Search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ decays with an inclusive tagging method at the Belle II experiment

55th Rencontres de Moriond
Electroweak Interactions & Unified Theories
March 24, 2021

Filippo Dattola on behalf of the Belle II Collaboration
The $B^+ \rightarrow K^+ \nu \bar{\nu}$ decay
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In the Standard Model:

- $b \rightarrow s \nu \bar{\nu}$ flavour-changing neutral-current transition;
- occurs at the loop level, suppressed by the extended GIM mechanism;
- clean theoretical prediction:

$$\text{BR}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}} = (4.6 \pm 0.5) \times 10^{-6}$$

[David M. Straub et al. Rare B decays as tests of the Standard Model]
The $B^+ \rightarrow K^+\nu\bar{\nu}$ decay

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Optimal measurement to probe the SM and to constrain scenarios beyond it.

A challenging measurement:

- decay with 2 neutrinos in the final state leaving no signature in the detector;
- can be measured at $B$ factories because of the clean event environment and the well defined initial state.
Filippo Dattola | Search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ decays with an inclusive tagging method at the Belle II experiment
SuperKEKB

- Asymmetric-energy $e^+e^-$ collider operating at $\sqrt{s} = 10.58$ GeV $\rightarrow Y(4S)$ resonance.

- Second generation B factory based on the **nanobeam scheme**: major upgrade of its predecessor KEKB.

- **World highest instantaneous luminosity**: $2.4 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ recorded in June 2020.

- Total integrated luminosity up to now (2021) $\sim 90$ fb$^{-1}$.  

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- **For this study:**
  - $63$ fb$^{-1}$ of data collected at $\sqrt{s} \rightarrow \Upsilon(4S)$ resonance $\sim 68$ million $B\bar{B}$ pairs.
  - $9$ fb$^{-1}$ of (off-resonance) data collected 60 MeV below the $\Upsilon(4S)$ resonance for background studies.

Filippo Dattola | Search for $B^+ \rightarrow K^+\nu\bar{\nu}$ decays with an inclusive tagging method at the Belle II experiment
The Belle II detector
The Belle II detector

New detector with respect to the predecessor Belle.

- **Electromagnetic Calorimeter ECL** (CsI(Tl) crystals)
- **KL and muon detector** (resistive plates and scintillators)
- **1.5T Magnet**
- **Electron (7 GeV)**
- **Positron (4 GeV)**
- **Vertex Detector** (pixels detector PXD and silicon strips detector)
- **Central Drift Chamber** (cylindrical wire chamber with 14336 sense wires)
- **Particle ID:**
  - Time-of-Propagation counter (barrel)
  - Aerogel RICH (fwd)
Previous searches for $B^+ \rightarrow K^+\nu\bar{\nu}$
Previous searches for $B^+ \rightarrow K^+ \nu \bar{\nu}$

The previous studies all adopted an explicit reconstruction of the B$_{\text{tag}}$
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Previous searches for $B^+ \rightarrow K^+ \nu \bar{\nu}$

The previous studies all adopted an explicit reconstruction of the $B_{\text{tag}}$ followed by the signal reconstruction.

$e^- \rightarrow \Upsilon(4S) \leftarrow e^+$

Hadronic reconstruction:
$B_{\text{tag}}^\pm \rightarrow$ hadrons

OR

Semileptonic reconstruction:
$B_{\text{tag}}^\pm \rightarrow D^{(*)} l \nu_l$
Previous searches for $B^+ \rightarrow K^+ \nu \bar{\nu}$

The previous studies all adopted an explicit reconstruction of the $B_{tag}$ followed by the signal reconstruction.

Low reconstruction efficiency because of the low tag-reconstruction efficiency:

- hadronic tag $\epsilon_{sig} \cdot \epsilon_{tag} \sim 0.04\%$
- semileptonic tag $\epsilon_{sig} \cdot \epsilon_{tag} \sim 0.2\%$

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Only upper limits on the branching ratios were set:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Year</th>
<th>Observed limit on $\text{BR}(B^+ \rightarrow K^+ \nu \bar{\nu})$</th>
<th>Approach</th>
<th>Data [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BABAR</td>
<td>2013</td>
<td>$&lt; 1.6 \times 10^{-5}$ [Phys.Rev.D87,112005]</td>
<td>$\text{SL + Had tag}$</td>
<td>429</td>
</tr>
<tr>
<td>Belle</td>
<td>2013</td>
<td>$&lt; 5.5 \times 10^{-5}$ [Phys.Rev.D87,111103(R)]</td>
<td>$\text{Had tag}$</td>
<td>711</td>
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<tr>
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</table>
The inclusive tagging

$B^+ \rightarrow K^+ \nu \bar{\nu}$
The inclusive tagging

The idea
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- Signal reconstructed as the highest $p_T$ track with at least 1 PXD hit (correct match $\sim 80\%$)
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- Signal reconstructed as the highest $p_T$ track with at least 1 PXD hit (correct match $\sim 80\%$) followed by inclusive reconstruction of the rest of the event (ROE).

