

Search for  $B \rightarrow h^{(*)} \nu \bar{\nu}$  Decays at Belle

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We present a search for the rare decays  $B \rightarrow h^{(*)} \nu \bar{\nu}$ , where  $h^{(*)}$  stands for a light meson. A data sample of  $535 \times 10^6 B\bar{B}$  pairs collected with the Belle detector at the KEKB  $e^+e^-$  collider is used. Signal candidates are required to have an accompanying  $B$  meson fully reconstructed in a hadronic mode and signal side particles consistent with a single  $h^{(*)}$  meson. No significant signal is observed and we set upper limits on the branching fractions at 90% confidence level. The limits on  $B^0 \rightarrow K^{*0} \nu \bar{\nu}$  and  $B^+ \rightarrow K^+ \nu \bar{\nu}$  decays are more stringent than the previous constraints, while the first searches for  $B^0 \rightarrow K^0 \nu \bar{\nu}$ ,  $\pi^0 \nu \bar{\nu}$ ,  $\rho^0 \nu \bar{\nu}$ ,  $\phi \nu \bar{\nu}$  and  $B^+ \rightarrow K^{*+} \nu \bar{\nu}$ ,  $\rho^+ \nu \bar{\nu}$  are reported.

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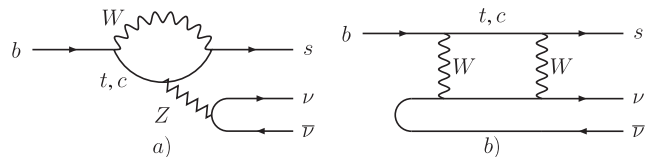
The decays  $B \rightarrow K^{(*)} \nu \bar{\nu}$  proceed through the flavor-changing neutral-current process  $b \rightarrow s \nu \bar{\nu}$ , which is sensitive to physics beyond the standard model (SM). The dominant SM diagrams are shown in Fig. 1. Similarly, the decays  $B \rightarrow (\pi, \rho) \nu \bar{\nu}$  proceed through  $b \rightarrow d \nu \bar{\nu}$  processes. The SM branching fractions are estimated to be  $1.3 \times 10^{-5}$  and  $4 \times 10^{-6}$  for  $B \rightarrow K^* \nu \bar{\nu}$  and  $B \rightarrow K \nu \bar{\nu}$  decays [1], respectively, and are expected to be much lower for other modes. Theoretical calculation of the decay amplitudes for  $B \rightarrow h^{(*)} \nu \bar{\nu}$  is particularly reliable, owing to the absence of long-distance interactions that affect charged-lepton channels  $B \rightarrow h^{(*)} l^+ l^-$ . New physics such as SUSY particles or a possible fourth generation could potentially contribute to the penguin loop or box diagram and enhance the branching fractions [1]. Reference [2] also discusses the possibility of discovering light dark matter in  $b \rightarrow s$  transitions with large missing momentum.

Experimental measurements [3] of the  $b \rightarrow s$  transitions with two charged leptons are in good agreement with SM calculations [1]. Further investigation of the forward-backward asymmetry in  $B \rightarrow K^* l^+ l^-$  [4] is consistent with the SM although the statistics are still limited. Because of the challenge of cleanly detecting rare modes with two final-state neutrinos, only a few studies of  $K^{(*)} \nu \bar{\nu}$  have been carried out to date [5–7]; there is only one examination of the corresponding  $b \rightarrow d$  transitions [7]. In this Letter, we report our first search for the decays  $B \rightarrow h^{(*)} \nu \bar{\nu}$  [ $h^{(*)}$  stands for  $K^+$ ,  $K_S^0$ ,  $K^{*0}$ ,  $K^{*+}$ ,  $\pi^+$ ,  $\pi^0$ ,  $\rho^0$ ,  $\rho^+$ ,

and  $\phi$ ] using a  $492 \text{ fb}^{-1}$  data sample recorded at the  $\Upsilon(4S)$  resonance, corresponding to  $535 \times 10^6 B$ -meson pairs. Charge-conjugate decays are implied throughout this Letter.

The Belle detector is a large-solid-angle magnetic spectrometer located at the KEKB collider [8], and it consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid that provides a 1.5 T magnetic field. An iron flux-return located outside the coil is instrumented to detect  $K_L^0$  mesons and to identify muons (KLM). The detector is described in detail elsewhere [9].

