$b \rightarrow s, d \nu \bar{\nu}$ FROM B-FACTORIES

KAI-FENG CHEN
NATIONAL TAIWAN UNIVERSITY
The FCNC $b \to s(d)\nu\nu$ processes only occur via $Z$-penguin or $W$-box diagrams.

The decay branching fractions in the Standard Model are small, but:

- Theoretically clean: absence of long distance effects.
- Loop processes are ideal places to look for new physics, e.g.
  - Light scalar dark matter;
  - MSSM through chargino or charged Higgs;
  - Extra dimensions;
  - Unparticle;
  - etc.

If any of these NP exists, we should observe a large boost on the $b \to s(d)\nu\nu$ branching fractions!
WANTED

$B$ mesons decaying into a kaon or a pion together with invisible neutrinos
Using a well-reconstructed $B$ meson as a "tag". Utilize the fact that the $B$ mesons are actually produced through $\Upsilon(4S)$ at $B$-factories. Invisible particles are not produced. Require **no particle** and **no energy** left after removing $B_{\text{tag}}$ and visible particles of $B_{\text{sig}}$ in the recoil system.
Belle: Fully reconstruct B mesons in one of the hadronic channels, e.g. $D^{(*)}\pi$, $D^{(*)}\rho$, $D^{(*)}a_1$, $D^{(*)}D_s^{(*)}$, etc.

BaBar: Full reconstruction with $D^{(*)} +$ many light hadrons (include hadrons up to 5 $K^+/\pi^+$, up to 2 $K_S$, and up to 2 $\pi^0$)

Pro: Higher purity, good resolution, full kinematics can be examined.

Con: Lower efficiency (can be as low as 0.1~<1%)

Identify the signal with $\Delta E$ and $M_{bc}/M_{ES}$
BaBar: Reconstruct a $B \rightarrow D^{(*)} l \nu$ decay with a clean $D^{(*)}$ meson plus a high momentum charged lepton.

Belle: Not implemented for this analysis yet.

**Pro:** Higher efficiency

**Con:** Lower purity, bad resolution, additional neutrino

Histograms are the MC distributions.
**KEY KINEMATICAL VARIABLES**

**Extra energy in calorimeter**
- The most powerful variable for separating signal and background.
- Sum up neutral clusters that are not associated with $B_{\text{tag}}$ and $B_{\text{sig}}$.
- Signal: zero or tiny extra energy from beam background.

**Momentum of visible $B_{\text{sig}}$ daughter(s)**
- Signal: large momentum according to the kinematic constraint of $b \rightarrow s(d)\nu\nu$.
- However, tight selection also reduces the sensitivity to the heavier invisible NP particles, e.g. dark matters.
BaBar has adopted some multi-variant analysis tools in order to improve the sensitivity for $K^+\nu\nu$ and $K^*\nu\nu$.

**Neutral network** is used in BaBar’s $B \rightarrow K^*\nu\nu$ hadronic tag analysis. These variables are included:
- $R_2$, $\cos\theta^*(B_{\text{tag}}, T)$,
- $E_{\text{miss}} + P_{\text{miss}}$, $\cos\theta_{\text{miss}}$, $M_{K^*}$, $M_{K_S}$, $E_{\text{Extra}}$

**Bagged decision tree** is introduced in $B \rightarrow K^+\nu\nu$ and $K^0\nu\nu$, total 26/38 variables included for $K^+/K^0$ leptonic tag analysis:
- Signal kinematics, tag qualities, missing qualities, event qualities, e.g.
- $E_{\text{Extra}}$, $P^*_{K}$, $\cos\theta^*_{K}$, $E_{\text{miss}}$, $P_{\text{miss}}$, ...
RESULTS TO BE SHOWN IN THIS PRESENTATION

<table>
<thead>
<tr>
<th>Particle</th>
<th>Belle</th>
<th>BaBar</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+\nu\nu$</td>
<td>&lt;1.4</td>
<td>&lt;1.3</td>
</tr>
<tr>
<td>$K^0\nu\nu$</td>
<td>&lt;5.6</td>
<td>&lt;16</td>
</tr>
<tr>
<td>$\pi^+\nu\nu$</td>
<td>&lt;1.3</td>
<td>&lt;11.7</td>
</tr>
<tr>
<td>$\pi^0\nu\nu$</td>
<td>&lt;10</td>
<td>&lt;22</td>
</tr>
<tr>
<td>$K^*^0\nu\nu$</td>
<td>&lt;12</td>
<td>&lt;34</td>
</tr>
<tr>
<td>$K^*+\nu\nu$</td>
<td>&lt;8</td>
<td>&lt;14</td>
</tr>
<tr>
<td>$\rho^0\nu\nu$</td>
<td>&lt;12</td>
<td>&lt;44</td>
</tr>
<tr>
<td>$\rho^+\nu\nu$</td>
<td>&lt;15</td>
<td>&lt;15</td>
</tr>
<tr>
<td>$\varphi^0\nu\nu$</td>
<td>&lt;5.8</td>
<td>&lt;15</td>
</tr>
<tr>
<td>invisible</td>
<td>&lt;22</td>
<td>&lt;22</td>
</tr>
<tr>
<td>$\gamma\nu\nu$</td>
<td>&lt;4.7</td>
<td>&lt;22</td>
</tr>
</tbody>
</table>