$e^- \rightarrow \Upsilon(4S) \leftarrow e^+$

ROE: Remaining tracks and ECL clusters

Filippo Dattola | Search for $B^+ \rightarrow K^+\nu\bar{\nu}$ decays with an inclusive tagging method at the Belle II experiment
The inclusive tagging

The idea

- Signal reconstructed as the highest $p_T$ track with at least 1 PXD hit (correct match $\sim 80\%$) followed by inclusive reconstruction of the rest of the event (ROE).

- Higher signal efficiency $\epsilon_{\text{sig}} \sim 4\%$ but larger background contributions from generic $B$ decays and continuum production ($u\bar{u}, dd, c\bar{c}, s\bar{s}$).

$$\epsilon_{\text{sig}} \sim 4\%$$

$$p_T^\sim 80\%$$

$$\epsilon_{\text{sig}} \sim 4\%$$

The inclusive tagging method at the Belle II experiment

$e^- \rightarrow \Upsilon(4S) \leftarrow e^+$

$B_{\text{tag}}^\pm$

$B_{\text{sig}}^\pm$

ROE:
Remaining tracks
and ECL clusters

Filippo Dattola | Search for $B^+ \rightarrow K^+\nu\bar{\nu}$ decays with an inclusive tagging method at the Belle II experiment
Features of $B^+ \rightarrow K^+\nu\bar{\nu}$
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Signal identification exploiting topological features of $B^+ \rightarrow K^+\nu\bar{\nu}$
Features of $B^+ \rightarrow K^+ \nu \bar{\nu}$

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• For example the event shape:

$B \bar{B}$

$B(\rightarrow K \nu \bar{\nu}) \bar{B}$

$q \bar{q}$
Features of $B^+ \rightarrow K^+ \nu \bar{\nu}$

Signal identification exploiting topological features of $B^+ \rightarrow K^+ \nu \bar{\nu}$.

- For example the event shape:
  $B \bar{B} \quad B(\rightarrow K \nu \bar{\nu}) \bar{B} \quad q\bar{q}$

- But also:
  - other variables related to the event features;
  - variables related to the kinematics of the signal $K$ candidate;
  - variables related to the ROE;
  - variables related to the $D^0/D^+$ suppression.

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Multivariate classification
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51 well separating variables are used to train 2 consecutive binary classifiers (FastBDT) \( BDT_1 \) and \( BDT_2 \).
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- train $\text{BDT}_1$ on $1.6M$ signal events and
  $1.6M \times (B^+B^-, B^0\bar{B}^0, u\bar{u}, d\bar{d}, c\bar{c}, s\bar{s}, \tau^+\tau^-)$ events:
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**FIRST SIGNAL IDENTIFICATION**
**Multivariate classification**

51 well separating variables are used to train 2 consecutive binary classifiers (FastBDT) BDT$_1$ and BDT$_2$.

- train BDT$_1$ on 1.6M signal events and 1.6M \( (B^+B^-, B^0\bar{B}^0, u\bar{u}, d\bar{d}, c\bar{c}, s\bar{s}, \tau^+\tau^-) \) events:

**FIRST SIGNAL IDENTIFICATION**

- train BDT$_2$ - same features - on the events with BDT$_1 > 0.9$ among 100 fb$^{-1}$ events of generic background and 1.6M events of signal:
Multivariate classification

51 well separating variables are used to train 2 consecutive binary classifiers (FastBDT) BDT₁ and BDT₂.

• train BDT₁ on 1.6M signal events and 1.6M \times (B⁺B⁻, B⁰\bar{B}⁰, u\bar{u}, d\bar{d}, c\bar{c}, s\bar{s}, \tau^+\tau^-) events:

FIRST SIGNAL IDENTIFICATION

• train BDT₂ - same features - on the events with BDT₁ > 0.9 among 100 fb⁻¹ events of generic background and 1.6M events of signal:

IMPROVEMENT OF SIGNAL SENSITIVITY

(+10%, up to ~50%)

IN THE HIGH PURITY REGION
Multivariate classification

51 well separating variables are used to train 2 consecutive binary classifiers (FastBDT) $\text{BDT}_1$ and $\text{BDT}_2$.