Candidate  $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$  events are characterized by a fully reconstructed tag-side  $B$  meson ( $B_{\text{tag}}$ ). The remaining particles are assumed to be products of the signal-side  $B$  meson ( $B_{\text{sig}}$ ). The  $B_{\text{tag}}$  candidates are reconstructed in one of the following modes:  $B^0 \rightarrow D^{(*)-} \pi^+$ ,

FIG. 1. The quark-level diagrams for  $B \rightarrow K^* \nu \bar{\nu}$  decays.

$D^{(*)-} \rho^+$ ,  $D^{(*)-} a_1^+$ ,  $D^{(*)-} D_s^{(*)+}$ ,  $B^+ \rightarrow \bar{D}^{(*)0} \pi^+$ ,  $\bar{D}^{(*)0} \rho^+$ ,  $\bar{D}^{(*)0} a_1^+$ , and  $\bar{D}^{(*)0} D_s^{(*)+}$ . The  $D^-$  mesons are reconstructed as  $D^- \rightarrow K_S^0 \pi^-$ ,  $K_S^0 \pi^- \pi^0$ ,  $K_S^0 \pi^- \pi^+ \pi^-$ ,  $K^+ \pi^- \pi^-$ , and  $K^+ \pi^- \pi^- \pi^0$ . The following decay channels are included for  $\bar{D}^0$  mesons:  $\bar{D}^0 \rightarrow K^+ \pi^-$ ,  $K^+ \pi^- \pi^0$ ,  $K^+ \pi^- \pi^+ \pi^-$ ,  $K_S^0 \pi^0$ ,  $K_S^0 \pi^- \pi^+$ ,  $K_S^0 \pi^- \pi^+ \pi^0$ , and  $K^- K^+$ . The  $D^{*-}$  ( $\bar{D}^{*0}$ ) mesons are reconstructed as  $\bar{D}^0 \pi^-$  ( $\bar{D}^0 \pi^0$  and  $\bar{D}^0 \gamma$ ). Furthermore,  $D_s^{*+} \rightarrow D_s^+ \gamma$ ,  $D_s^+ \rightarrow K_S^0 K^+$ , and  $K^+ K^- \pi^+$  decays are reconstructed.  $B_{\text{tag}}$  candidates are selected using the beam-energy constrained mass  $M_{\text{bc}} \equiv \sqrt{E_{\text{beam}}^2 - p_B^2}$  and the energy difference  $\Delta E \equiv E_B - E_{\text{beam}}$ , where  $E_B$  and  $p_B$  are the reconstructed energy and momentum of the  $B_{\text{tag}}$  candidate in the  $\Upsilon(4S)$  center-of-mass (c.m.) frame, and  $E_{\text{beam}}$  is the beam energy in this frame.

We require  $B_{\text{tag}}$  candidates satisfy the requirements  $M_{\text{bc}} > 5.27 \text{ GeV}/c^2$  and  $-80 \text{ MeV} < \Delta E < 60 \text{ MeV}$ . If there are multiple  $B_{\text{tag}}$  candidates in an event, the candidate with the smallest  $\chi^2$  based on the deviations from the nominal values of  $\Delta E$ , the  $D$  meson mass, and the mass difference between the  $D^*$  and the  $D$  (for candidates with a  $D^*$  in the final state) is chosen. We reconstruct  $7.88 \times 10^5$  and  $4.91 \times 10^5$  charged and neutral  $B$  mesons, respectively.

The particles in the event not associated with the  $B_{\text{tag}}$  meson are used to reconstruct a  $B_{\text{sig}} \rightarrow h^{(*)} \nu \bar{\nu}$  candidate. Prompt charged tracks are required to have a maximum distance to the interaction point (IP) of 5 cm in the beam