**References**

Belle Collaboration  

Babar Collaboration  
C. Vuosalo’s talk at LLWI’10  

Several non-$b\to s,d\nu\nu$ channels but with a similar analysis technique are also included.
$B \to K^+ \nu\nu$ & $K^0 \nu\nu$

<table>
<thead>
<tr>
<th></th>
<th>$N_{\text{obs}}$</th>
<th>$N_b$</th>
<th>U.L.</th>
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</thead>
<tbody>
<tr>
<td>$K^+ \nu\nu$</td>
<td>10</td>
<td>20.0±4.0</td>
<td>$&lt; 1.4 \times 10^{-5}$</td>
</tr>
<tr>
<td>$K^0 \nu\nu$</td>
<td>2</td>
<td>2.0±0.9</td>
<td>$&lt; 1.6 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

• Belle hadronic tag analysis with a robust cut-and-count method:

Expected signal x 20 (with SM BF ~ $4 \times 10^{-6}$ x 20)
**$B \rightarrow K^+ \nu \nu$ & $K^0 \nu \nu$**

- **BaBar semi-leptonic tag analysis with Bagged Decision Tree classifier:**

The most stringent limit to date, but it’s still 3x larger than the SM branching fraction.

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>$K^+ \nu \nu$ (high $P^*_K$)</td>
<td>19.4±4.4</td>
<td>17.6±2.8</td>
<td>$&lt; 1.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>$K^+ \nu \nu$ (low $P^*_K$)</td>
<td>164±13</td>
<td>187±47</td>
<td></td>
</tr>
<tr>
<td>$K^0 \nu \nu$</td>
<td>6.1 $^{+4.0}_{-2.2}$</td>
<td>3.9±1.4</td>
<td>$&lt; 5.6 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Ref. C. Vuosalo’s talk at LLWI’10

![Graphs showing data and background MC for $B^+ \rightarrow K^+ \nu \bar{\nu}$ and $K^0 S \nu \bar{\nu}$]
$B \rightarrow \pi^+ \nu \nu$

- **Belle/BaBar hadronic tag analysis**:

<table>
<thead>
<tr>
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<th>$N_b$</th>
<th>U.L.</th>
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</thead>
<tbody>
<tr>
<td><strong>Belle</strong></td>
<td>33</td>
<td>$25.9 \pm 3.9$</td>
<td>$&lt; 1.7 \times 10^{-4}$</td>
</tr>
<tr>
<td><strong>BaBar</strong></td>
<td>21</td>
<td>$24.1 \pm 3.6$</td>
<td>$&lt; 1.0 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
$B \rightarrow K^{*+} \nu \nu$ & $K^{*0} \nu \nu$

Belle hadronic tag analysis:

- Belle hadronic tag analysis:

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<th>$N_{\text{obs}}$</th>
<th>$N_b$</th>
<th>U.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^{*0} \nu \nu$</td>
<td>7</td>
<td>$4.2 \pm 1.4$</td>
<td>$&lt; 3.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$K^{*+} \nu \nu$</td>
<td>4</td>
<td>$5.6 \pm 1.8$</td>
<td>$&lt; 1.4 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
\( B \rightarrow K^{*+}\nu\nu \) & \( K^{*0}\nu\nu \)

- **BaBar semi-leptonic tag analysis:**

<table>
<thead>
<tr>
<th></th>
<th>Expected Yields</th>
<th>Fitted Yields</th>
<th>Semileptonic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N_s )</td>
<td>( N_b )</td>
<td>( N_s )</td>
</tr>
<tr>
<td>( K^{*+}(\rightarrow K^+\pi^0)\nu\nu )</td>
<td>3.31</td>
<td>697</td>
<td>-22 ±16</td>
</tr>
<tr>
<td>( K^{*+}(\rightarrow K_S\pi^+)\nu\nu )</td>
<td>2.54</td>
<td>827</td>
<td>3 ±17</td>
</tr>
<tr>
<td>( K^{*0}(\rightarrow K^+\pi^-)\nu\nu )</td>
<td>4.07</td>
<td>468</td>
<td>35 ±13</td>
</tr>
</tbody>
</table>
\[ B \rightarrow K^{*+}\nu\nu \ & \ K^{*0}\nu\nu \]

- \text{BaBar hadronic tag analysis with neural network:}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
 & Expected Yields & & & Fitted Yields & & \\
 & & & & & Hadronic & Combined \\
 & & & & & U.L. & U.L. \\
\hline
\hline
K^{*+}(\rightarrow K^+\pi^0)\nu\nu & 0.87 & 46 & & 5 \pm 6 \pm 4 & 39 \pm 9 & < 21 \times 10^{-5} & < 8 \times 10^{-5} \\
K^{*+}(\rightarrow K_S\pi^+)\nu\nu & 0.77 & 35 & & 3 \pm 7 \pm 4 & 51 \pm 10 & < 11 \times 10^{-5} & < 12 \times 10^{-5} \\
K^{*0}(\rightarrow K^+\pi^-)\nu\nu & 1.64 & 73 & & -10 \pm 9 \pm 6 & 77 \pm 13 & < 11 \times 10^{-5} & < 12 \times 10^{-5} \\
\hline
\end{tabular}
\end{table}
Small excess found (<2σ); Need more data to verify.