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**IN THE HIGH PURITY REGION**
Definition of the fit region
Definition of the fit region

Optimised bin boundaries set up in the $p_T(K^+) \times $BDT$_2$ space:

![Graph](image_url)

$B^+ \to K^+\nu\bar{\nu}$
Definition of the fit region

Optimised bin boundaries set up in the $p_T(K^+) \times \text{BDT}_2$ space:

Bins 4, 5, 6, 7, 8, 9, 10:
Definition of the fit region

Optimised bin boundaries set up in the $p_T(K^+) \times BDT_2$ space:

Bins $4, 5, 6, 7, 8, 9, 10$:
- **Signal Region (SR)**: fit of data at the $\Upsilon(4S)$ resonance;
Definition of the fit region

Optimised bin boundaries set up in the $p_T(K^+) \times BDT_2$ space:

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Bins 1,2,3:
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Definition of the fit region

Optimised bin boundaries set up in the $p_T(K^+) \times \text{BDT}_2$ space:

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Bins $1, 2, 3$:
- Control Region 1 (CR1): fit of data at the $\Upsilon(4S)$ resonance;
- Control Region 3 (CR3): fit of off-resonance data.
**Definition of the fit region**

Optimised bin boundaries set up in the $p_T(K^+) \times BDT_2$ space:

<table>
<thead>
<tr>
<th>p_T(K^+) [GeV/c]</th>
<th>0.5</th>
<th>2.0</th>
<th>2.4</th>
<th>3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDT_2</td>
<td>0.93</td>
<td>0.95</td>
<td>0.97</td>
<td>0.99</td>
</tr>
<tr>
<td>Bins 1,2,3:</td>
<td></td>
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<tr>
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<td>9</td>
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<td>4</td>
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<td></td>
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</tbody>
</table>

- **Signal Region (SR):** fit of data at the $\Upsilon(4S)$ resonance;
- **Control Region 2 (CR2):** fit of off-resonance data.

Control Region 1-2-3 to constrain bkg’s yields.
Validation using $B^+ \rightarrow K^+ J/\psi \rightarrow \mu^+ \mu^-$
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Mode with large branching ratio characterised by clean experimental signature.
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Identification of $B^+ \rightarrow K^+ J/\psi \rightarrow \mu^+ \mu^-$ events
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Strategy to mimic reconstructed $B^+ \rightarrow K^+ \bar{\nu} \bar{\nu}$ events.
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**Identification of $B^+ \rightarrow K^+ J/\psi \rightarrow \mu^+ \mu^-$ events**

Strategy to mimic reconstructed $B^+ \rightarrow K^+ \nu \bar{\nu}$ events.

- Ignore the $\mu^+ \mu^-$ from the selected $J/\psi$ decay.
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Mode with large branching ratio characterised by clean experimental signature.

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Strategy to mimic reconstructed \( B^+ \rightarrow K^+\nu\bar{\nu} \) events.

- Ignore the \( \mu^+\mu^- \) from the selected \( J/\psi \) decay.

- 2-body \( \rightarrow \) 3-body kinematics: replace the 4-momentum of the \( K^+ \) with the generator-level 4-momentum taken from the \( K^+ \) in \( B^+ \rightarrow K^+\nu\bar{\nu} \).
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- Reconstruct the modified \( B^+ \rightarrow K^+ J/\psi \rightarrow \mu^+ \mu^- \) events with the inclusive tagging algorithm.
Validation using $B^+ \rightarrow K^+ J/\psi \rightarrow \mu^+ \mu^-$

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Validation using $B^+ \rightarrow K^+J/\psi_{\mu^+\mu^-}$

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Excellent Data-MC agreement for the BDT's.

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Validation using off-resonance data
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Investigation of the Data-MC agreement between simulated continuum and off-resonance data in CR2-CR3.
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Investigation of the Data-MC agreement between simulated continuum and off-resonance data in CR2-CR3.

- Very good Data–MC shape agreement.
Validation using off–resonance data


- Very good Data–MC shape agreement.
- But discrepancy in yields: data/simulation = 1.4 ± 0.1
Validation using off-resonance data


• Very good Data–MC shape agreement.
• But discrepancy in yields: data/simulation = 1.4 ± 0.1.
• Introduction of conservative 50% normalisation uncertainty in the fit for each bkg yield individually.
Fit procedure
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Statistical interpretation with statistical model for multi-bin histogram-based analysis.
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Statistical interpretation with statistical model for multi-bin histogram-based analysis.

