Rare and forbidden decays at Belle

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Overview

Outline

- $B^0$ decays to invisible final states
- $B \rightarrow h^{(*)} \nu \bar{\nu}$
- Search for heavy neutral lepton
$B^0 \rightarrow \text{invisible}$

- $B^0 \rightarrow \nu\bar{\nu}$ highly helicity suppressed in the Standard Model ($\mathcal{B} \sim \mathcal{O}(10^{-20})$)


- Experimental signature: missing energy and momentum corresponding to the presence of a $B^0$ meson

Figure 1.1: Feynman diagrams for $B^0 \rightarrow \nu\bar{\nu}$ decay in the Standard Model.
$B^0 \to \text{invisible}$

- $B^0 \to \nu \bar{\nu}$ highly helicity suppressed in the SM ($\mathcal{B} \sim \mathcal{O}(10^{-20})$)
  

- Experimental signature: missing energy and momentum corresponding to the presence of a $B^0$ meson

- Same signature from new particles beyond the SM

- Example: $B^0 \to \bar{\nu} \chi_1^0$
  ($\mathcal{B} \sim \mathcal{O}(10^{-6} - 10^{-7})$)


Figure 1.2: Feynman diagrams for $B^0 \to \bar{\nu} \chi_1^0$ decay in the $R$-parity violation model.
$B^0 \rightarrow \text{invisible: reconstruction}$

- Data sample: $605 \text{fb}^{-1}$ at the $\Upsilon(4S)$ resonance ($657 \times 10^6 B\bar{B}$ pairs)
- One $B$ meson fully reconstructed in hadronic modes ($B_{\text{tag}}$)
- $9.5 \times 10^5$ neutral $B_{\text{tag}}$ candidates
- Candidate selection requirements: no additional charged tracks, $\pi^0$ or $K_L^0$ candidates left in the event
- Continuum background ($e^+ e^- \rightarrow q\bar{q}$) suppressed using cut on $\cos \theta_T$: angle between the $B_{\text{tag}}$ thrust axis and the beam axis in the CM frame
- $\cos \theta_B$ to extract the signal yield: angle between the $B_{\text{tag}}$ flight direction and the beam axis in the CM frame (cut away the region around $\pm 1$ as differences between data and MC were observed in the sideband)

![Graphs showing signal and background distributions in $\cos \theta_B$ and $\cos \theta_T$](image)
$B^0 \rightarrow \text{invisible: reconstruction}$

- Most powerful variable: sum of the energies of ECL (electromagnetic calorimeter) clusters that are not associated with $B_{tag}$ tracks or neutrals ($E_{ECL}$)
- The signal yield is extracted from an extended unbinned maximum likelihood fit to $E_{ECL}$ and $\cos \theta_B$
- Most of the background components models obtained from MC simulation (non-B background from off-resonance data)
- Validation of the $E_{ECL}$ simulation using doubly tagged samples: hadronic $B_{tag} + B^0 \rightarrow D^{(\ast)}^- l^+ \nu$ ($l = e, \mu$)

![Comparison between data and MC for the control samples](attachment:image.png)
$B^0 \rightarrow \text{invisible}$: results (*Belle preliminary*)

- **Upper limit:** $\mathcal{B}(B \rightarrow \text{invisible}) < 1.3 \times 10^{-4}$
  (limit estimation performed using the fit likelihood as a function of the branching fraction)

- **Signal yield:** $N_{\text{sig}} = 8.9^{+6.3}_{-5.5}$
\[ B \rightarrow h(\ast)\nu\bar{\nu} \]

**Motivation**

- Flavor changing neutral currents forbidden at tree level
- \( b \rightarrow s\nu\bar{\nu} \) and \( b \rightarrow d\nu\bar{\nu} \) highly suppressed
- Very precise theoretical predictions (only one hadron in the final state, no charged leptons)
- Models beyond SM (SUSY, non-standard Z coupling, fourth generation) could enhance these decays
$B \rightarrow h^{(*)} \bar{\nu} \nu$: reconstruction

- Larger data sample and improved reconstruction compared to the previous Belle analysis
- Data sample: $711 \text{fb}^{-1}$ at the $\Upsilon(4S)$ resonance ($771 \times 10^6 B \bar{B}$ pairs)
- Data reprocessed with new improved tracking
- One $B$ meson fully reconstructed in hadronic modes ($B_{tag}$) using new full reconstruction [NIM A 654, 432-440 (2011)]
  - 1104 decay channels exclusively reconstructed
  - Hierarchical reconstruction procedure
  - Multivariate approach (neural net package NeuroBayes) instead of cuts
  - Efficiency improvement of factor $\sim 2$ for the same purity
$B \rightarrow h^{(*)} \nu \bar{\nu}$: reconstruction

