}q$ penguin diagrams are much more interesting. For these decays the SM prediction of CP asymmetry is to a good approximation the same as for $b \to c\bar{c}s$ decays [1] (i.e. $\sin 2\phi_1$), but the presence of new heavy particles in penguin loops can change this value [2, 3]. Thus, any significant difference between these two values would be a clear sign of a new CP-violating phase and new physics. To date none of the measurements of CPV in $b \to s\bar{q}q$ modes shows a significant disagreement with the SM predictions, but the relatively large measurements errors still allow for new physics contributions.

Among several B^0 decay modes that are dominated by the $b \to s\bar{q}q$ penguin process, the decay $B^0 \to \eta' K_S^0$ is the best from an experimental point of view, allowing the most precise measurement because of the relatively large branching fraction and low background level.

1.1 What to measure ?

The Standard Model predicts CP asymmetry in time dependent rates of $B^0(t)$ and $\bar{B}^0(t)$ decays to a common CP eigenstate ($\eta' K_S^0$ in our case). By $B^0(t)$ and $\bar{B}^0(t)$ we denote the states that were pure $B^0(d\bar{b})$ and $\bar{B}^0(\bar{d}b)$ states at time $t = 0$. While propagating in time these states mix, due to $B^0 - \bar{B}^0$ mixing. The decay rate time dependence is given by[3]

$$P_{\eta' K_S}(t,q) = \frac{e^{-t/\tau_{B^0}}}{4\tau_{B^0}} \left[1 + q \cdot A_{CP}(t)\right], \tag{1.1}$$

where τ_{B^0} is the B^0 lifetime, A_{CP} is the time-dependent CP asymmetry and $q = +1(-1)$ for $\bar{B}^0$ (B^0). The time-dependent CP asymmetry can be expressed as

$$A_{CP}(t) \equiv \frac{\Gamma(B^0(t) \to \eta' K_S) - \Gamma(\bar{B}^0(t) \to \eta' K_S)}{\Gamma(B^0(t) \to \eta' K_S) + \Gamma(\bar{B}(t)^0 \to \eta' K_S)} = S_{\eta' K_S} \sin(\Delta m t) + A_{\eta' K_S} \cos(\Delta m t), \tag{1.2}$$

where Γ's are the decay rates. The second equality in (1.2) follows from the $B^0 - \bar{B}^0$ mixing time dependencies, Δm is the mass difference between the two B^0 mass eigenstates, and we introduced CP-violating parameters $S_{\eta' K_S}$ and $A_{\eta' K_S}$. The SM predicts the value of $A_{\eta' K_S}$ to be zero, and the value of $S_{\eta' K_S}$ to be very close to $\sin 2\phi_1$. Measuring a significant deviation from this values would be a clear signal of new physics.

[1] Collaboration and detector working on the KEKB accelerator in KEK, Japan.

[2] Collaboration and detector working on the PEPII accelerator in SLAC, USA.

[3] See for example [4].

2. Principle of measurement

The Belle detector operated at the KEKB energy-asymmetric e^+e^- (with 3.5 and 8.0 GeV, respectively) collider. During its operation (from 1999 to 2010) it collected about 772 millions of $B\bar{B}$ pairs, which is the world's largest sample.

At the KEKB collider B mesons are produced in the process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$. A B meson pair from $\Upsilon(4S)$ decay is produced in a C-odd state and this coherence between B^0 and $\bar{B}^0$ is preserved until one of them decays. By demanding one of them, which we call B_{tag}, to decay into a flavor specific final state[4], we can determine its flavor at its decay time, t_{tag}. Due to a quantum coherence the other B meson, which we call B_{sig}, has flavor opposite to that of B_{tag} at time t_{tag}. The probability for B_{sig} to decay into $\eta' K_S$ at time t_{sig} is then given by $P_{\eta' K_S}(\Delta t, q)$ (1.1), with $\Delta t = t_{sig} - t_{tag}$.

Due to the small B^0 meson lifetime, $\tau_{B^0} \sim 1.5$ ps, the time difference Δt is too small for a direct measurement. However, thanks to the energy-asymmetric design of the KEKB collider, we are able to measure it indirectly. The $\Upsilon(4S)$ resonance is produced with a known Lorentz boost and, since its mass is just above the threshold for $B\bar{B}$ production, the produced B mesons are approximately at rest in the $\Upsilon(4S)$ center-of-mass system (CMS). This allows us to obtain Δt by measuring the distance between B meson decay vertices (Δz) and using the relation $\Delta t = \frac{1}{c}\frac{\Delta z}{\beta\gamma}$, with $\beta\gamma = 0.425$ being the $\Upsilon(4S)$ boost.