Extended Maximum Likelihood Binned Fit:

\[ f(n, a | \eta, \chi) = \]

\( \eta = \text{parameter of interest} \)
\( \chi = \text{nuisance parameters} \)

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Statistical interpretation with statistical model for multi-bin histogram-based analysis.

Extended Maximum Likelihood Binned Fit:

$$f(n, a | \eta, \chi) = \prod_{r \in \text{regions}} \prod_{b \in \text{bins}} \text{Pois}(n_{cb} | \nu_{cb}(\eta, \chi))$$

Simultaneous measurements of multiple regions

$\eta = \text{parameter of interest}$

$\chi = \text{nuisance parameters}$
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\[ \eta = \text{parameter of interest} \]
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Regions = \{SR, CR1, CR2, CR3\}
Bins 1 to 12:

<table>
<thead>
<tr>
<th></th>
<th>10</th>
<th>11</th>
<th>12</th>
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Simultaneous measurements of multiple regions
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Simultaneous measurements of multiple regions

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<tr>
<th></th>
<th>10</th>
<th>11</th>
<th>12</th>
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</thead>
<tbody>
<tr>
<td>7</td>
<td>8</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

[Heinrich, Lukas and Feickert, Matthew and Stark, Giordon. pyhf:v0.5.4.]
Fit procedure

Statistical interpretation with statistical model for multi-bin histogram-based analysis.

Extended Maximum Likelihood Binned Fit:

\[
f(n, a | \eta, \chi) = \prod_{r \in \text{regions}} \prod_{b \in \text{bins}} \text{Pois}(n_{cb} | \nu_{cb}(\eta, \chi)) \prod_{\chi} c(\chi | \chi) \]

- Systematic uncertainties (normalisations of bkg’s yields, BR of the leading B-decays, PID correction, ...) as (175) nuisance parameters.
- **1 parameter of interest:** signal strength \( \mu \): multiplicative factor with respect to the SM expectation.

Regions = \{SR, CR1, CR2, CR3\}

Bins 1 to 12:

<table>
<thead>
<tr>
<th>BDT2</th>
<th>0.93</th>
<th>0.95</th>
<th>0.97</th>
<th>1.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>10</td>
<td>7</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>2.0</td>
<td>11</td>
<td>8</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>2.4</td>
<td>12</td>
<td>9</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( \mu = 1 \rightarrow \text{SM BF} = 4.6 \times 10^{-6} \)
Fit to the Data
Fit to the Data

• Profile likelihood scan for the signal strength $\mu$: 
Fit to the Data

• Profile likelihood scan for the signal strength $\mu$:

Asymmetric uncertainty on $\mu$ estimated by fitting the scanned points with an asymmetric parabola $f(x) = (x/\sigma^-)^2$ for $x < 0$ and $f(x) = (x/\sigma^+)^2$ for $x > 0$. 

Belle II preliminary
$\int \mathcal{L} dt = (63 + 9)$ fb$^{-1}$

Filippo Dattola | Search for $B^+ \rightarrow K^+\nu\bar{\nu}$ decays with an inclusive tagging method at the Belle II experiment
Fit to the Data

Fit to the Data

Fit to the Data

Fit to the Data

Fit to the Data

Fit to the Data

Fit to the Data

Fit to the Data

Fit to the Data
Fit to the Data

- Measured signal strength $\mu$:
Fit to the Data

• Measured signal strength $\mu$:

$$\mu = 4.2^{+2.9}_{-2.8}\text{(stat)}^{+1.8}_{-1.6}\text{(syst)} = 4.2^{+3.4}_{-3.2}$$

$$\text{BR}(B^+ \to K^+\nu\bar{\nu}) = 1.9^{+1.3}_{-1.3}\text{(stat)}^{+0.8}_{-0.7}\text{(syst)} \times 10^{-5} = 1.9^{+1.6}_{-1.5} \times 10^{-5}$$
Fit to the Data

- Measured signal strength $\mu$:

$$\mu = 4.2^{+2.9}_{-2.8} (\text{stat})^{+1.8}_{-1.6} (\text{syst}) = 4.2^{+3.4}_{-3.2}$$

$$\text{BR}(B^+ \rightarrow K^+ \nu \bar{\nu}) = 1.9^{+1.3}_{-1.3} (\text{stat})^{+0.8}_{-0.7} (\text{syst}) \times 10^{-5} = 1.9^{+1.6}_{-1.5} \times 10^{-5}$$

- Consistent with the SM expectation ($\mu = 1$) at CL = 1σ.
Fit to the Data

- Measured signal strength $\mu$:

$$\mu = 4.2^{+2.9}_{-2.8}^{(\text{stat})}^{+1.8}_{-1.6}^{(\text{syst})} = 4.2^{+3.4}_{-3.2}$$