- Larger data sample and improved reconstruction compared to the previous Belle analysis
- Find one light meson ($K^+, K^*, K^0_s, K^{*0}, \pi^+, \pi^0, \rho^+, \rho^0, \phi$)
- No additional charged tracks or $\pi^0$ candidates left in the event
- Continuum background ($e^+ e^- \rightarrow q\bar{q}$) suppressed using $\cos \theta_T$: angle between the $B_{tag}$ thrust axis and the beam axis in the CM frame
- Most powerful variable: sum of the energies of ECL (electromagnetic calorimeter) clusters that are not associated with $B_{tag}$ tracks or neutrals ($E_{ECL}$)
- The signal yield is extracted from an extended binned maximum likelihood fit to $E_{ECL}$

**Example:** $B^0 \rightarrow K^{*0} \nu \bar{\nu}$
\( B \rightarrow h^{(*)}\nu\bar{\nu} : \text{expected limits} \)

- Comparison of sensitivity of the new analysis to the previous one

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected branching ratio limit at 90% CL (711fb(^{-1}))</th>
<th>Expected branching ratio limit at 90% CL, previous Belle analysis (492fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^+ \rightarrow K^+\nu\bar{\nu} )</td>
<td>( 2.2 \times 10^{-5} )</td>
<td>( 10 \times 10^{-5} )</td>
</tr>
<tr>
<td>( B^+ \rightarrow K^{*+}\nu\bar{\nu} )</td>
<td>( 4.2 \times 10^{-5} )</td>
<td>( 22 \times 10^{-5} )</td>
</tr>
<tr>
<td>( K^{*+} \rightarrow K^+\pi^0 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( B^+ \rightarrow K^{*+}\nu\bar{\nu} )</td>
<td>( 4.4 \times 10^{-5} )</td>
<td>( 22 \times 10^{-5} )</td>
</tr>
<tr>
<td>( K^{*+} \rightarrow K^0\pi^+ )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( B^+ \rightarrow \pi^+\nu\bar{\nu} )</td>
<td>( 3.9 \times 10^{-5} )</td>
<td>( 10 \times 10^{-5} )</td>
</tr>
<tr>
<td>( B^+ \rightarrow \rho^+\nu\bar{\nu} )</td>
<td>( 9.8 \times 10^{-5} )</td>
<td>( 19 \times 10^{-5} )</td>
</tr>
<tr>
<td>( B^0 \rightarrow K^0_{s}\nu\bar{\nu} )</td>
<td>( 7.3 \times 10^{-5} )</td>
<td>( 16 \times 10^{-5} )</td>
</tr>
<tr>
<td>( B^0 \rightarrow K^{*0}\nu\bar{\nu} )</td>
<td>( 5.0 \times 10^{-5} )</td>
<td>( 20 \times 10^{-5} )</td>
</tr>
<tr>
<td>( K^{*0} \rightarrow K^+\pi^- )</td>
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</tr>
<tr>
<td>( B^0 \rightarrow \pi^0\nu\bar{\nu} )</td>
<td>( 3.6 \times 10^{-5} )</td>
<td>( 10 \times 10^{-5} )</td>
</tr>
<tr>
<td>( B^0 \rightarrow \rho^0\nu\bar{\nu} )</td>
<td>( 16.5 \times 10^{-5} )</td>
<td>( 16 \times 10^{-5} )</td>
</tr>
<tr>
<td>( B^0 \rightarrow \phi\nu\bar{\nu} )</td>
<td>( 9.1 \times 10^{-5} )</td>
<td>( 13 \times 10^{-5} )</td>
</tr>
</tbody>
</table>
$B \rightarrow h^{(*)}\nu\bar{\nu}$: results (Belle preliminary)

$B^+ \rightarrow K^+\nu\bar{\nu}$

$K^+$

$B^0 \rightarrow K^0_s\nu\bar{\nu}$

$K^0_s$

$$N_{\text{Sig}} = 13.3^{+7.4}_{-6.6}$$

$$S_{\text{stat}} = 2.1\sigma$$

$$S_{\text{stat+syst}} = 2.0\sigma$$

$$N_{\text{Sig}} = 1.8^{+3.3}_{-2.4}$$

$$S_{\text{stat}} = 0.6\sigma$$

$$S_{\text{stat+syst}} = 0.6\sigma$$
$B \rightarrow h^{(*)} \nu \bar{\nu}$: results (*Belle preliminary*)

