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# Study of $B$ and $B_s$ Decays at Belle

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We report results on the search for $B_s \to \eta'\eta$ decay, and the searches for $B^0 \to$ invisible and $B^0 \to$ invisible $+\,\gamma$ decays. The former result is based on a data sample of 121.4 fb$^{-1}$ recorded at the $\Upsilon(5S)$ resonance while the later results are obtained from a 711 fb$^{-1}$ of data sample collected at $\Upsilon(4S)$ resonance with the Belle detector at the KEKB $e^+e^-$ collider. We observe no significant signal for the decays and set upper limit on their branching fractions at 90% confidence level of $\mathcal{B}(B_s \to \eta'\eta) < 7.1 \times 10^{-5}$, $\mathcal{B}(B^0 \to \text{invisible}) < 7.8 \times 10^{-5}$ and $\mathcal{B}(B^0 \to \text{invisible} + \gamma) < 1.6 \times 10^{-5}$.

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## 1. Introduction

In the Standard Model (SM), $B_s^0 \to \eta'\eta$ decay proceeds via tree-level $b \to u$ and penguin $b \to s$ transitions. Penguin transitions are sensitive to Beyond-the-Standard-Model (BSM) physics scenarios and could affect its branching fraction and $CP$ asymmetry [1]. Once the branching fractions for two-body decays $B_{s,d} \to \eta\eta, \eta\eta', \eta'\eta'$ are measured, and the theoretical uncertainties are reduced, it would be possible to extract $CP$ violating parameters from the data using the formalism based on SU(3)/U(3) symmetry [2]. The formalism requires at least four of these six branching fractions and the result on $B_s^0 \to \eta'\eta$ is a potential input. The predicted branching fractions of the decays $B^0 \to$ invisible and $B^0 \to$ invisible + $\gamma$, where "invisible" defined as particles that leave no signal in the Belle detector, could be as high as $10^{-6} - 10^{-7}$ in the New Physics (NP) models [3, 4]. Decays with similar signature such as $B^0 \to (\gamma)\nu\bar{\nu}$ and $B^0 \to \nu\bar{\nu}\nu\bar{\nu}$ are highly suppressed in the SM [5–7]. A very low background from the SM indicates that a signal of $B^0 \to$ invisible+$(\gamma)$ in the current B-factory data would indicate NP.

## 2. Belle detector

The Belle detector [8] was a large-solid-angle magnetic spectrometer that operated at the KEKB asymmetric-energy $e^+e^-$ collider [9]. The detector components include a tracking system comprising a silicon vertex detector (SVD) and a central drift chamber (CDC), a particle identification (PID) system that consists of a barrel-like arrangement of time-of-flight scintillation counters (TOF) and an array of aerogel threshold Cherenkov counters (ACC), and a CsI(Tl) crystal-based electromagnetic calorimeter (ECL). All these components are located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. Outside the coil, the $K_L^0$ and muon detector (KLM) is instrumented to detect $K_L^0$ mesons and to identify muons.

## 3. Search for the Decay $B_s^0 \to \eta'\eta$

In this paper we report the preliminary result of the first search for the decay $B_s^0 \to \eta'\eta$ using the full Belle data sample of 121.4 fb$^{-1}$ collected at the $\Upsilon(5S)$ resonance. The $\Upsilon(5S)$ decays into $B_s^{*0}\bar{B}_s^{*0}$, $B_s^{*0}\bar{B}_s^0$ or $B_s^0\bar{B}_s^{*0}$, and $B_s^0\bar{B}_s^0$ pairs followed by the decays of the excited vector states to $B_s^0$, by emitting a photon. Our data sample contains $(6.53 \pm 0.66) \times 10^6$ $B_s^{(*)0}\bar{B}_s^{(*)0}$ pairs [10]. A set of Monte Carlo (MC) simulated events are used for the selection optimization and estimation of reconstruction efficiency.

