



HELMHOLTZ RESEARCH FOR
GRAND CHALLENGES



Search for the rare electroweak decay $B^+ \rightarrow K^+ \nu \bar{\nu}$
in the early Belle II dataset
[2104.12624]

Cyrille Praz, *on behalf of the Belle II collaboration*

Phenomenology Symposium — 2021.05.26, Pittsburgh

Belle II talks at PHENO 2021

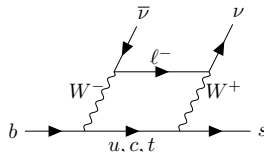
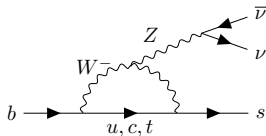
- Christoph Schwanda, *Beauty physics from Belle II*, [\[link\]](#).
- Soumen Halder, *Results and Prospects of Radiative and Electroweak Penguin Decays at Belle (II)*, [\[link\]](#).
- Güney Polat, *Tau physics prospects at Belle II*, [\[link\]](#).
- Katharina Dort, *Dark-sector physics at Belle II*, [\[link\]](#).
- Sebastiano Raiz, *Charmless B decays at Belle II*, [\[link\]](#).
- Chiara La Licata, *The re-discovery of the decays for the CP violation measurements*, [\[link\]](#).
- Cyrille Praz, *Search for the rare electroweak decay $B^+ \rightarrow K^+ \nu \bar{\nu}$ in the early Belle II dataset*, [\[link\]](#).

Outline

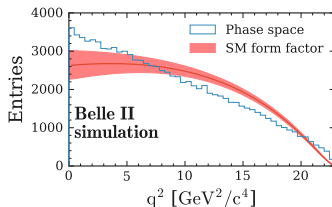
- 1 Theoretical motivation
- 2 The Belle II experiment
- 3 Search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ decays
 - Introduction
 - Binary classification
 - Signal-strength extraction
- 4 Conclusion and outlook

Branching fraction in the Standard Model

- $B^+ \rightarrow K^+ \nu \bar{\nu}$ is suppressed in the SM and has never been observed.



- $\text{BR}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}} = (4.6 \pm 0.5) \times 10^{-6}$ [1606.00916].
- 10% theoretical uncertainty mainly from $B \rightarrow K$ form factors.
- $B \rightarrow K$ form factors from [1409.4557] used for signal simulation.



Beyond the Standard Model

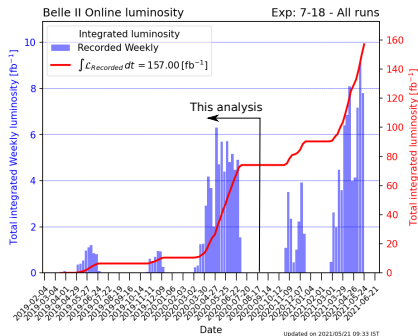
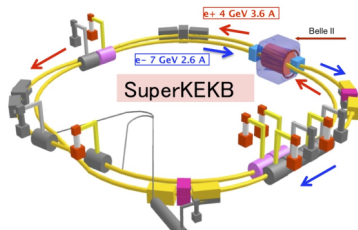
- Since ν_e , ν_μ and ν_τ contribute, $B^+ \rightarrow K^+ \nu \bar{\nu}$ is sensitive to potential lepton flavour universality violation.
- Complementary probe of BSM physics scenarios proposed to explain anomalies observed in $b \rightarrow s \ell^+ \ell^-$ transitions [\[2005.03734\]](#).
- Multiple models beyond the SM constrained by $\text{BR}(B^+ \rightarrow K^+ \nu \bar{\nu})$:
 - dark matter particles [\[1911.03490\]](#).
 - leptoquarks [\[1806.05689\]](#).
 - axions [\[2002.04623\]](#).
 - ...