$B^+ \rightarrow K^{*+}(K^{+}\pi^0)\nu \bar{\nu}$

$B^+ \rightarrow K^{*+}(K^0_\pi)\nu \bar{\nu}$

$B^0 \rightarrow K^0\nu \bar{\nu}$

$N_{Sig} = -1.9^{+1.7}_{-1.1}$

$N_{Sig} = 0.0$

$N_{Sig} = -2.3^{+10.1}_{-3.5}$
$B \rightarrow h^{(*)} \nu \bar{\nu}$: results (*Belle preliminary*)

$B^+ \rightarrow \pi^+ \nu \bar{\nu}$

$N_{\text{Sig}} = 15.2^{+7.1}_{-6.2}$

$S_{\text{stat}} = 2.8\sigma$

$S_{\text{stat+syst}} = 2.6\sigma$

$B^0 \rightarrow \pi^0 \nu \bar{\nu}$

$N_{\text{Sig}} = 3.5^{+2.6}_{-1.9}$

$S_{\text{stat}} = 2.2\sigma$

$S_{\text{stat+syst}} = 2.0\sigma$
$B \rightarrow h(\ast)\nu\bar{\nu}$: results (Belle preliminary)

$B^+ \rightarrow \rho^+\nu\bar{\nu}$

$N_{Sig} = 11.3^{+6.3}_{-5.4}$
$S_{stat} = 2.3\sigma$
$S_{stat+syst} = 1.7\sigma$

$B^0 \rightarrow \rho^0\nu\bar{\nu}$

$N_{Sig} = 1.6^{+5.0}_{-4.1}$
$S_{stat} = 0.4\sigma$
$S_{stat+syst} = 0.4\sigma$

$B^0 \rightarrow \phi\nu\bar{\nu}$

$N_{Sig} = 1.5^{+2.85}_{-0.9}$
$S_{stat} = 0.6\sigma$
$S_{stat+syst} = 0.5\sigma$
**$B \rightarrow h^{(*)} \nu \bar{\nu}$: results (Belle preliminary)**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Branching ratio limit at 90% CL</th>
<th>Branching ratio limit at 90% CL previous Belle analysis</th>
<th>PDG limit at 90% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow K^+ \nu \bar{\nu}$</td>
<td>$5.5 \times 10^{-5}$</td>
<td>$1.4 \times 10^{-5}$</td>
<td>$1.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*+} \nu \bar{\nu}$</td>
<td>$3.3 \times 10^{-5}$</td>
<td>$14 \times 10^{-5}$</td>
<td>$8 \times 10^{-5}$</td>
</tr>
<tr>
<td>$K^{*+} \rightarrow K^+ \pi^0$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*0} \nu \bar{\nu}$</td>
<td>$2.9 \times 10^{-5}$</td>
<td>$14 \times 10^{-5}$</td>
<td>$8 \times 10^{-5}$</td>
</tr>
<tr>
<td>$K^{*+} \rightarrow K^0 \pi^+ $</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^+ \rightarrow \pi^+ \nu \bar{\nu}$</td>
<td>$9.8 \times 10^{-5}$</td>
<td>$17 \times 10^{-5}$</td>
<td>$10 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B^+ \rightarrow \rho^+ \nu \bar{\nu}$</td>
<td>$21.4 \times 10^{-5}$</td>
<td>$44 \times 10^{-5}$</td>
<td>$15 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^0_s \nu \bar{\nu}$</td>
<td>$9.4 \times 10^{-5}$</td>
<td>$16 \times 10^{-5}$</td>
<td>$5.6 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^{*0} \nu \bar{\nu}$</td>
<td>$5.4 \times 10^{-5}$</td>
<td>$34 \times 10^{-5}$</td>
<td>$1.2 \times 10^{-5}$</td>
</tr>
<tr>
<td>$K^{*0} \rightarrow K^+ \pi^-$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^0 \rightarrow \pi^0 \nu \bar{\nu}$</td>
<td>$6.9 \times 10^{-5}$</td>
<td>$22 \times 22^{-5}$</td>
<td>$22 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \rho^0 \nu \bar{\nu}$</td>
<td>$20.8 \times 10^{-5}$</td>
<td>$44 \times 10^{-5}$</td>
<td>$44 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \phi \nu \bar{\nu}$</td>
<td>$12.5 \times 10^{-5}$</td>
<td>$5.8 \times 10^{-5}$</td>
<td>$5.8 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
$B \rightarrow \text{heavy neutral lepton}$

