Search for $B^\pm \rightarrow K^\pm \nu \bar{\nu}$ and other electroweak/radiative penguin processes at Belle II

EPS-HEP 2021

Simon Kurz on behalf of the Belle II collaboration
July 26-30, 2021
**SuperKEKB**

*B-Factory for the Belle II Experiment*

Asymmetric e⁺e⁻ *B*-factory to study
CP-violation and rare decays

- \( E_{cm} = m(\Upsilon(4S)) = 10.58 \text{ GeV} \)
- >96% decay to \( B\bar{B} \)
- Forward boost of \( B\bar{B} \) system

Set world record: highest instantaneous luminosity of \( L = 3.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)

- Total recorded luminosity of 213.49 fb⁻¹
  until summer shutdown
- Target: 50 ab⁻¹ (50x Belle)

63 fb⁻¹ used by the presented analyses (until summer 2020)

... and 9 fb⁻¹ of off-resonance data (60 MeV below \( \Upsilon(4S) \))
The Belle II Detector

A significant upgrade

New detector design motivated by high inst. luminosity and its challenges

The Belle II Detector

150°

EM Calorimeter

Kμ-Muon Detector

17°

e^− (7 GeV)

e^+ (4 GeV)

solenoid @ 1.5T

Central Drift Chamber

Barrel and Forward Particle ID Detector

Vertex Detectors

taken from C. Marinas
**Overview and First Results**

**Observation of** $B \to X_s \gamma$ **decays** [Belle2-NOTE-PL-2021-004]

- FCNC $b \to s \gamma$ transition sensitive to many SM extensions
- Measure inclusive photon energy spectrum
  - Expect monochromatic (smeared) photon spectrum with $E_\gamma^* > 1.4$ GeV

**In a Nutshell**
(of course, there are more subtleties)

1. Simple selection requirements
2. Designated $\pi^0$ and $\eta$ veto
3. Suppression of continuum background
   (BDT using event-shape variables)
4. Subtract expected contributions from continuum and $B$ backgrounds from data
   (using off-resonance data and sidebands)
5. Excess clearly visible in expected region

**Measurement with more data in preparation!**
Overview and First Results

Study of $B^\pm \rightarrow K^\pm \ell^+ \ell^-$  BELLE2-NOTE-PL-2020-014

• Important to have independent measurement of **FCNC decay** $B^\pm \rightarrow K^\pm \ell^+ \ell^-$ (with $\ell = e, \mu$) to shed more light onto results from LHCb arXiv:2103.11769 (submitted to Nature Physics)

• **Rediscovery** of $B^\pm \rightarrow K^\pm \ell^+ \ell^-$:

---

**Observed** $8.6^{+4.3}_{-3.9} \pm 0.4$ (stat./syst.) signal events in 2D fit ($M_{bc}$, $\Delta E$)

$$M_{bc} = \sqrt{s/(4c^4) - p_B^*^2/c^2}$$

$$\Delta E = E_B^* - \sqrt{s/2}$$

---

• Available data not enough to determine key observables like branching fraction, isospin asymmetry, $R_K$ (ratio of BRs of muon and electron channel)
  • Prepare/rehearse analysis using $B \rightarrow J/\Psi(\ell^+ \ell^-) K$ (with $K = K^\pm, K_S^0$) control sample (same final state but large BR)
What we can already do…

Search for $B^{\pm} \rightarrow K^{\pm}\nu\bar{\nu}$ arXiv:2104.12624

- Complementary probe of BSM physics scenarios proposed to explain anomalies observed in $b \rightarrow s\ell\bar{\ell}$ transitions arXiv:2005.03734, including recent measurement of $R_K$ by LHCb arXiv:2103.11769 (submitted to Nature Physics)

- … but does not suffer from charm-loop contributions
  
  $\mathcal{B}(B^{\pm} \rightarrow K^{\pm}\nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$ arXiv:1606.00916
  
  (uncertainty dominated by $B \rightarrow K$ form factor, simulation weighted with FFs arXiv:1409.4557)

- Flavour-changing neutral current process $B^{\pm} \rightarrow K^{\pm}\nu\bar{\nu}$ not observed yet

- Many other BSM models can be constrained like dark matter PRD 98, 055003 (2018), leptoquarks PRD 102, 015023 (2020), axions PRD 101, 095006 (2020)
Analysis Strategy: Inclusive Tagging