The principle described above that enables us to extract $A_{CP}(t)$ and therefore the values of $S_{\eta' K_S^0}$ and $A_{\eta' K_S^0}$ is schematically shown in figure 1.

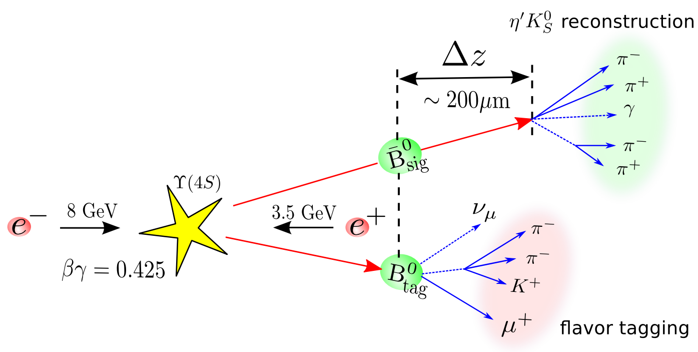

Figure 1: Principle of measurement of time dependent CP-violating parameters in $B^0 \to \eta' K_S$ decays at Belle experiment.

3. Event reconstruction and selection

We reconstruct $B^0 \to \eta' K_S^0$ decays using the following sub-decay modes of η': $\eta' \to \rho^0\gamma$ with $\rho^0 \to \pi^+\pi^-$, and $\eta' \to \eta\pi^+\pi^-$ with $\eta \to \gamma\gamma$ and with $\eta \to \pi^+\pi^-\pi^0$. For K_S^0 we use the $K_S^0 \to \pi^+\pi^-$ decay. The event selection is mainly based on mass windows around $\rho^0, \eta, \eta', \pi^0$ and K_S^0 nominal masses. Some additional cuts used are minimal energy of gammas, cuts on particle identification and the demand for charged tracks to originate from the interaction point.

[4]By flavor specific we mean final state into which only B^0 or $\bar{B}^0$ can decay.

For each event containing a reconstructed B^0 candidate we calculate the probability that it is a signal event. To do this, we study the distribution of candidates in the $M_{bc} - \Delta E - LR$ space. Here ΔE and M_{bc} are given by $\Delta E = E_B^{cms} - E_{beam}^{cms}$ and $M_{bc} \equiv \sqrt{(E_{beam}^{cms})^2 - (p_B^{cms})^2}$, where E_{beam}^{cms} is beam energy in CMS, and E_B^{cms} and p_B^{cms} are candidate's energy and momentum in CMS. LR is the likelihood ratio that we form from event shape variables. We then fit this distribution with the sum of a signal and background shape, obtaining a probability density function (PDF) that is finally used to determine candidate signal probability. According to MC studies, the main source of background comes from continuum $e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$ events. In figure 2 an example of such a fit is shown.

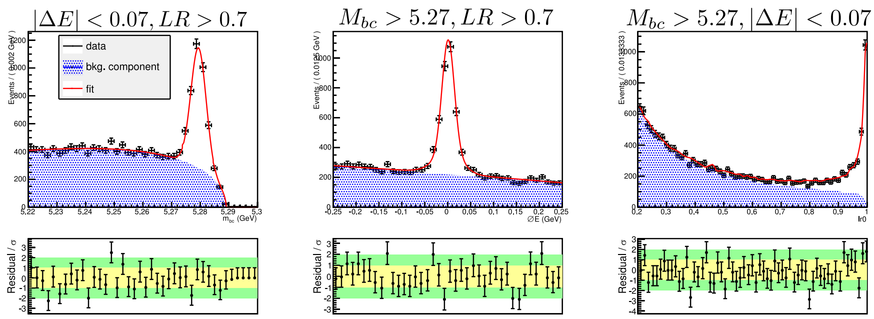

Figure 2: One dimensional projections of fitted PDF on $M_{bc}, \Delta E$ and LR. Red line shows PDF, blue shaded area shows contribution of background events, and data points show the distribution of B^0 candidates reconstructed from the $\eta' \to \rho^0\gamma$ sub-decay mode. The data sample used here (with simulated events) is four times larger than the Belle final data sample.

