Status and prospects for rare decays at Belle II

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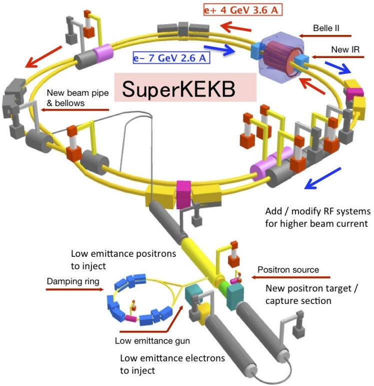
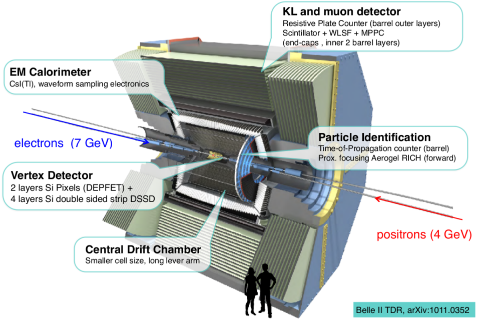
Outline

- Introduction
- Measurement of $B \to K^*\gamma$ branching fraction
- Study of $B \to X_s\gamma$
- Study of $B^+ \to K^+\ell^+\ell^-$
- Search for $B^+ \to K^+\nu\bar{\nu}$
- Summary & outlook

SuperKEKB accelerator and Belle II experiment

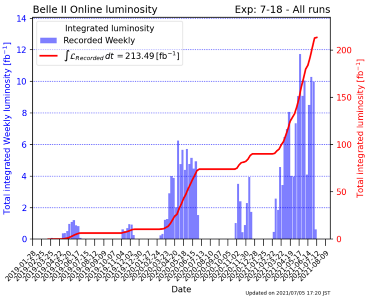




- $e^{-}(7\ \mathrm{GeV}) \rightarrow\leftarrow \mathrm{e}^{+}(4\ \mathrm{GeV})$
- $\sqrt{s} = 10.58\ \mathrm{GeV} = \mathrm{m}(\Upsilon(4\mathrm{S}))$
- $\mathcal{B}\ (\Upsilon(4S) \to B\bar{B}) > 96\%$

- Clean environment; well defined initial state
- Efficient neutral reconstruction capability ($\gamma,\ \pi^0,\ \eta,\ K^0_S,\ K^0_L$)
- Excellent vertexing and flavour tagging performance

Belle II status



- Collected $213\ \mathrm{fb}^{-1}$ of data since 2019

- Today's results: $63\ \mathrm{fb}^{-1}$ at $\Upsilon(4S)$ + $9\ \mathrm{fb}^{-1}$ off-resonance ($60\ \mathrm{MeV}$ below the $\Upsilon(4S)$)

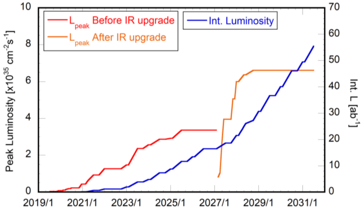
- World record of luminosity:

$\rightarrow$ $L = 3.1 \times 10^{34} \mathrm{cm}^{-2}\mathrm{sec}^{-1}$

- Despite the pandemic, data taking has been very successful:

$\rightarrow$ $12\ \mathrm{fb}^{-1}$/week, $40.3\ \mathrm{fb}^{-1}$/month

Tentative long-term operation plan

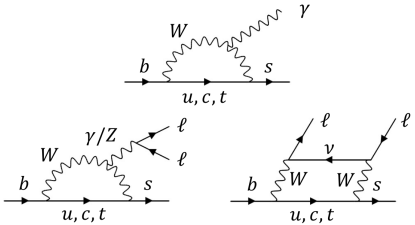


- Long-term target:
$L_{\mathrm{int}} \sim 50\ \mathrm{ab}^{-1}$,
$L_{\mathrm{peak}} \sim 6 \times 10^{35} \mathrm{cm}^{-2}\mathrm{sec}^{-1}$

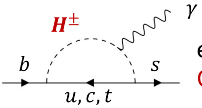
Radiative and electroweak penguin B decays

- B-decays with flavor changing neutral currents (FCNC), $b \to s(d)$ transitions
- Forbidden at tree level in the SM and can only proceed via suppressed loop or box-level amplitudes
- BSM model allowing FCNC at tree level or new particles appearing in loop can change branching fractions and/or other observables

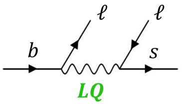
Radiative and electroweak penguin decays in SM