direction ( $z$ ), of 2 cm in the transverse plane ( $r - \phi$ ), and a minimum momentum of 0.1 GeV/ $c$  in the transverse plane. We reconstruct  $K^\pm$  ( $\pi^\pm$ ) candidates from charged tracks having a kaon likelihood greater than 0.6 (less than 0.4) with an efficiency of 84%–91% (87%–92%). The kaon likelihood is defined by  $\mathcal{R}_K \equiv \mathcal{L}_K / (\mathcal{L}_K + \mathcal{L}_\pi)$ , where  $\mathcal{L}_K$  ( $\mathcal{L}_\pi$ ) denotes a combined likelihood measurement from the ACC, the TOF, and a  $dE/dx$  from the CDC for the  $K^\pm$  ( $\pi^\pm$ ) tracks. Pairs of oppositely charged tracks are used to reconstruct  $K_S^0 \rightarrow \pi^+ \pi^-$  decays, with an invariant mass that is within  $\pm 15 \text{ MeV}/c^2$  ( $> 5\sigma$ ) from the nominal  $K_S^0$  meson mass. The  $\pi^+ \pi^-$  vertex is required to be displaced from the IP by a minimum distance of 0.22 cm. The direction of the pion pair momentum in the transverse plane must agree with the direction defined by the IP and the vertex displacement within 0.03 rad. For  $\pi^0 \rightarrow \gamma\gamma$ , a minimum photon energy of 50 MeV is required and the  $\gamma\gamma$  invariant mass must be within  $\pm 16 \text{ MeV}/c^2$  ( $\sim 2.5\sigma$ ) of the nominal  $\pi^0$  mass.

The decays  $B_{\text{sig}} \rightarrow K^+ \nu \bar{\nu}$ ,  $\pi^+ \nu \bar{\nu}$ ,  $K_S^0 \nu \bar{\nu}$ , and  $\pi^0 \nu \bar{\nu}$  are reconstructed from single  $K^+$ ,  $\pi^+$ ,  $K_S^0$ , and  $\pi^0$  candidates, respectively. The  $B^0 \rightarrow K^{*0} \nu \bar{\nu}$  candidate is reconstructed from a charged pion and an oppositely charged kaon, while  $B^+ \rightarrow K^{*+} \nu \bar{\nu}$  decays are reconstructed from a  $K_S^0$  candidate and a charged pion, or a charged kaon and a  $\pi^0$  candidate. The reconstructed mass of the  $K^{*0}$  ( $K^{*+}$ ) candidate should be within a  $\pm 75 \text{ MeV}/c^2$  window around the nominal  $K^{*0}$  ( $K^{*+}$ ) mass. Furthermore, pairs of charged pions with opposite charge are used to form  $B^0 \rightarrow \rho^0 \nu \bar{\nu}$  candidates where the  $\pi^+ \pi^-$  invariant mass should be

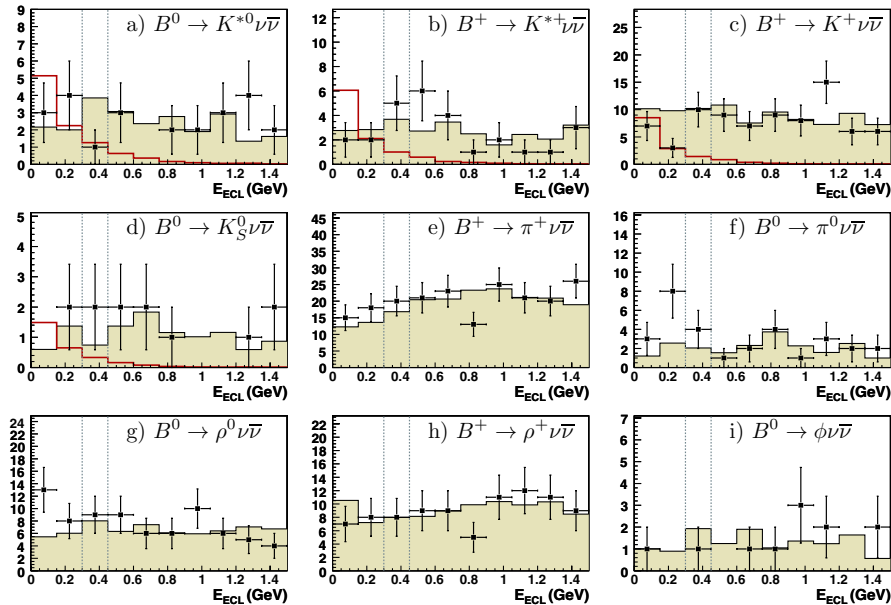


FIG. 2 (color online). The  $E_{\text{ECL}}$  distributions for  $B \rightarrow h^{(*)} \nu \bar{\nu}$  decays. The shaded histograms show the background distributions from MC simulations and are normalized to sideband data. The open histograms show the SM expected signal distributions for  $B \rightarrow K^{(*)} \nu \bar{\nu}$  decays multiplied by a factor of 20 for the comparison. The vertical dashed lines show the upper bound (left) of the signal box and the lower bound (right) of the sideband region.