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- Consistent with the SM expectation ($\mu = 1$) at $\text{CL} = 1\sigma$.
- Consistent with the bkg-only hypothesis ($\mu = 0$) at $\text{CL} = 1.3\sigma$. 
Fit to the Data

- Measured signal strength $\mu$:

$$\mu = 4.2^{+2.9}_{-2.8}\text{(stat)}^{+1.8}_{-1.6}\text{(syst)} = 4.2^{+3.4}_{-3.2}$$

$$\text{BR}(B^+ \to K^+\nu\bar{\nu}) = 1.9^{+1.3}_{-1.3}\text{(stat)}^{+0.8}_{-0.7}\text{(syst)} \times 10^{-5} = 1.9^{+1.6}_{-1.5} \times 10^{-5}$$

- Consistent with the SM expectation ($\mu = 1$) at CL = 1$\sigma$.
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Filippo Dattola | Search for $B^+ \to K^+\nu\bar{\nu}$ decays with an inclusive tagging method at the Belle II experiment
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$$\mu = 4.2^{+2.9}_{-2.8} \text{(stat)}^{+1.8}_{-1.6} \text{(syst)} = 4.2^{+3.4}_{-3.2}$$

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- Consistent with the SM expectation ($\mu = 1$) at CL = $1\sigma$.
- Consistent with the bkg-only hypothesis ($\mu = 0$) at CL = $1.3\sigma$. 

![CLs upper limit scan](image1.png)

![Data vs post-fit predictions in CR1 + SR](image2.png)
Measurement summary
Measurement summary

• This measurement represents the first search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ performed with an inclusive tag.
Measurement summary

• This measurement represents the first search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ performed with an inclusive tag.

• No signal observed yet, but an observed upper limit on the branching ratio of $4.1 \times 10^{-5}$ is set at the 90% CL.
Measurement summary

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- With 63 fb$^{-1}$ of $\Upsilon(4S)$ data recorded by the Belle II experiment, the inclusive tagging is competitive with the previous searches despite the much lower integrated luminosity.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Year</th>
<th>Observed limit on BR($B^+ \rightarrow K^+ \nu \bar{\nu}$)</th>
<th>Approach</th>
<th>Data [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BABAR</td>
<td>2013</td>
<td>$&lt; 1.6 \times 10^{-5}$ [Phys.Rev.D87,112005]</td>
<td>SL + Had tag</td>
<td>429</td>
</tr>
<tr>
<td>Belle</td>
<td>2013</td>
<td>$&lt; 5.5 \times 10^{-5}$ [Phys.Rev.D87,111103(R)]</td>
<td>Had tag</td>
<td>711</td>
</tr>
<tr>
<td>Belle</td>
<td>2017</td>
<td>$&lt; 1.9 \times 10^{-5}$ [Phys.Rev.D96,091101(R)]</td>
<td>SL tag</td>
<td>711</td>
</tr>
<tr>
<td>Belle II</td>
<td>2021</td>
<td>$&lt; 4.1 \times 10^{-5}$</td>
<td>Inclusive tag</td>
<td>63</td>
</tr>
</tbody>
</table>
Measurement summary

- This measurement represents the **first search for** $B^+ \rightarrow K^+ \nu \bar{\nu}$ performed with an inclusive tag.

- **No signal observed yet, but an observed upper limit on the branching ratio of** $4.1 \times 10^{-5}$ **is set at the 90% CL.**

- With 63 fb$^{-1}$ of $\Upsilon(4S)$ data recorded by the Belle II experiment, the inclusive tagging is **competitive with the previous searches despite the much lower integrated luminosity.**

![Graph showing comparison between SM, Average, and different experiments]

$10^5 \times \text{Br}(B^+ \rightarrow K^+ \nu \bar{\nu})$

Filippo Dattola | Search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ decays with an inclusive tagging method at the Belle II experiment
Supplemental material
Summary of the $B^+ \rightarrow K^+ \nu\bar{\nu}$ searches

- Uncertainty on BR: Belle II vs Belle vs Babar.
  - BR: measured branching ratio of $B^+ \rightarrow K^+ \nu\bar{\nu}$;
  - $\sigma$: total symmetric uncertainty on the BR
  - L: integrated luminosity