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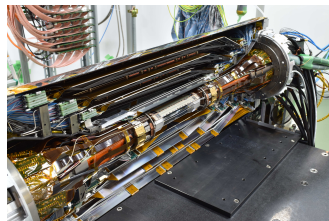
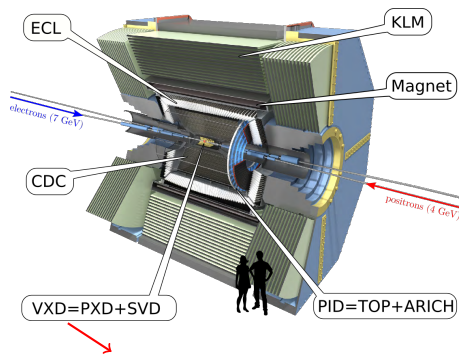
The SuperKEKB accelerator

- e^+e^- collider in Tsukuba, Japan.
- $\sqrt{s} = 10.6 \text{ GeV} = m(\Upsilon(4S))$.
- $\text{BR}(\Upsilon(4S) \rightarrow B\bar{B}) > 96\%$.
- $\int_{2019.02.04}^{2021.05.21} L dt \approx 157 \text{ fb}^{-1}$.
- World highest instant. luminosity.
 - $L = 2.96 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ achieved in May 2021.



The Belle II detector

- Pixel Detector (PXD).
- Silicon Vertex Detector (SVD).
- Central Drift Chamber (CDC).
- Calorimeter (ECL).
- Aerogel Ring-Imaging Cherenkov (ARICH).
- Time-Of-Propagation (TOP) counter.
- K_L^0 and μ detection (KLM).



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Data samples used for this analysis

- 63 fb^{-1} collected at $\sqrt{s} = m(\Upsilon(4S))$ ("on-resonance").
- 9 fb^{-1} collected at $\sqrt{s} = m(\Upsilon(4S)) - 60 \text{ MeV}$ ("off-resonance").

Signal and background after high-level trigger

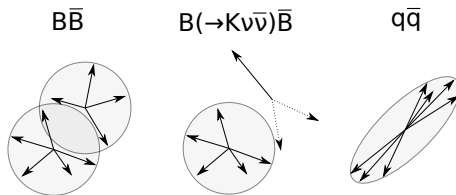
- Signal.

- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+(\rightarrow K^+\nu\bar{\nu})B^-$.

- Background.

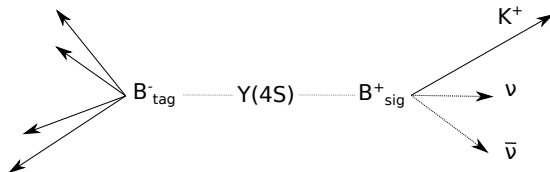
- Generic B -meson decays: $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+B^-$ or $B^0\bar{B}^0$.

- Continuum events: $e^+e^- \rightarrow q\bar{q}$ or $\tau^+\tau^-$ ($q = u, d, s, c$ quarks).



B -meson tagging

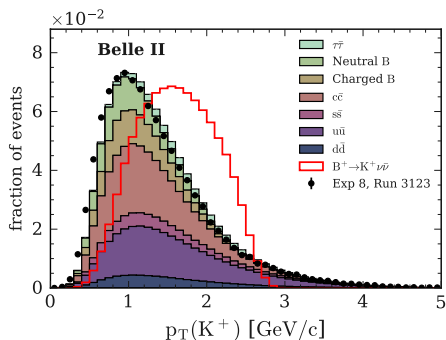
- Previous searches used tagged approaches, where the second B -meson is reconstructed...
 - ...in a hadronic decay: $\varepsilon_{\text{sig}} = \mathcal{O}(0.04\%)$ [1303.7465 (Babar)].
 - ...in a semileptonic decay: $\varepsilon_{\text{sig}} = \mathcal{O}(0.2\%)$ [1702.03224 (Belle)].



- In the following, an inclusive tagging approach is used.
 - No explicit reconstruction of the second B -meson.
 - Exploitation of the distinctive topological features of $B^+ \rightarrow K^+ \nu \bar{\nu}$.

Signal kaon candidate selection

- Highest- p_T track in event as K^+ candidate.
 - Correct candidate in 80% of the cases.
 - PID requirement to suppress pion background.