TABLE I. A summary of the number of observed events in the signal box ( $N_{\text{obs}}$ ) and sideband regions ( $N_{\text{side}}$ ), expected background yields ( $N_b$ ) in the signal box, reconstruction efficiencies including both  $B_{\text{tag}}$  and  $B_{\text{sig}}$  ( $\epsilon$ ), and the upper limits (U.L.) on the branching fractions at 90% C.L.

Mode	$N_{\text{obs}}$	$N_{\text{side}}$	$N_b$	$\epsilon(\times 10^{-5})$	U.L.
$K^{*0} \nu \bar{\nu}$	7	16	$4.2 \pm 1.4$	$5.1 \pm 0.3$	$< 3.4 \times 10^{-4}$
$K^{*+} \nu \bar{\nu}$	4	18	$5.6 \pm 1.8$	$5.8 \pm 0.7$	$< 1.4 \times 10^{-4}$
$\rightarrow K_S^0 \pi^+$	1	7	$2.3 \pm 1.2$	$2.8 \pm 0.3$	
$\rightarrow K^+ \pi^0$	3	11	$3.3 \pm 1.4$	$3.0 \pm 0.4$	
$K^+ \nu \bar{\nu}$	10	60	$20.0 \pm 4.0$	$26.7 \pm 2.9$	$< 1.4 \times 10^{-5}$
$K^0 \nu \bar{\nu}$	2	8	$2.0 \pm 0.9$	$5.0 \pm 0.3$	$< 1.6 \times 10^{-4}$
$\pi^+ \nu \bar{\nu}$	33	149	$25.9 \pm 3.9$	$24.2 \pm 2.6$	$< 1.7 \times 10^{-4}$
$\pi^0 \nu \bar{\nu}$	11	15	$3.8 \pm 1.3$	$12.8 \pm 0.8$	$< 2.2 \times 10^{-4}$
$\rho^0 \nu \bar{\nu}$	21	46	$11.5 \pm 2.3$	$8.4 \pm 0.5$	$< 4.4 \times 10^{-4}$
$\rho^+ \nu \bar{\nu}$	15	66	$17.8 \pm 3.2$	$8.5 \pm 1.1$	$< 1.5 \times 10^{-4}$
$\phi \nu \bar{\nu}$	1	9	$1.9 \pm 0.9$	$9.6 \pm 1.4$	$< 5.8 \times 10^{-5}$

within  $\pm 150 \text{ MeV}/c^2$  from the nominal  $\rho^0$  mass. For  $B^+ \rightarrow \rho^+ \nu \bar{\nu}$ , a charged pion and a  $\pi^0$  candidate are used, and a  $\pm 150 \text{ MeV}/c^2$  mass window is required. A  $\phi$  meson is formed from a  $K^+ K^-$  pair with a reconstructed mass within  $\pm 10 \text{ MeV}/c^2$  ( $\sim 2\sigma$ ) from the nominal  $\phi$  mass.

No additional charged tracks or  $\pi^0$  candidates are allowed in the event. We select  $B_{\text{sig}}$  candidates using the variable  $E_{\text{ECL}} \equiv E_{\text{tot}} - E_{\text{rec}}$ , where  $E_{\text{tot}}$  and  $E_{\text{rec}}$  are the total visible energy measured by the ECL detector and the measured energy of reconstructed objects including the  $B_{\text{tag}}$  and the signal-side  $h^{(*)}$  candidate, respectively. A minimum threshold of 50 (100, 150) MeV on the cluster energy is applied for the barrel (forward end cap, backward end cap) region of the ECL detector. The decays  $B \rightarrow D^* \ell \nu$  are examined as control samples; the observed  $E_{\text{ECL}}$  distributions are found to be in good agreement with Monte Carlo (MC) simulations [10]. The signal region is defined by  $E_{\text{ECL}} < 0.3 \text{ GeV}$  while the sideband region is given by  $0.45 \text{ GeV} < E_{\text{ECL}} < 1.5 \text{ GeV}$ .