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Year</th>
<th>Approach</th>
<th>L [fb$^{-1}$]</th>
<th>BR [$\times 10^{-5}$]</th>
<th>$\sigma$ [$\times 10^{-5}$]</th>
<th>$\sqrt{\frac{L}{L_{\text{Belle2}}}}$ [$\times 10^{-5}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BABAR(*)</td>
<td>2013</td>
<td>SL + Had tag</td>
<td>429</td>
<td>0.8</td>
<td>0.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Belle(***)</td>
<td>2013</td>
<td>Had tag</td>
<td>711</td>
<td>3.0</td>
<td>1.6</td>
<td>5.5</td>
</tr>
<tr>
<td>Belle(***)</td>
<td>2017</td>
<td>SL tag</td>
<td>711</td>
<td>1.0</td>
<td>0.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Belle II</td>
<td>2021</td>
<td>Inclusive tag</td>
<td>63</td>
<td>1.9</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

(*) Combined central value of $B^+ \rightarrow K^+ \nu\bar{\nu}$ / $B^0 \rightarrow K^0 \nu\bar{\nu}$

(**) Computed from $N_{\text{sig}}/(c_{\text{sig}} \cdot N_{\text{BB}})$. 

BABAR 2013 - [Phys.Rev.D87,112005]
Belle 2013 - [Phys.Rev.D87,111103(R)]
Belle 2017 - [Phys.Rev.D96,091101(R)]
The $B^+ \to K^+ \nu \bar{\nu}$ decay

Scenarios beyond the SM $\to$ possible contribution of right-handed operators $Q^l_R$

$$\mathcal{H}_{\text{eff.}} = -\frac{4 G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_l (C^l_L Q^l_L + C^l_R Q^l_R) \quad \text{where} \quad Q^l_{L(R)} = \left( \bar{s}_{L(R)} \gamma_\mu b_{L(R)} \right) \left( \bar{\nu}^l_{L(R)} \gamma^\mu \nu^l_{L(R)} \right) \quad l = e, \mu, \tau$$

2 combinations of 6 Wilson Coefficients:

$$\begin{align*}
\frac{\text{Br}(B \to K \nu \bar{\nu})}{\text{Br}(B \to K \nu \bar{\nu})_{\text{SM}}} &= \frac{1}{3} \sum_\ell (1 - 2 \eta_\ell) \epsilon^2_\ell, \\
\frac{\text{Br}(B \to K^* \nu \bar{\nu})}{\text{Br}(B \to K^* \nu \bar{\nu})_{\text{SM}}} &= \frac{1}{3} \sum_\ell (1 + \kappa_\ell \eta_\ell) \epsilon^2_\ell, \\
\epsilon_\ell &= \sqrt{|C^\ell_L|^2 + |C^\ell_R|^2} / |C^\text{SM}_L|, \\
\eta_\ell &= -\text{Re} \left( C^\ell_L C^\ell_R^* \right) / |C^\ell_L|^2 + |C^\ell_R|^2.
\end{align*}$$

Constraint on new-physics contributions: Wilson coefficients $C^\text{NP}_L$ and $C^\text{NP}_R$ normalised to the SM value of $C_L$ (Belle II from expected 50 ab$^{-1}$).
• Peak luminosity projections:

• Nano-beam scheme:

Filippo Dattola | Search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ decays with an inclusive tagging method at the Belle II experiment
Features of $B^+ \rightarrow K^+\nu\bar{\nu}$

- Number of reconstructed tracks in the event.
Features of $B^+ \rightarrow K^+ \nu \bar{\nu}$

• Variables related to the signal $K^+$ candidate.

• Variables related to the event topology.

Filippo Dattola | Search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ decays with an inclusive tagging method at the Belle II experiment
Features of $B^+ \rightarrow K^+\nu\bar{\nu}$

- Variables related to $D^0/D^+$ suppression.

- Variables related to the ROE.
More on multivariate classification

- No overfitting observed neither for BDT1 nor for BDT2.

- Signal sensitivity of BDT1:
Reweighting of continuum MC

Discrepancies between simulated continuum and off-resonance data.

**Data-driven correction** by means of an additional fastBDT: BDT\(_c\).

- Select simulated continuum (100 fb\(^{-1}\)) with BDT\(_1\) > 0.9;
- Select off-resonance data (9 fb\(^{-1}\)) with BDT\(_1\) > 0.9;
- Train BDT\(_c\) with the set of 51 variables using data as signal and simulation as bkg;
- Being \(p\) the BDT\(_c\) score, apply the event weight
  \[ w_{\text{event}} = \frac{P(\text{Data} - \text{like})}{P(\text{MC} - \text{like})} \]
  to correct the simulated continuum.