We reconstruct $\eta$ candidates using pairs of photons of energy that exceeds 50 (100) MeV in the barrel (end-cap) region of the ECL and requiring the invariant mass to be in the range $515 \leq M(\gamma\gamma) \leq 580$ MeV/c$^2$. Candidates for the decay $\eta' \to \pi^+\pi^-\eta$ are reconstructed using pairs of oppositely-charged pions and $\eta$. We require the reconstructed $\eta'$ invariant mass to be in the range $920 \leq M(\pi^+\pi^-\eta) \leq 980$ MeV/c$^2$. To identify $B_s^0 \to \eta'\eta$ candidates we use beam-energy constrained $B_s^0$ mass, $M_{\rm bc} = \sqrt{E_{\rm beam}^2 - p_{B_s}^2}$, the energy difference, $\Delta E = E_{B_s} - E_{\rm beam}$, and the reconstructed invariant mass of the $\eta'$, where $E_{\rm beam}$, $p_{B_s}$ and

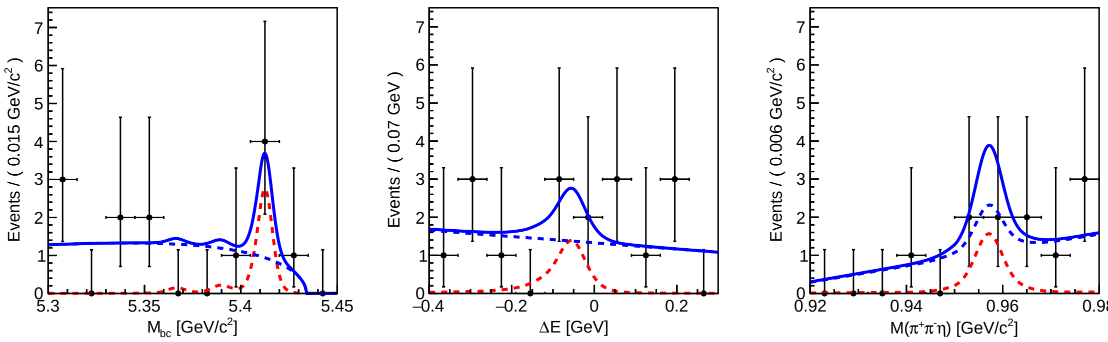


**Figure 1:** Signal-region projections of 3D fit to $B_s^0 \to \eta'\eta$ data. Points with error bars represent data, blue solid curves show the resulting fit-projection, while the red dash-dotted and blue dash-dotted curves show the signal and background components.

$E_{B_s}$ are the beam energy, the momentum magnitude and the reconstructed energy of $B_s^0$ candidate, respectively.

The primary source of background are $e^+e^- \to q\bar{q}$ ($q = u, d, c, s$) continuum events. Because of large initial momenta of the light quarks, continuum events exhibit a “jet-like” event shape, while $B_s^{(*)0}\bar{B}_s^{(*)0}$ events are distributed isotropically. We use modified Fox-Wolfram moments [11], which describe the topology of the event, to discriminate between signal and continuum background.

To extract the signal yield, we perform an unbinned extended maximum likelihood fit to the three-dimensional (3D) distribution of $M_{\rm bc}$, $\Delta E$, and $M(\pi^+\pi^-\eta)$. MC sample is used to determine signal and background probability density functions (PDF). We use $B^0 \to \eta' K_S^0$ data recorded at the $\Upsilon(4S)$ resonance to adjust the PDF shape parameters used to describe the signal.

To test and validate our fitting model, ensemble tests are performed by generating MC pseudoexperiments using PDFs obtained from the simulation and the $B^0 \to \eta' K_S^0$ data. We use the results of pseudoexperiments to construct classical confidence intervals using Neyman construction [12]. These confidence intervals are then used to prepare a classical confidence belt [13] and used to make a statistical interpretation of the results obtained from fit to data.