Potential BSM contributions

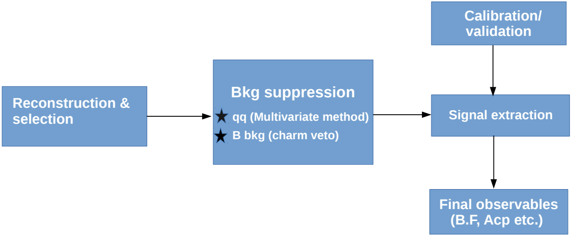


e.g.
Charged Higgs



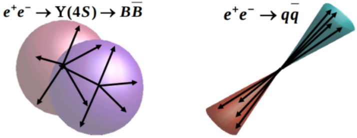
e.g.
Leptoquark

Analysis of radiative and electroweak penguin decays



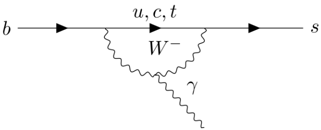
Multivariate analyzer

- A boosted decision tree (BDT) to suppress background from light quark $(\mathrm{u}, \mathrm{d}, \mathrm{s} \text{ and } \mathrm{c})$ pairs (denoted as $q\bar{q}$ events)
  $\rightarrow$ Use event shape variables and vertex information as input
  $\rightarrow$ A requirement on the BDT output removes most of the $q\bar{q}$ background



$q\bar{q}$ background is $\sim 10^6$ times more abundant than signal events

Measurement of $B \to K^*\gamma$ branching fraction



- $b \to s\gamma$ electroweak amplitude
- Sensitive to new physics particles that can enter the loop
- SM prediction of branching fraction suffers from large uncertainties owing to form factors

- Other observables:

$$A_{CP} = \frac{\Gamma(\bar{B}\to\bar{K}^*\gamma)-\Gamma(B\to K^*\gamma)}{\Gamma(\bar{B}\to\bar{K}^*\gamma)+\Gamma(B\to K^*\gamma)}$$

$$\Delta_{+0} = \frac{\Gamma(B^0\to K^*\gamma)-\Gamma(B^+\to K^{*+}\gamma)}{\Gamma(B^0\to K^{*0}\gamma)+\Gamma(B^+\to K^{*+}\gamma)}$$

- Reliably predicted due to form-factor cancellation
- The latest measurement by Belle reported evidence for isospin violation with a significance of 3.1 standard deviations:

$\Delta_{+0} = [+6.2 \pm 1.5(\mathrm{stat}) \pm 0.6(\mathrm{syst}) \pm 1.2(f_{+-}/f_{00})]\%$

(Phys. Rev. Lett. **119** (2017) 19, 191802)

$B \to K^*\gamma$: Analysis overview

- All final states are explicitly reconstructed,

  $K^* \to K^+\pi^-,\ K_S^0\pi^0,\ K^+\pi^0,\ K_S^0\pi^+\ (K_S^0 \to \pi^+\pi^-,\ \pi^0 \to \gamma\gamma)$

- Signal yield is obtained from an unbinned maximum likelihood (ML) fit to $\Delta E\ (= E_B^* - \sqrt{s}/2)$ distribution

Dominant background:

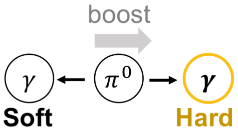
- $q\bar{q}$ events with γ from π^0, η decay

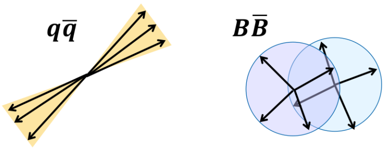
$\to$ π^0, η veto using kinematic information by combining hard and soft-photons

$\to$ $q\bar{q}$ suppression with BDT

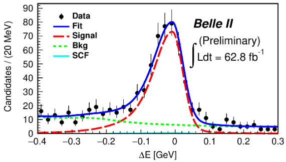
Bkg rejection: 70 -90 %

Signal loss: 10-21 %

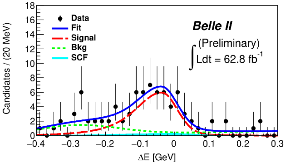




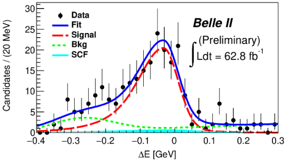
$B \to K^*\gamma$: Fit results



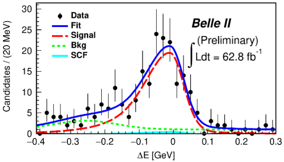
(a) $B^0 \to K^{*0}[K^+\pi^-]\gamma$



(b) $B^0 \to K^{*0}[K_S^0\pi^0]\gamma$



(c) $B^+ \to K^{*+}[K^+\pi^0]\gamma$



(d) $B^+ \to K^{*+}[K_S^0\pi^+]\gamma$

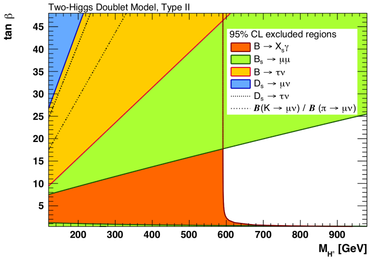
- Studies ongoing for the measurement of *CP* and isospin asymmetries