4. Fitting the time evolution

To be able to perform the fit of the time dependent decay rate we have to reconstruct the vertices of B_{sig} and B_{tag}, and determine the flavor (B^0 or $\bar{B}^0$) of B_{sig}. To reconstruct the decay vertex of B_{sig} we perform the vertex fit of charged tracks in the final state (π^+, π^- from ρ^0 or from η'). The spatial resolution of reconstructed vertex is $\sim 80\mu$m. For the reconstruction of B_{tag} vertex (resolution $\sim 140\mu$m) and determination of its flavor, we use the standard Belle algorithms, the details of which can be found in [5, 6].

Finally we determine the values of $S_{\eta' K_S^0}$ and $A_{\eta' K_S^0}$ by performing a maximum likelihood fit of a sum of the signal (given in eq. 1.2) and background PDFs (obtained from the data in M_{bc} sideband) to the Δt distribution of reconstructed candidates in signal region ($M_{bc} > 5.27, |\Delta E| < 0.08$). To validate the analysis procedure we perform a variety of fits to simulated data. For example, we fit a large sample of simulated signal events to check for possible fit biases. This is shown in figure 3. Values of parameters obtained from the fit were consistent with the simulation input parameters.

4.1 Sensitivity estimation

We estimate the sensitivity of our measurement of $S_{\eta' K_S^0}$ and $A_{\eta' K_S^0}$ on the Belle final data sample by performing a fit to a sample of simulated events containing the expected number of signal and background events. Table 1 shows the number of signal events in the signal region after event reconstruction and selection, and the corresponding numbers from previous analyses by Belle

[7] (in 2006). The expected number of signal events is greater by almost 100%, while the size of the data sample is less than 50% larger than in 2006. This improvement is due to the reprocessing of all Belle data (increased tracking efficiency) and some new reconstruction algorithms.

We fit a few independent samples of simulated data to obtain the expected statistical errors

$$\delta S_{\eta' K^0_S} = 0.080 \quad , \quad \delta A_{\eta' K^0_S} = 0.055$$

We also evaluated various possible sources of systematic error using the simulated data, obtaining $\delta S^{syst}_{\eta' K^0_S} \sim 0.03, \delta A^{syst}_{\eta' K^0_S} \sim 0.04$. These values are to be compared with the 2006 measurement results [7], $S_{\eta' K^0_S} = 0.71 \pm 0.11^{(stat)} \pm 0.04^{(syst)}$, $A_{\eta' K^0_S} = 0.05 \pm 0.07^{(stat)} \pm 0.05^{(syst)}$.

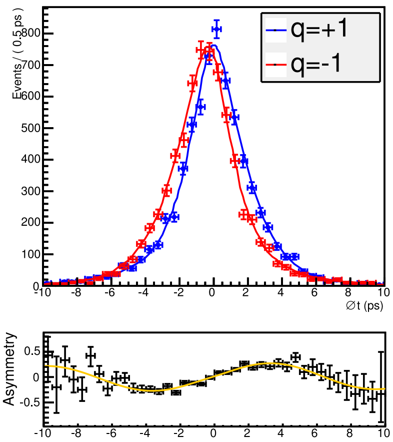

Figure 3: Fit of a large sample of simulated signal events (20 times Belle expected). Blue (red) line and points show fitted PDF and data Δt distribution for B^0s ($\bar{B}^0$s).

mode	This analysis (772 M $B\bar{B}$) N_{sig}	2006 analysis (534 M $B\bar{B}$) N_{sig}
ρ^0	1420.5 ± 48.5	794.3 ± 34.1
$\eta \to \gamma\gamma$	632.3 ± 27.9	362.5 ± 21.0
$\eta \to 3\pi$	171.3 ± 13.5	99.8 ± 10.5
sum	2224.1 ± 89.9	1256.6 ± 42.1

Table 1: Number of $B^0 \to \eta' K^0_S$ signal events in the Belle final data sample as expected from the simulation study. The right column shows the numbers from previous Belle analysis.

5. Conclusions

We have presented the principles of time dependent CPV measurement at the Belle experiment and a MC sensitivity estimation of the measurement of CPV in $B^0 \to \eta' K^0_S$ decays with the Belle full data sample. The results of this analysis will be prepared for the 2013 summer conferences and will represent the most precise measurement of CPV parameters in $b \to s\bar{q}q$ decays to date.

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