We obtain 2.7±2.5 signal and 57.3±7.8 background events from the 3D fit to data. We show the signal-region projections of the fit in Fig. 1. We observe no signal and estimate the 90% confidence-level (CL) upper limit on the branching fraction of the decay $B_s^0 \to \eta'\eta$ using the frequentist approach [12] and the following formula:

$$\mathcal{B}(B_s^0 \to \eta'\eta) < \frac{N_{\rm UL}^{90\%}}{2 \cdot N_{B_s^{(*)0}\bar{B}_s^{(*)0}} \cdot \varepsilon \cdot \mathcal{B}_{\rm dp}}, \tag{1}$$

where $N_{B_s^{(*)0}\bar{B}_s^{(*)0}}$ is the number of $B_s^{(*)0}\bar{B}_s^{(*)0}$ pairs in the full Belle data sample, $\varepsilon$ is the overall reconstruction efficiency for the signal $B_s^0$ decay, and $\mathcal{B}_{\rm dp}$ is the product of the secondary branching fractions for all daughter particles in our final state. Further,

| Component | Yields |
|---|---|
| Signal | $18.8^{+15.3}_{-14.5}$ |
| Generic $B$ | $68.1^{+12.2}_{-11.7}$ |
| Non-$B$ | $-3.9^{+19.5}_{-17.5}$ |

**Table 1:** Fitting yield ($B^0 \to$ invisible).

$N^{90\%}_{\rm UL}$ is the expected signal yield at 90% CL obtained from the confidence belt, which is approximately 6 events. Using Eq. (1) we obtain a 90% CL upper limit on the branching fraction of $\mathcal{B}(B^0_s \to \eta'\eta) < 7.1 \times 10^{-5}$. The total systematic uncertainty on the upper limit is estimated to be 17%.

## 4. Search for $B^0$ decays to invisible final states (+$\gamma$)

These searches are based on a data sample containing $772 \times 10^6$ $B\bar{B}$ pairs accumulated at the $\Upsilon(4S)$ resonance, corresponding to an integrated luminosity of 711 fb$^{-1}$. Ten million MC simulated events for $B^0 \to \nu\bar{\nu}$ and $B^0 \to \nu\bar{\nu}\gamma$ decays are generated and used to determine signal efficiency and optimize signal event selection.

Since the signal side particle, except photon, cannot be detected, the other $B$ meson in the event ($B_{\rm tag}$) is reconstructed. Then the signal is searched in the remaining part of the event. $B_{\rm tag}$ mesons are reconstructed from 494 hadronic decay modes by assigning signal probability to reconstructed particles using a neural network (NN) package [14]. After reconstruction of $B_{\rm tag}$, no extra particles but photons are expected in the event. Thus events with extra tracks, $\pi^0$s, or $K^0_L$s are rejected.

The sum of all remaining energies of ECL clusters that are not associated with $B_{\rm tag}$ daughters and signal photons in case of $B^0 \to$ invisible + $\gamma$, denoted by $E_{\rm ECL}$, is a strong variable to identify signal events. Since the distribution for signal events peaks at zero, the $E_{\rm ECL}$ signal box is defined as $E_{\rm ECL} < 0.3$ GeV and the sideband is defined as 0.3GeV $< E_{\rm ECL} <$ 1.2GeV. Continuum events are the dominant source of background (Non-$B$) followed by $B\bar{B}$ decay with a $b \to c$ transition (Generic $B$). Two NNs are implemented to suppress these backgrounds.

A two dimensional (2D) extended unbinned maximum likelihood fit is applied with fitting variables $E_{\rm ECL}$ and $\cos\theta_T$ to extract signal yield for the decay $B^0 \to$ invisible. Here $\cos\theta_T$ is the cosine of the angle between the two thrust axes in the $e^+e^-$ c.m. frame. The two thrust axes are defined as the directions that maximizes the longitudinal momenta of $B_{\rm tag}$ daughters and particles in the remaining part of the event. All PDFs are obtained from signal MC and off-resonance data. The projections of the 2D fit results are shown in Fig. 2 and the corresponding fitting yiels for each component are listed in Table. 1. No significant signal is observed and a 90% CL upper limit on the branching fraction is estimated to be $\mathcal{B}(B^0 \to \text{invisible}) < 7.8 \times 10^{-5}$ [15]. Systematic uncertainty is estimated to be 7.9% using control samples $B^{0,\pm} \to B^{*,\pm} l\nu$.