Search for $B^\pm \rightarrow K^{\pm} \nu \bar{\nu}$ arXiv:2104.12624

• Previous searches explicitly reconstruct the second $B$ meson
  • semi-leptonic tag:
    signal efficiency of $\sim 0.2\%$
    (Belle, PRD 96, 091101 (2017))
  • hadronic tag:
    signal efficiency of $\sim 0.04\%$
    (BaBar, PRD 87, 112005 (2013))

• Idea: exploit distinct topology and kinematics to achieve higher signal efficiency ($\sim 4\%$)
  (rather spherical, missing energy, displaced kaon track,...)

Inclusive tagging

Semi-leptonic/hadronic tag
Overview

Search for $B^\pm \rightarrow K^\pm \nu \bar{\nu}$ arXiv:2104.12624

1. Basic event selection
   (mainly $4 \leq N_{\text{tracks}} \leq 10$)
2. Select highest $p_T$ track as signal
   kaon candidate
3. Train BDT to identify signal
   (topology, rest-of-event, missing
   energy, vertex separation, …)
4. Validate the BDT using data of
   $B^+ \rightarrow K^+ + J/\psi(\rightarrow \mu^+\mu^-)$ decays
   where the muons can be removed
   to mimic signal
5. Use off-resonance data (60 MeV
   below $\Upsilon(4S)$) to constrain yields
   from continuum processes ($q\bar{q}, \tau\bar{\tau}$)
6. Statistical interpretation
Training of Binary Event Classifier

Search for $B^\pm \rightarrow K^{\pm} \nu \bar{\nu}$ arXiv:2104.12624

- Select features for training of BDT:
  - excluded variables with little discrimination power or poor modelling in simulation
  - Resulting in 51 training variables

\[ \Delta E = E_B^* - \sqrt{s}/2 \quad (E^* \text{ of second } B \text{ meson}) \]

- Background: random combination of objects from both $B$ mesons, some objects might be missing

- R1: Momentum imbalance in the event, signal has neutrinos
Boosting to Signal Region

Search for $B^\pm \rightarrow K^\pm \nu \bar{\nu}$ arXiv:2104.12624

- **2-step procedure**: $\text{BDT}_1 \rightarrow \text{BDT}_2$
  - Train $\text{BDT}_1$ with **51 variables**
  - Select events with $\text{BDT}_1 > 0.9$ and train $\text{BDT}_2$ with larger sample (same training variables)
  - Significant improvement in discrimination power

- Define $2 \times 12$ regions in $\text{BDT}_2 \times p_T(K^+)$ space (on- and off-resonance data)
  - Important to constrain background yields in fit (see later)

Maximum sensitivity at $\text{BDT}_2 \gtrsim 0.95$

Signal Efficiency ~4.3% (SM signal)
Validation Channel: $B^+ \to K^+ + J/\psi(\to \mu^+\mu^-)$

Search for $B^\pm \to K^\pm \nu \bar{\nu}$ arXiv:2104.12624

• Compare response of BDTs in data and simulation:
  • Reconstruct $J/\psi$ from two muons and remove them to mimic signal neutrinos
  • Correct kaon momentum using simulated signal events (2- vs 3-body decay)

• High level of agreement:
  • Fraction of events in signal region ($\text{BDT}_2 > 0.95$, data/simulation) = $1.06 \pm 0.10$
Extraction of Signal Yields

Search for $B^\pm \rightarrow K^\pm \nu \bar{\nu}$ arXiv:2104.12624

Perform a binned maximum likelihood fit to extract signal strength $\mu$

- Templates for background and signal yields from simulation
- Systematic uncertainties included as nuisance parameters (event count modifiers)
- Leading systematic uncertainty: background normalisation of individual contributions

Yields after simultaneous fit of all 24 regions

Signal purity:
- 6\% for SR
- 22\% for $BDT_2 > 0.99$

On-resonance Data

Off-resonance Data

Factor wrt. SM expectation $(4.6 \times 10^{-6})$

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

Total uncertainty from profiled likelihood scan around minimum; statistical component derived using toys
Results

Search for $B^{\pm} \rightarrow K^{\pm} \nu\bar{\nu}$ arXiv:2104.12624

No signal observed; setting upper limit on BR using CLs method (assuming SM signal)