**Before reweighting:** no perfect overlap at 0.5 \(\rightarrow\) mismodelling.

**Protection against large weights:** clipping at \(w = 10\)

Continuum MC yields scaled up to Data of normalisation ratio 1.22

Filippo Dattola | Search for \(B^+ \rightarrow K^+ \nu \bar{\nu}\) decays with an inclusive tagging method at the Belle II experiment
The fit region

- 1 signal region + 3 control regions.

**Bin boundaries in the SR** specifically optimised by minimisation of the expected upper limit on the BR($B^+ \rightarrow K^+\nu\bar{\nu}$).

<table>
<thead>
<tr>
<th>Region</th>
<th>2D Bin Boundary Definition</th>
<th>Physics Processes</th>
<th>$\sqrt{s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Region</td>
<td>$p_T(K^+) \in [0.5, 2.0, 2.4, 3.5]$ GeV/c</td>
<td>signal + all backgrounds</td>
<td>T (4S)</td>
</tr>
<tr>
<td>Control Region</td>
<td>$BDT_2 \leq 0.95, 0.97, 0.99, 1.0$</td>
<td>signal + all backgrounds</td>
<td>T (4S)</td>
</tr>
<tr>
<td>Region (SR)</td>
<td>$p_T(K^+) \in [0.5, 2.0, 2.4, 3.5]$ GeV/c</td>
<td>continuum backgrounds</td>
<td>off-resonance (60 MeV/c²)</td>
</tr>
<tr>
<td>Control Region</td>
<td>$BDT_2 \leq 0.95, 0.97, 0.99, 1.0$</td>
<td>continuum backgrounds</td>
<td>off-resonance (60 MeV/c²)</td>
</tr>
<tr>
<td>Region 1 (CR1)</td>
<td>$p_T(K^+) \in [0.5, 2.0, 2.4, 3.5]$ GeV/c</td>
<td>continuum backgrounds</td>
<td></td>
</tr>
<tr>
<td>Control Region</td>
<td>$BDT_2 \leq 0.95, 0.97, 0.99, 1.0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Region 2 (CR2)</td>
<td>$p_T(K^+) \in [0.5, 2.0, 2.4, 3.5]$ GeV/c</td>
<td>continuum backgrounds</td>
<td></td>
</tr>
<tr>
<td>Control Region</td>
<td>$BDT_2 \leq 0.95, 0.97, 0.99, 1.0$</td>
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</tr>
<tr>
<td>Region 3 (CR3)</td>
<td>$p_T(K^+) \in [0.5, 2.0, 2.4, 3.5]$ GeV/c</td>
<td>continuum backgrounds</td>
<td></td>
</tr>
<tr>
<td>Control Region</td>
<td>$BDT_2 \leq 0.95, 0.97, 0.99, 1.0$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Signal efficiency in SR**

By stat. uncertainty

$N_{\text{rec}}/N_{\text{gen}}$ [%]

$q^2 \left[ \text{GeV}^2/c^4 \right] = (p_\nu^2 + p_{\bar{\nu}}^2)$

Filippo Dattola | Search for $B^+ \rightarrow K^+\nu\bar{\nu}$ decays with an inclusive tagging method at the Belle II experiment
Identification of $B^+ \rightarrow K^+J/\psi \rightarrow \mu^+\mu^-$ events

$M_{\mu\mu} \text{ [GeV/c}^2\text{]}$

$M_{bc} \text{ [GeV/c}^2\text{]}$

$\Delta E \text{ [GeV]}$

$M_{bc} = \sqrt{E_{\text{beam}}^2 - (\vec{P}_B^{\text{CMS}})^2}$

$\Delta E = \sum_i E_i^{\text{CMS}} - E_{\text{beam}}$

1720 data events from 63 fb$^{-1}$ + bkg suppressed to percent level.
Results of the validation on $B^+ \rightarrow K^+ J/\psi \rightarrow \mu^+ \mu^-$

Filippo Dattola | Search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ decays with an inclusive tagging method at the Belle II experiment
Background composition in the fit region

- $B^0\bar{B}^0$ signal side:

- $B^0\bar{B}^0$ tag side:

- $B^+B^-$ signal side:

- $B^+\bar{B}^-$ tag side:

Filippo Dattola | Search for $B^+ \rightarrow K^+\nu\bar{\nu}$ decays with an inclusive tagging method at the Belle II experiment
Validation in the BDT sideband

- Agreement between Y(4S) on-resonance data and simulation in the sideband $0.9 < \text{BDT}_1 < 0.99$ and $\text{BDT}_2 < 0.7$:

- Only if the continuum background is scaled by a factor of 1.22 as obtained from the comparison with off-resonance data, the data/MC ratio is then 1.00 in the moderate BDT sideband.
SM form factor vs $q^2$

- $q^2$ spectrum from PHSP simulation compared to the SM form factor from [J. High Energ. Phys. 2015, 184 (2015)] as a function of $q^2$. 