$B^0 \to$ invisible + $\gamma$ decays are searched by counting events in $E_{\rm ECL}$ signal box in the bins of squared missing mass defined as:

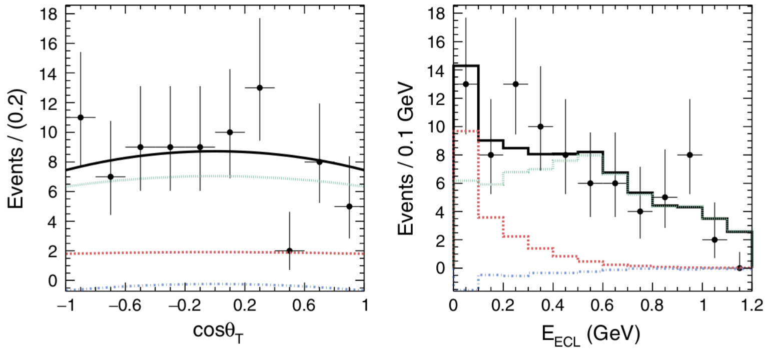


**Figure 2:** Projections of the fit result on $\cos\theta_T$ (left) and $E_{\rm ECL}$ (right) for $B^0 \to$ invisible. Points with error bars are data, black solid line is the fit result, red dotted line is the signal component, green short-dashed line is the generic $B$ background component and blue dash-dotted line is the non-$B$ background component.

| | $N^{\rm data}_{\rm bkg,box}$ | $N^{\rm data}_{\rm box}$ |
|---|---|---|
| $B^0 \to$ invisible + $\gamma$ | $16.1 \pm 6.3$ | 11 |
| $M^2_{\rm miss} < 5$ GeV$^2/c^4$ | $3.2 \pm 2.1$ | 2 |
| 5 GeV$^2/c^4 < M^2_{\rm miss} < 10$ GeV$^2/c^4$ | $1.0 \pm 0.8$ | 2 |
| 10 GeV$^2/c^4 < M^2_{\rm miss} < 15$ GeV$^2/c^4$ | $4.4 \pm 2.6$ | 3 |
| 15 GeV$^2/c^4 < M^2_{\rm miss} < 20$ GeV$^2/c^4$ | $7.1 \pm 2.9$ | 4 |
| 20 GeV$^2/c^4 < M^2_{\rm miss}$ | $6.6 \pm 2.9$ | 7 |

**Table 2:** Estimated number of background events in the signal box ($N^{\rm data}_{\rm bkg,box}$) and the number of events in the signal box ($N^{\rm data}_{\rm box}$ ) for $B^0 \to$ invisible + $\gamma$ and $M^2_{\rm miss}$ bins.

$$M^2_{\rm miss} = (\vec{P}_{\rm beam} - \vec{P}_{B_{\rm tag}} - \vec{P}_\gamma)^2/c^2, \tag{2}$$

where $\vec{P}_{\rm beam}$, $\vec{P}_{B_{\rm tag}}$ and $\vec{P}_\gamma$ are four-momenta of $e^+e^-$ system, the $B_{\rm tag}$ and the signal photon. The number of background events in the $E_{\rm ECL}$ signal box is estimated from the data sideband by multiplying the fraction of events in signal box to the sideband, estimated in the MC. The counting results in $E_{\rm ECL}$ signal box and in bins of $M^2_{\rm miss}$ are summarized in Table. 2. The observed number of events is consistant with no signal. We set a 90% CL upperlimit on the branching fraction $\mathcal{B}(B^0 \to \text{invisible} + \gamma) < 1.6 \times 10^{-5}$ [15] with an associated systematic uncertainty of 8.4%.

## 5. Conclusions

In summary, we have used the full data sample recorded by the Belle experiment at $\Upsilon(5S)$ and $\Upsilon(4S)$ resonances to search for the decays $B^0_s \to \eta'\eta$ and $B^0 \to$ invisible + ($\gamma$) and no evidence is found. We set world's first upper limits on the branching fraction of $B^0_s \to \eta'\eta$ and improved the existing upper limit on $B^0 \to$ invisible + $\gamma$.

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