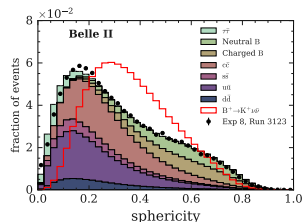
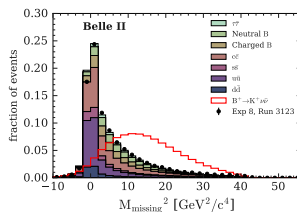
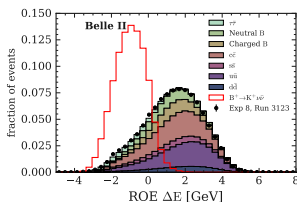
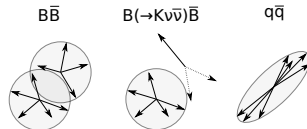


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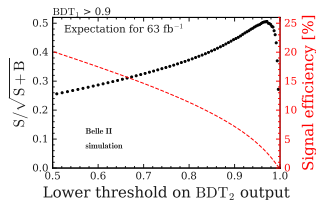
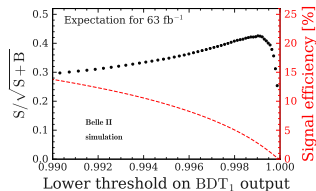
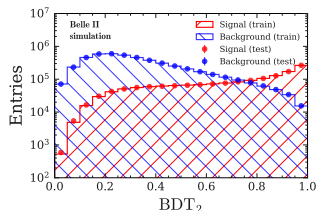
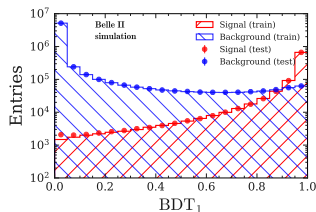
Features

- Boosted decision trees (BDT) [1609.06119] trained with 51 features.
 - Event topology (Fox-Wolfram moments, sphericity, ...).
 - Rest-of-event (ROE) variables.
 - Missing energy, momentum.
 - Vertex separation.
 - ...



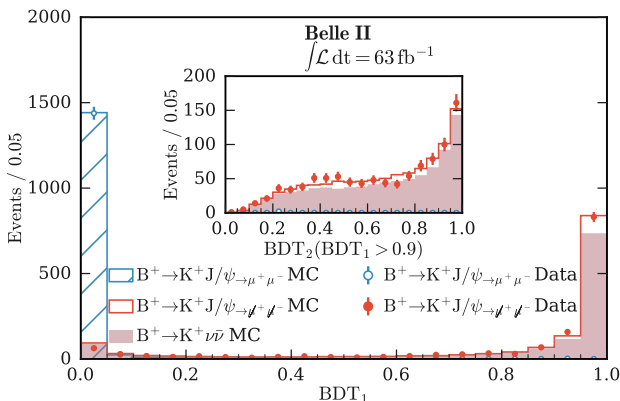
Binary classifiers in series

- Train BDT_1 on $\mathcal{O}(10^7)$ simulated events.
- Train BDT_2 on $\mathcal{O}(10^7)$ simulated events with $\text{BDT}_1 > 0.9$.
- $\max(S/\sqrt{S+B})$ reached around $\text{BDT}_2 > 0.95$.



Validation channel: $B^+ \rightarrow K^+ J/\psi (\rightarrow \mu^+ \mu^-)$

- To check the data-simulation agreement, $B^+ \rightarrow K^+ J/\psi (\rightarrow \mu^+ \mu^-)$ decays are selected.
 - Muons are removed from the reconstruction to mimic the signal.
 - Kaon 3-momentum is sampled from simulated signal events.

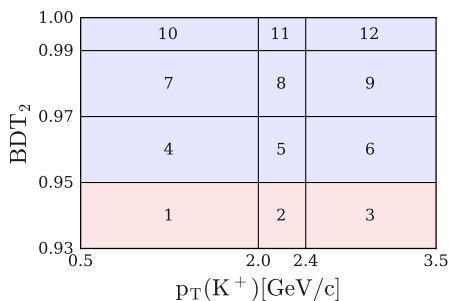


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Statistical model

- Binned likelihood defined in the $\text{BDT}_2 \times p_{\text{T}}(K^+) \times \sqrt{s}$ space.
- $4 \times 3 \times 2 = 24$ bins.
 - $\text{BDT}_2 \in [0.93, 0.95, 0.97, 0.99, 1.00]$.
 - $p_{\text{T}}(K^+) \in [0.5, 2.0, 2.4, 3.5] \text{ GeV}/c$.
 - $\sqrt{s} \in \{m(\Upsilon(4S)), m(\Upsilon(4S)) - 60 \text{ MeV}/c^2\}$.