The dominant background source is  $B\bar{B}$  decays involving a  $b \rightarrow c$  transition. A lower bound of  $1.6 \text{ GeV}/c$  on  $P^*$ , the momentum of the  $h^{(*)}$  candidate in the  $B_{\text{sig}}$  rest frame, suppresses this background, while an upper bound of  $2.5 \text{ GeV}/c$  rejects the contributions from radiative two-

body modes such as  $B \rightarrow K^* \gamma$ . The  $P^*$  requirement is removed for  $\phi$  candidates due to the lack of theoretical calculations for  $B_d \rightarrow \phi$  form factors. Furthermore, the cosine of the angle between the missing momentum in the laboratory frame and the beam is required to lie between  $-0.86$  and  $0.95$ . The missing momentum is calculated using the momenta of the reconstructed  $B_{\text{tag}}$  and  $h^{(*)}$  candidates. These criteria suppress backgrounds with particles produced along the beam pipe. Other background sources, such as  $e^+ e^- \rightarrow q\bar{q}$  ( $q = u, d, c, s$ ) continuum background and rare  $B$  decays involving  $b \rightarrow u$ ,  $b \rightarrow s$ , or  $b \rightarrow d$  processes, are found to be small.

The reconstructed  $E_{\text{ECL}}$  distributions are shown in Fig. 2. The  $E_{\text{ECL}}$  distributions of background are estimated with MC simulations; in particular, a large  $b \rightarrow c$  MC sample corresponding to 10 times the data luminosity is introduced with a preselection on the generator information. The background  $E_{\text{ECL}}$  distributions are normalized by the number of events in the sideband region. None of the signal modes has a significant signal. Including the effects of both statistical and systematic uncertainties, an extension of the Feldman-Cousins method [11,12] is used to calculate the upper limits on the branching fractions. The observed number of events in the signal box and sideband region, expected background contributions in the signal box, reconstruction efficiencies, and the obtained upper limits at 90% confidence level (C.L.) are shown in Table I. The reconstruction efficiencies are estimated with MC simulations using the  $B \rightarrow h^{(*)}$  form factors from Ref. [13]. The  $B^0 \rightarrow \phi \nu \bar{\nu}$  MC samples are generated with the  $B \rightarrow K^*$  form factors.

The uncertainties associated with the background yields are dominated by the data sideband statistics and MC statistics, and they are summarized in Table II. The possible disagreement in the  $E_{\text{ECL}}$  distributions between data and MC calculations is checked using wrong-flavor combinatorial events, and an uncertainty of 0.1–2.0 events is included. Possible backgrounds from rare  $B$  decays are examined using a large MC sample corresponding to 50 times the data luminosity. We change the relative normalizations of rare  $B$  components by  $\pm 50\%$ , and the variation in the background yield (0.1–1.8 events) is included as a systematic uncertainty.

Various sources of uncertainties are considered for the signal normalization and are summarized in Table III. The

TABLE II. Summary of the uncertainties associated with the background yields (in the number of events).

Uncertainties	$K^{*0} \nu \bar{\nu}$	$K^{*+} \nu \bar{\nu}$	$K^+ \nu \bar{\nu}$	$K^0 \nu \bar{\nu}$	$\pi^+ \nu \bar{\nu}$	$\pi^0 \nu \bar{\nu}$	$\rho^0 \nu \bar{\nu}$	$\rho^+ \nu \bar{\nu}$	$\phi \nu \bar{\nu}$
Sideband statistics	1.0	1.3	2.6	0.7	2.1	1.0	1.7	2.2	0.6
MC statistics	0.9	1.2	2.6	0.6	2.0	0.8	1.3	1.6	0.6
MC/data difference	0.3	0.3	1.5	0.2	2.0	0.3	0.9	1.4	0.1
Rare $B$	0.1	0.3	0.2	0.2	1.8	0.1	0.1	0.9	0.3
Total	1.4	1.8	4.0	0.9	3.9	1.3	2.3	3.2	0.9

TABLE III. Summary of the relative uncertainties for signal normalization (in %).