- Mass generation in SM: coupling of the Higgs boson to left and right components of the particle
- No right-handed neutrino in SM $\rightarrow$ neutrinos should be massless
- Neutrino oscillation show that neutrinos do have a mass
- $\Rightarrow$ sterile right-handed neutrinos?
- Heavy neutral leptons appear in many models beyond SM(SUSY, $\nu$MSM, GUT)

![Diagrams](image)

**FIG. 1.** Heavy neutrino production (a) and decay (b) diagrams.

- No strong interaction (lepton)
- No weak interaction (right handed)
- No electromagnetic interaction (neutral)
- Only way to interact: mixing with left-handed neutrinos
$B \rightarrow \nu_h$: reconstruction

- Search for $B \rightarrow l\nu_h(X), \nu_h \rightarrow l\pi$ decays ($l = e, \mu$)
- $M(\nu_h) = M(l_1\pi)$
- 'small' masses ($< 2\text{GeV}$): pick out $B \rightarrow D^{(*)}l\nu_h$,
  'large' masses ($> 2\text{GeV}$): inclusive reconstruction
- Distinctive feature of $\nu_h$: large flight length ($cT \sim 20\text{m}$)
- Selection to strongly suppress the background:
  - Strict lepton identification requirements to suppress physical
    background from decay with similar topology
  - $\nu_h$ vertex quality requirements to suppress combinatorial background
- Background reduced by a factor $\sim 10^6$
- Efficiency depends on $B$ meson decay mode and $\nu_h$ mass ($\sim 3.3\% - 17\%$)
$B \rightarrow \nu_h$: results (Belle preliminary)

**Expectations from MC**  
(obtained from 3 streams)

- $ee\pi$: $2.3 \pm 1.0$
- $\mu\mu\pi$: $2.3 \pm 0.9$
- $e\mu\pi + \mu e\pi$: $4.0 \pm 1.2$

**Results on data**

- $ee\pi$: $6 \pm 2.5$
- $\mu\mu\pi$: $2 \pm 1.4$
- $e\mu\pi + \mu e\pi$: $3 \pm 1.7$
$B \rightarrow \nu_h$: results (Belle preliminary)

- Upper limit on mixing in the mass range 0.5 – 5 GeV/c$^2$ was set
- Maximum sensitivity is reached around 2 GeV/c$^2$
- Upper limit for product branching fraction was set:
  \[ \mathcal{B}(B \rightarrow l\nu_h(X)) \times \mathcal{B}(\nu_h \rightarrow l\pi) < 6.6 \times 10^{-7} \text{ for } l = e, \mu \]
Summary

- Search for rare decays offers an opportunity to search for New Physics beyond the Standard Model
- In the clean environment of Belle a study of decays with neutrinos in the final state is possible using the full reconstruction
- No significant signal observed in $B^0 \rightarrow \nu \bar{\nu}$ and $B^0 \rightarrow h^{(*)} \nu \bar{\nu}$: upper limits were evaluated
- Search for heavy neutrinos was performed and limit on the mixing was set
Figure 1: Exemplary fully reconstructed event. The $B_{\text{sig}}$ (signal side) is the decay of physics interest, while the $B_{\text{tag}}$ (tag side) is the other $B$ meson, reconstructed by the full reconstruction method.
Full reconstruction

Figure 3: The 4 stages of the full reconstruction
Full reconstruction

(a) $B^+$ selection with roughly equal purity

(b) $B^+$ selection with roughly equal background level

(c) $B^+$ selection with roughly equal efficiency

(d) $B^0$ selection with roughly equal efficiency

Figure 2: M_{bc} plots for different selections. The dashed red line is the 3-$\sigma$ limit.
\[ B \rightarrow h^{(*)}\nu\bar{\nu} : \text{signal side selection} \]

- **\( B_{\text{tag}} \):**
  - Correct charge combination with the signal-side candidate
  - \( M_{bc} > 5.27 \text{ GeV} \)
  - \(-0.08 \text{ GeV} < \Delta E < 0.06 \text{ GeV} \)
  - \( B_{\text{TagNBout}} > 0.02 \)

- No remaining \( \pi^0 \) candidates or charged tracks

- Missing momentum: \(-0.86 < \cos \theta_{\text{miss}} < 0.95 \) (to avoid events with particles escaping through the beam pipe)

- Continuum supression: \(-0.8 < \cos TOB < 0.7 \) (angle between the thrust axis of the \( B_{\text{sig}} \) and the rest of the charged tracks)

- Momentum of the light meson: \( 1.6 \text{ GeV} < p < 2.5 \text{ GeV} \)
$B \rightarrow h(\ast)\nu\bar{\nu}$: number of events