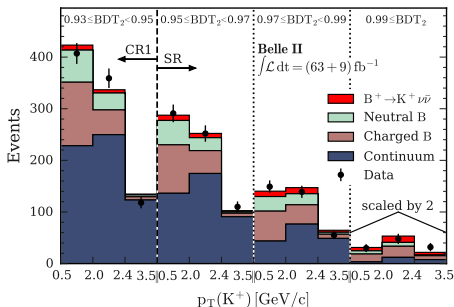
Statistical model

- Likelihood function = product of Poisson probability density functions combining the information from the 24 bins.
 - Templates for the yields of the signal and background derived from simulation.
 - Implementation in the `pyhf` package, maximum-likelihood fit using `scipy`.
- Fit parameters:
 - Signal strength μ (factor w.r.t. SM expectation for signal yield).
 - Nuisance parameters to include the systematic uncertainties *via* event-count modifiers.
 - Main systematic source: background yield normalisation.

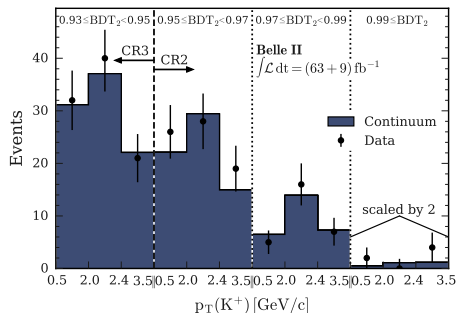
Fit to data

- Maximum-likelihood fit to 24 bins of the $\text{BDT}_2 \times p_{\text{T}}(K^+) \times \sqrt{s}$ space.

- On-resonance.

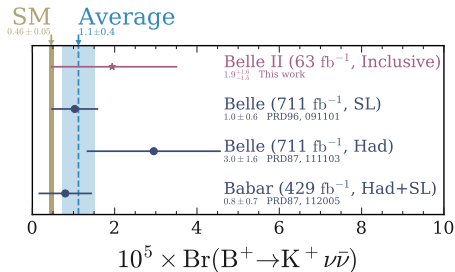
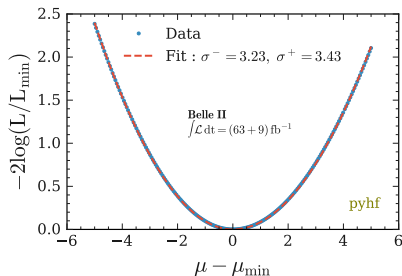


- Off-resonance.



Result

- $\mu = 4.2_{-3.2}^{+3.4} = 4.2_{-2.8}^{+2.9}(\text{stat})_{-1.6}^{+1.8}(\text{syst})$.
- $\text{BR}(B^+ \rightarrow K^+ \nu \bar{\nu}) = [1.9_{-1.5}^{+1.6}] \times 10^{-5} = [1.9_{-1.3}^{+1.3}(\text{stat})_{-0.7}^{+0.8}(\text{syst})] \times 10^{-5}$.



- Total uncertainty on μ : profile likelihood scan, fitting the model with fixed values of μ while keeping the other fit parameters free.

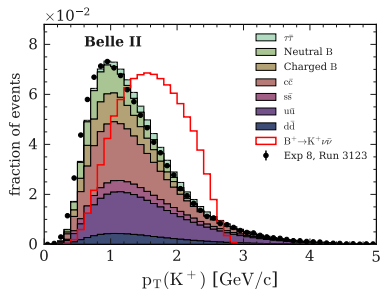
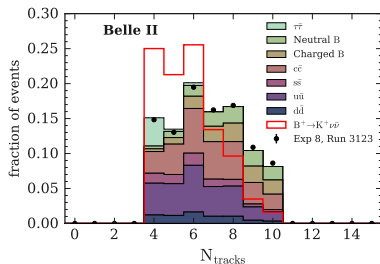
Conclusion and outlook

- Search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ decays with an inclusive tagging approach was performed at Belle II with $(63 + 9) \text{ fb}^{-1}$ of data.
- $\text{BR}(B^+ \rightarrow K^+ \nu \bar{\nu}) = \left[1.9^{+1.6}_{-1.5} \right] \times 10^{-5} \quad (< 4.1 \times 10^{-5} \text{ @ 90\% C.L.}).$
- Pre-print available [[2104.12624](#)], submitted for publication.
- Next iteration of the analysis will include:
 - More data.
 - More channels ($B^0 \rightarrow K^{*0} \nu \bar{\nu}$, $B^0 \rightarrow K_S^0 \nu \bar{\nu}$, ...).
 - More classifiers (neural networks).