---

Filippo Dattola | Search for $B^+ \rightarrow K^+\nu\bar{\nu}$ decays with an inclusive tagging method at the Belle II experiment
Fit procedure

- **pyhf modifiers and constraints:**

\[
\nu_{cb}(\phi) = \sum_{s \in \text{samples}} \nu_{scb}(\eta, \chi) = \sum_{s \in \text{samples}} \left( \prod_{\kappa \in \kappa} \kappa_{scb}(\eta, \chi) \right) \left[ \nu_{scb}^0(\eta, \chi) + \sum_{\Delta \in \Delta} \Delta_{scb}(\eta, \chi) \right].
\]

<table>
<thead>
<tr>
<th>Description</th>
<th>Modification</th>
<th>Constraint Term $c_{\chi}$</th>
<th>Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrelated Shape</td>
<td>$\kappa_{scb}(\gamma_b) = \gamma_b$</td>
<td>$\prod_b \text{Pois} \left( r_b = \sigma_b^{-2}</td>
<td>\rho_b = \sigma_b^{-2} \gamma_b \right)$</td>
</tr>
<tr>
<td>Correlated Shape</td>
<td>$\Delta_{scb}(\alpha) = f_p \left( \alpha</td>
<td>\Delta_{scb,\alpha=-1}, \Delta_{scb,\alpha=1} \right)$</td>
<td>$\text{Gaus} \left( \alpha = 0</td>
</tr>
<tr>
<td>Normalisation Unc.</td>
<td>$\kappa_{scb}(\alpha) = g_p \left( \alpha</td>
<td>\kappa_{scb,\alpha=-1}, \kappa_{scb,\alpha=1} \right)$</td>
<td>$\text{Gaus} \left( \alpha = 0</td>
</tr>
<tr>
<td>MC Stat. Uncertainty</td>
<td>$\kappa_{scb}(\gamma_b) = \gamma_b$</td>
<td>$\prod_b \text{Gaus} \left( \sigma_{\gamma_b} = 1</td>
<td>\gamma_b, \delta_b \right)$</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$\kappa_{scb}(\lambda) = \lambda$</td>
<td>$\text{Gaus} \left( \ell = \lambda_0</td>
<td>\lambda, \sigma_\lambda \right)$</td>
</tr>
<tr>
<td>Normalisation</td>
<td>$\kappa_{scb}(\mu_0) = \mu_0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data-driven Shape</td>
<td>$\kappa_{scb}(\tau_b) = \tau_b$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fit validation

- **Test with injected signal:**
  
  Check the pulls \( \frac{\mu_{\text{fit}} - \mu_{\text{inj}}}{\sigma_{\mu}} \)

- **Test the fit quality:**
  
  Check the p-value of the fit on observations

---

No biases observed ✔

High p-value ✔
Good agreement with \( \chi^2 \) ✔

Filippo Dattola | Search for \( B^+ \rightarrow K^+\nu\bar{\nu} \) decays with an inclusive tagging method at the Belle II experiment
Cross validation of PyHf with a simplified Gaussian model

![Graph showing the cross validation of PyHf with a simplified Gaussian model. The graph compares the mu values from PyHf and sghf for different mu_s values.](image)

- $\mu_{\text{sig}} = 1.0$
- $\mu_{\text{sig}} = 5.0$
- $\mu_{\text{sig}} = 20.0$

Belle II preliminary simulation
Fit to the Data

• Post-fit shifts of the bkg’s normalisations.

- 50% pre-fit uncertainty attached to each of the bkg's normalisations.

- No post-fit shift wrt to expectations for $B^+B^-$ and $B^0\bar{B}^0$ that are the larger bkg’s.

- Post-fit shift of $\sim 1\sigma$ wrt to the expectations for some continuum sources ($c\bar{c}, s\bar{s}$) consistent with the observed Data-MC normalisation discrepancy.
**Fit to the Data**

- Post-fit predictions for continuum vs off-resonance data.
Fit to the Data

- Correlation of post-fit shifts of the bkg’s normalisations.

![Correlation Matrix](image)

Belle II preliminary

\[ \int L \, dt = (63 + 9) \text{ fb}^{-1} \]
Limit vs uncertainties

Belle II preliminary simulation

Gaussian 90% c.l. $\times 10^{-5}$