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected total number of background events (Monte Carlo)</th>
<th>Observed number of events in data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow K^+\nu\bar{\nu}$</td>
<td>33.6 ± 2.7</td>
<td>43</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*+}\nu\bar{\nu}$</td>
<td>17.2 ± 1.9</td>
<td>21</td>
</tr>
<tr>
<td>$K^{*+} \rightarrow K^+\pi^0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*+}\nu\bar{\nu}$</td>
<td>2.4 ± 0.7</td>
<td>0</td>
</tr>
<tr>
<td>$K^{*+} \rightarrow K^0\pi^+$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^+ \rightarrow \pi^+\nu\bar{\nu}$</td>
<td>101, 4 ± 4.7</td>
<td>107</td>
</tr>
<tr>
<td>$B^+ \rightarrow \rho^+\nu\bar{\nu}$</td>
<td>117.0 ± 5.1</td>
<td>90</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^0_s\nu\bar{\nu}$</td>
<td>3.4 ± 0.9</td>
<td>4</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^{*0}\nu\bar{\nu}$</td>
<td>13.8 ± 1.7</td>
<td>10</td>
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<tr>
<td>$K^{*0} \rightarrow K^+\pi^-$</td>
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<tr>
<td>$B^0 \rightarrow \pi^0\nu\bar{\nu}$</td>
<td>7.3 ± 1.3</td>
<td>6</td>
</tr>
<tr>
<td>$B^0 \rightarrow \rho^0\nu\bar{\nu}$</td>
<td>33, 7 ± 2.7</td>
<td>31</td>
</tr>
<tr>
<td>$B^0 \rightarrow \phi\nu\bar{\nu}$</td>
<td>2.1 ± 0.6</td>
<td>3</td>
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</table>
$B \rightarrow h^{(*)} \nu \bar{\nu}$ signal efficiency

<table>
<thead>
<tr>
<th>Channel</th>
<th>branching fraction factor</th>
<th>$\epsilon_{sig}[10^{-5}]$ raw</th>
<th>averaged $B_{tag}$ correction</th>
<th>$\epsilon_{sig}[10^{-5}]$ final</th>
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</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow K^+ \nu \bar{\nu}$</td>
<td>-</td>
<td>71.6</td>
<td>0.79</td>
<td>56.76 ± 0.67</td>
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<tr>
<td>$B^+ \rightarrow K^{*+} \nu \bar{\nu}$</td>
<td>0.33</td>
<td>22.5</td>
<td>0.8</td>
<td>17.89 ± 0.66</td>
</tr>
<tr>
<td>$K^+ \pi^0$</td>
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</tr>
<tr>
<td>$B^+ \rightarrow K^{*+} \nu \bar{\nu}$</td>
<td>$0.692 \times 0.666 \times$</td>
<td>12.9</td>
<td>0.79</td>
<td>10.20 ± 0.60</td>
</tr>
<tr>
<td>$K_{s0} \pi^+$</td>
<td>0.5</td>
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<td>$B^+ \rightarrow \pi^+ \nu \bar{\nu}$</td>
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<td>42.3</td>
<td>0.8</td>
<td>33.8 ± 0.52</td>
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<tr>
<td>$B^+ \rightarrow \rho^+ \nu \bar{\nu}$</td>
<td>-</td>
<td>17.1</td>
<td>0.78</td>
<td>13.47 ± 0.32</td>
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<tr>
<td>$B^0 \rightarrow K_{s0} \nu \bar{\nu}$</td>
<td>0.692</td>
<td>11.93</td>
<td>0.70</td>
<td>8.36 ± 0.29</td>
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<tr>
<td>$B^0 \rightarrow K^{*0} \nu \bar{\nu}$</td>
<td>0.66</td>
<td>18.5</td>
<td>0.74</td>
<td>14.4 ± 0.40</td>
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<tr>
<td>$K^+ \pi^-$</td>
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<td></td>
</tr>
<tr>
<td>$B^0 \rightarrow \pi^0 \nu \bar{\nu}$</td>
<td>-</td>
<td>23.4</td>
<td>0.71</td>
<td>16.6 ± 0.34</td>
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<tr>
<td>$B^0 \rightarrow \rho^0 \nu \bar{\nu}$</td>
<td>-</td>
<td>8.8</td>
<td>0.72</td>
<td>6.34 ± 0.21</td>
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<tr>
<td>$B^0 \rightarrow \phi \nu \bar{\nu}$</td>
<td>0.492</td>
<td>7.9</td>
<td>0.73</td>
<td>5.77 ± 0.15</td>
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