Thank you for your attention!

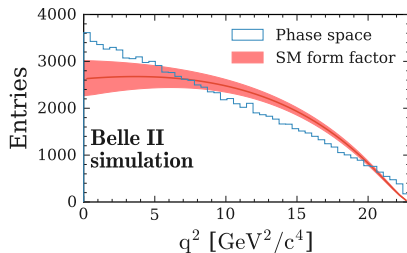
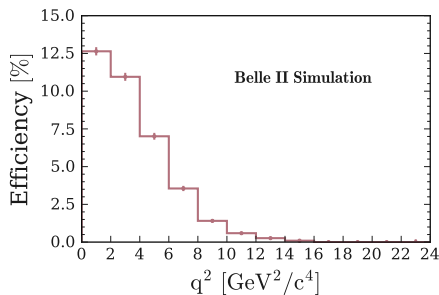
Signal kaon candidate selection and event pre-selection

- Basic track cleanup:
 - $p_T > 0.1 \text{ GeV}/c$, $\theta \in \text{CDC}$,
 $|dr| < 0.5 \text{ cm}$, $|dz| < 3.0 \text{ cm}$.
- Highest- p_T clean track in event as K^+ candidate.
 - Correct candidate in 80% of the cases.
 - $\# \text{ PXD hits} \geq 1$.
 - PID requirement to suppress pion background.
- Loose preselection:
 - $4 \leq N_{\text{tracks}} \leq 10$.
 - $0.3 < \theta(\mathbf{p}_{\text{miss}}) < 2.8 \text{ rad}$.
 - $E_{\text{visible}} > 4 \text{ GeV}$.



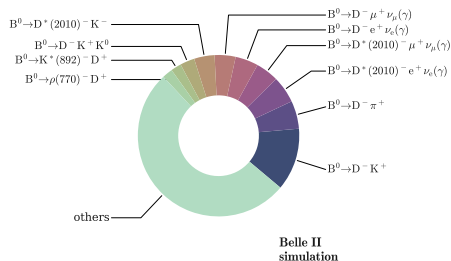
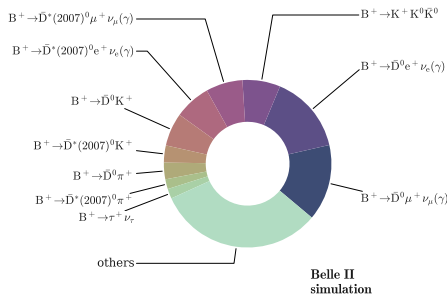
Signal efficiency at $\text{BDT}_2 > 0.95$

- At $\text{BDT}_2 > 0.95$, the signal efficiency is 12.5% for $q^2 \approx 0$ and drops to zero for $q^2 > 16 \text{ GeV}^2/c^4$.
- Sensitive to potential light dark matter candidates.



Background composition at $\text{BDT}_2 > 0.93$

- At $\text{BDT}_2 > 0.93$, D -mesons contribute a lot to the remaining background from B -meson decays.

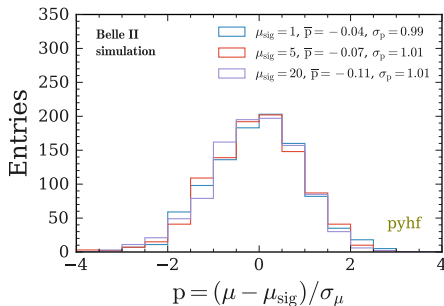


Fit validation

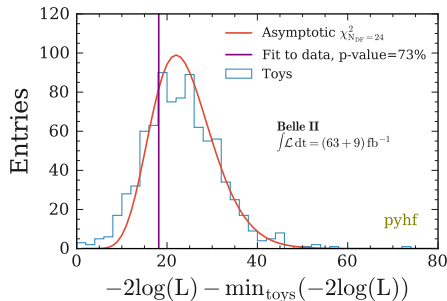
- Toys generated for the simulated data set.

- Poisson statistical fluctuations.
- Gaussian systematic fluctuations.

- Signal injection study, $\mu_{\text{sig}} \in \{1, 5, 20\}$.



- Data-model compatibility.



Limit setting

- Expected and observed upper limits on the branching fraction are determined using the **CLs method**.