Source	$K^{*0}\nu\bar{\nu}$	$K^{*+}\nu\bar{\nu}$	$K^+\nu\bar{\nu}$	$K^0\nu\bar{\nu}$	$\pi^+\nu\bar{\nu}$	$\pi^0\nu\bar{\nu}$	$\rho^0\nu\bar{\nu}$	$\rho^+\nu\bar{\nu}$	$\phi\nu\bar{\nu}$
$N(B\bar{B})$	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Tracking efficiency	2.1	1.1	1.0	...	1.0	...	2.2	1.1	2.0
$K_S^0/\pi^0$ reconstruction	...	4.4	...	4.9	...	4.0	...	4.0	...
Sub-branching fraction	...	...	...	...	...	...	...	...	1.2
Particle identification	1.3	0.7	0.7	...	0.5	...	1.0	0.5	2.0
MC statistics	3.5	2.4	1.9	3.2	2.0	2.8	3.3	3.4	2.3
Mass selection	0.8	2.3	...	...	...	...	1.1	2.6	2.0
$B_{\text{tag}}$ reconstruction	2.0	9.9	9.9	2.0	9.9	2.0	2.0	9.9	2.0
Track/ $\pi^0$ rejection	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
$B \rightarrow h^{(*)}$ form factor	1.6	1.3	2.6	0.4	3.0	1.0	1.7	3.7	13.0
Total	5.9	11.8	10.9	6.9	11.0	6.1	5.8	12.5	14.2

uncertainties in  $B_{\text{tag}}$  reconstruction (2.0% for  $B^0$  and 9.9% for  $B^\pm$ ) are estimated by comparing the yields of data and MC calculations from the  $B_{\text{tag}}$  candidates. Systematic uncertainty arising from the track and  $\pi^0$  rejection is studied using  $B \rightarrow D^{(*)}\ell\nu$  decays, and an error of 2.7% is assigned. The uncertainties in the efficiencies for detecting a  $K_S^0$  or  $\pi^0$  from  $B_{\text{sig}}$  are estimated to be 4.9% and 4.0%, respectively. We also vary the  $B \rightarrow h^{(*)}$  form factors used in the signal MC generation according to the uncertainties given by the Ref. [13], and an uncertainty of 0.4%–3.7% on the reconstruction efficiency is included. A larger uncertainty of 13%, which is estimated from the difference between the default decay model and a generic three-body phase-space model, is introduced for  $B^0 \rightarrow \phi\nu\bar{\nu}$  decays. Furthermore, the following uncertainties are also considered: the number of  $B\bar{B}$  events (1.3%), tracking efficiency (1.0%–2.2%), particle identification (0.5%–2.0%),  $h^{(*)}$  mass selection (0.8%–2.3%), and the  $\phi \rightarrow K^+K^-$  branching fraction (1.2%).

In conclusion, we have performed a search for  $B \rightarrow h^{(*)}\nu\bar{\nu}$  decays with a fully reconstructed  $B$  tagging method on a data sample of  $535 \times 10^6$   $B\bar{B}$  pairs collected at the  $\Upsilon(4S)$  resonance with the Belle detector. No significant signal is observed and we set upper limits on the branching fractions at 90% C.L. The limits obtained for  $B^0 \rightarrow K^{*0}\nu\bar{\nu}$  and  $B^+ \rightarrow K^+\nu\bar{\nu}$  decays are more stringent than the previous constraints from DELPHI [5] and BABAR [7]. The first searches for  $B^0 \rightarrow K^0\nu\bar{\nu}$ ,  $\pi^0\nu\bar{\nu}$ ,  $\rho^0\nu\bar{\nu}$ ,  $\phi\nu\bar{\nu}$ , and  $B^+ \rightarrow K^{*+}\nu\bar{\nu}$ ,  $\rho^+\nu\bar{\nu}$  are carried out, and upper limits on the branching fraction of order  $10^{-4}$  are obtained. The limit on  $B^+ \rightarrow \pi^+\nu\bar{\nu}$  is less restrictive than BABAR's result [7] due to a larger number of observed events in the signal box. The results on  $B \rightarrow K^{(*)}\nu\bar{\nu}$  reported here are 1 order of magnitude above the predictions of Buchalla *et al.* [1] and hence still allow room for substantial non-SM contributions. A higher luminosity  $B$ -factory experiment is required to probe the SM predictions for the branching fractions.

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