- $\mathcal{B}(B^{\pm} \rightarrow K^{\pm} \nu\bar{\nu}) < (4.1 \pm 0.5) \times 10^{-5}$ @ 90% CL
- For reinterpretation: signal efficiency as a function of the invariant mass of the dineutrino system

SM expectation: $\mathcal{B}(B^{\pm} \rightarrow K^{\pm} \nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$

\begin{itemize}
  \item When converted to the same luminosity, our measurement is better\(^*\) than semi-leptonic tagging by 10-20%
  \item … and than hadronic tagging by a factor 3.5!
\end{itemize}

\(^*\) assuming the total uncertainty on the branching-fraction scales with $1/\sqrt{L}$

Supplemental material arXiv:2104.12624
Summary

... interesting times are ahead of us!

• First excellent result with prospects prove the high capabilities of (relatively) new Belle II experiment

• Great performance of novel inclusive tagging used to study $B^\pm \rightarrow K^{\pm}\nu\bar{\nu}$ decays
  • Follow-up analysis in preparation:
    • more data (3x more on tape)
    • additional channels ($B^0 \rightarrow K^{*0}\nu\bar{\nu}$, $B^0 \rightarrow K^0_S\nu\bar{\nu}$)
    • improved technique (neural net)
  • Combination with results using semi-leptonic/hadronic tagging expected to further increase sensitivity (statistically independent events)
  • We may actually be able to observe $B^\pm \rightarrow K^{\pm}\nu\bar{\nu}$ soon for the first time!

Belle II is ready to look for new physics and make precision measurements of SM parameters
Signal Selection and Event Cleaning

Search for $B^\pm \rightarrow K^\pm \nu \bar{\nu}$

Signal $B$ has to be reconstructed as a single charged Kaon

- Select highest $p_T$ track in the event as Kaon candidate (correct match in 78% of signal events)
- Require at least 1 PXD hit on Kaon candidate track (ensures high resolution of the track impact parameter)

Basic event cleaning and background rejection

- Tracks
  \[ 0.1 \text{ GeV} < p_T, \quad |dz| < 3 \text{ cm}, \quad dr < 0.5 \text{ cm}, \quad \theta \text{ in CDC Acceptance} \]
- Photons
  \[ 0.1 \text{ GeV} < E_\gamma, \quad \theta \text{ in CDC Acceptance} \]
- All Objects
  \[ E < 5.5 \text{ GeV} \]
- Background rejection
  \[ 4 \leq N_{\text{tracks}} \leq 10, \quad E_{\text{visible}} > 5.5 \text{ GeV}, \quad 17^\circ < \theta_{\text{miss}} < 160^\circ \]
Input Variables: D0/D+ Suppression

Search for $B^\pm \rightarrow K^\pm \nu \bar{\nu}$

- Significant fraction of background events for the high purity region comes from D0/D+ decays
  - Dedicated variables to identify them
Boosting to Signal Region

Search for $B^\pm \rightarrow K^\pm \nu \bar{\nu}$

- **2-step procedure**: increase training statistics at high BDT values
  - Select events with $\text{BDT}_1 > 0.9$ and train $\text{BDT}_2$ with larger sample (same training variables)
  - Significant improvement in discrimination power

- Overfitting under control for both BDTs

- **Additional BDT used to correct modelling of continuum simulation**
  - BDT trained to distinguish off-resonance data from continuum simulation (and derive weights)
  - Same input variables as other BDTs

Maximum sensitivity at $\text{BDT}_2 \approx 0.95$
Definition of Signal and Control Regions

Search for $B^\pm \rightarrow K^{\pm}\nu\bar{\nu}$

- Define 24 Signal and Control Regions:
  - 12 regions in $\text{BDT}_2 \times p_T(K^\pm)$ space
  - Each defined in on- and off-resonance data
  - 9 SRs and 3+12 CRs to constrain background yields
  - Binning optimised for available integrated luminosity
  - Signal efficiency of 4.3% (for SM)

- Perform a binned maximum likelihood fit to extract signal strength $\mu$
  - Templates for background and signal yields from simulation
  - Systematic uncertainties included as nuisance parameters (event count modifiers)
  - Leading systematic uncertainty: background normalisation