### Belle hadronic tag analysis:

<table>
<thead>
<tr>
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<th>N_{obs}</th>
<th>N_{b}</th>
<th>U.L.</th>
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</thead>
<tbody>
<tr>
<td>$\rho^+\nu\bar{\nu}$</td>
<td>15</td>
<td>17.8±3.2</td>
<td>&lt; 1.5 x 10^{-4}</td>
</tr>
<tr>
<td>$\rho^0\nu\bar{\nu}$</td>
<td>21</td>
<td>11.5±2.3</td>
<td>&lt; 4.4 x 10^{-4}</td>
</tr>
<tr>
<td>$\pi^0\nu\bar{\nu}$</td>
<td>11</td>
<td>3.8±1.3</td>
<td>&lt; 2.2 x 10^{-4}</td>
</tr>
<tr>
<td>$\phi\nu\bar{\nu}$</td>
<td>1</td>
<td>1.9±0.9</td>
<td>&lt; 5.8 x 10^{-5}</td>
</tr>
</tbody>
</table>
- BaBar semi-leptonic tag analysis.
- SM $B \rightarrow \nu\nu$ is predicted to be strongly suppressed by the factor of $(m_\nu/m_B)^2$, but NP may contribute to the final state of $B \rightarrow \text{invisible}$.
- BF($B \rightarrow \gamma \nu\nu$) is predicted to be around $10^{-9}$.

### Fitted Yields

<table>
<thead>
<tr>
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<th>$N_s$</th>
<th>$N_b$</th>
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</thead>
<tbody>
<tr>
<td>$B \rightarrow \text{invisible}$</td>
<td>17$^{\pm9}$</td>
<td>19$^{+10}_{-8}$</td>
<td>$&lt; 2.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>$B \rightarrow \gamma \nu\nu$</td>
<td>$-1.1^{+2.4}_{-1.9}$</td>
<td>28$^{+6}_{-5}$</td>
<td>$&lt; 4.7 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
The best experimental limits from B-factories for $b \to s \nu \nu$, $d \nu \nu$, and other similar decay channels are summarized.

Limits of $10^{-4} \sim 10^{-5}$ are approached based on large data sets with hadronic tags and/or semi-leptonic tags.

The current sensitivity is still below the expected SM branching fractions; but they can be probed with the upcoming super B factory experiment(s).

Any deviations from the prediction could provide a hint to the physics beyond the SM, e.g. unparticle, dark matter, etc.
TH Predictions from C.Bird, PRL 93, 201803 (2004)

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>BaBar (2005)</th>
<th>CLEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to K^+ \nu \nu$ limits included</td>
<td>$&lt; 1.4 \times 10^{-5}$</td>
<td>$&lt; 5.2 \times 10^{-5}$</td>
<td>$&lt; 2.4 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

The curvature is due to the lower bound on $P^*(K^+)$. Note: the BaBar 2010 limit is not shown since $P^*(K^+)$ is included in the bagged decision tree classifier.
Key factors for such searches for the future super B-factories:

- Large statistics, since the reconstruction efficiency of $B_{\text{tag}}$ is not high.
- Detector acceptance: as high as possible (smaller CM boost will also help) - this improves both $B_{\text{tag}}$ efficiency and background suppression.
- Lower beam background will improve the resolution, but higher luminosity is accompanied by large beam backgrounds.

Prospects for the Super B project (assuming 20-30% improvement on eff.)

Ref. arXiv:1008.1541
We can easily improve the limits on the light dark matter by simply adding more data.

Extra energy scaled to $10/\text{ab}$ data. Assuming the same performance of Belle detector.
Significant analysis improvement is foreseeable even BEFORE Super B-factories era:

- We are only reconstructing <1% of the total $B$ decays at this moment - a large room for improvement is still there.
- Not all of the analyses utilize the full power of hadronic+semi-leptonic tags.
- For example – new Belle hadronic tags:

Old Hadronic Tags:

$N(B^±) = 66237 ± 1107$

New Hadronic Tags:

$N(B^±) = 141676 ± 1713$

Efficiency versus Purity

\[\varepsilon = 0.34\% \text{ (new tag)}\]

\[\varepsilon = 0.16\% \text{ (old tag)}\]
BACKUP SLIDES
$B \rightarrow K^+\nu\nu \ \& \ K^0\nu\nu$

- BaBar semi-leptonic tag analysis with random forest:

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<th>U.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+\nu\nu$</td>
<td>38</td>
<td>31±12</td>
<td>$&lt; 4.5 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

**Expected Signal Shape**

**Background Prediction**

$D^0 \rightarrow K^{-}\pi^+$