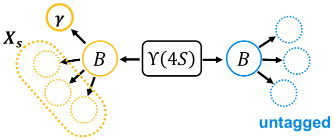
Mode	B.F ($\times 10^{-5}$)
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	$4.5 \pm 0.3 \pm 0.2$
$B^0 \to K^{*0}[K_S^0\pi^0]\gamma$	$4.4 \pm 0.9 \pm 0.6$
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	$5.0 \pm 0.5 \pm 0.4$
$B^+ \to K^{*+}[K_S^0\pi^+]\gamma$	$5.4 \pm 0.6 \pm 0.4$

Study of $B \to X_s\gamma$ with untagged method

- Strong constraint on the Charged Higgs is obtained from $\mathcal{B}\ (B \to X_s\gamma)$: $\mathrm{M_{H^\pm}} < 590\ \mathrm{GeV}$

Eur.Phys.J.C78(2018)8, 675





- Reconstruct only γ in the signal-side B meson
- Untagged method: No explicit reconstruction of recoil-side B meson

$\rightarrow$ Higher efficiency & lower purity

$\rightarrow$ Subtract expected background contributions

Study of $B \to X_s\gamma$ with untagged method

- Photon energy (E^*_γ) spectrum is used to extract signal after background suppression

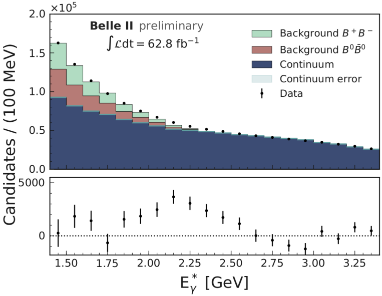
→ Monochromatic spectrum is expected for signal

→ $q\bar{q}$ is estimated from the off-resonance data

→ $B\bar{B}$ background is obtained from simulation

- Background subtracted plot on the bottom

BELLE2-NOTE-PL-2021-004

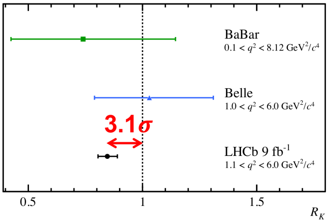


Excess clearly visible in the signal region

Study of $B^+ \to K^+\ell^+\ell^-$

- Tension between the observed and SM-predicted ratio: $\mathcal{R}_K \equiv \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$, suggests a lepton universality violation arXiv:2103.11769

$\to$ Important to have independent measurement of $B^+ \to K^+\ell^+\ell^-$ (with $\ell = e,\ \mu$)



- $B^+ \to K^+\ell^+\ell^-$ is reconstructed from both electron and muon modes

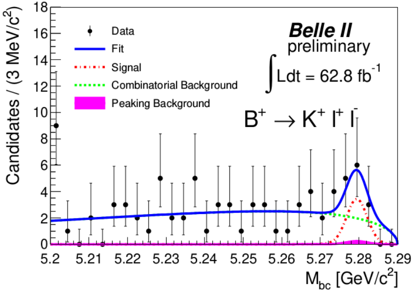
  $\to$ Similar electron and muon reconstruction performances, unlike LHCb

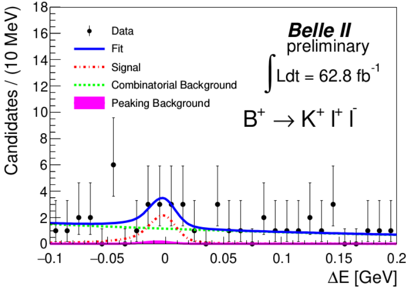
- Background suppression with BDT using event shape variables and vertex information
- Signal selection using two kinematic variables:

$$M_{bc} = \sqrt{E^{*2}_{\rm beam} - \vec{p}^{*2}_B}, \qquad \Delta E = E^*_B - E^*_{\rm beam}$$

Study of $B^+ \to K^+\ell^+\ell^-$

- 2D unbinned ML fit to $M_{\rm bc} - \Delta E$





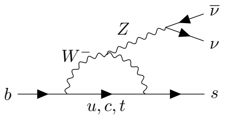
$\text{Signal yield} = 8.6^{+4.3}_{-3.9} \pm 0.4$ with 2.7σ significance

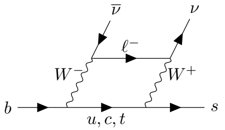
Search for $B^+ \to K^+\nu\bar{\nu}$ with a novel inclusive tagging

- $B^+ \to K^+\nu\bar{\nu}$ decay is not observed yet:

SM prediction: $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$
(Prog.Part.Nucl.Phys. **92** (2017) 50 – 91)

Upper limit on $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < (1.6 \pm 0.5) \times 10^{-5}$
(BaBar $429\ \mathrm{fb}^{-1}$, Phys.Rev.D **87** (2013) 11, 112005)





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

- Many other BSM models can be constrained like dark matter, leptoquarks and axions

(PRD **98**, 055003 (2018), PRD **102**, 015023 (2020), PRD **101**, 095006 (2020))

$B^+ \to K^+\nu\bar{\nu}$: Analysis strategies

- All previous studies used an explicit reconstruction of the B_{tag} followed by the signal reconstruction

$\rightarrow$ Reconstruction efficiency suffers because of the low tagging efficiency:

$\rightarrow$ Hadronic tagging: $\varepsilon_{\text{sig}}.\varepsilon_{\text{tag}} \sim 0.04\%$

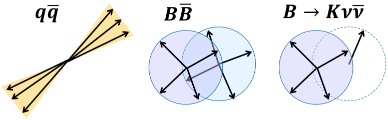
$\rightarrow$ Semileptonic tagging: $\varepsilon_{\text{sig}}.\varepsilon_{\text{tag}} \sim 0.2\%$

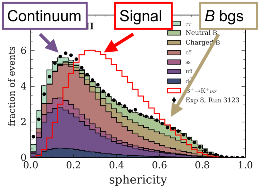
- Inclusive tagging:

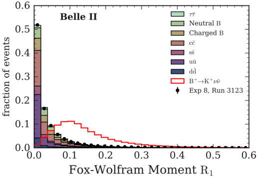
$\rightarrow$ Exploit distinct topology and kinematics to achieve higher signal efficiency ($\sim 4\%$)

$\rightarrow$ Higher efficiency & lower purity

Technique used first time in this channel!

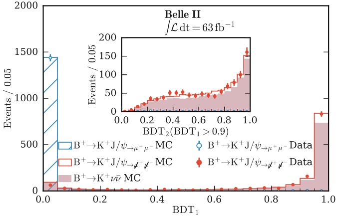


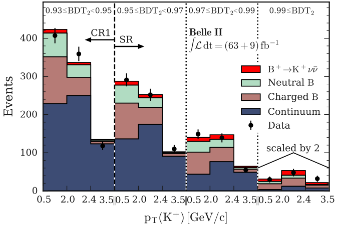




$B^+ \to K^+\nu\bar{\nu}$: Analysis procedure

- Select highest p_T track as signal kaon candidate
- Use of nested statistical-learning discriminators: BDT_1 & BDT_2 (topology, rest-of-event, missing energy, vertex separation,...)
- Validate the BDT using data of $B^+ \to K^+ J/\psi_{\to(\mu^+\mu^-)}$ decays where the muons are removed and the kaon momentum is reweighed to mimic the signal
- Signal strength is extracted by binned ML fit on the 2D ($p_T(K^+)$, BDT) histogram
- Use off-resonance data to constrain the yield from $q\bar{q}$ processes





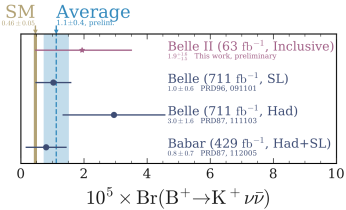
$B^+ \to K^+\nu\bar{\nu}$: Results

- Measured branching fraction
$\mathcal{B}(B^{\pm} \to K^{\pm}\nu\bar{\nu}) = [1.9^{+1.3}_{-1.3}(\text{stat})^{+0.8}_{-0.7}(\text{syst})] \times 10^{-5}$

- No significant signal observed; setting upper limit on branching fraction:

$\mathcal{B}(B^{\pm} \to K^{\pm}\nu\bar{\nu}) < (4.1 \pm 0.5) \times 10^{-5}$ @ 90% CL

arXiv:2104.12624 (Accepted to PRL!)



- Inclusive approach outperforms semileptonic tagging by 10-20% and hadronic tagging by 3.5x at given luminosity[1]

- This result based on the novel inclusive tagging approach already has an impact on the global picture of these decays

- Studies on additional channels $B^0 \to K^{*0}\nu\bar{\nu}$ and $B^0 \to K^0_S\nu\bar{\nu}$ etc. using more data are in preparation!

[1]assuming the total uncertainty in the branching-fraction scales with $1/\sqrt{L}$

Summary and outlook

- First results from Belle II on radiative and electroweak penguin decays with $(63 + 9)\ \mathrm{fb}^{-1}$ demonstrate the high capabilities of the experiment

→ Measurement of $B \to K^{*}\gamma$ branching fraction BELLE2-CONF-PH-2021-014

→ Study of $B \to X_s\gamma$ BELLE2-NOTE-PL-2021-004

→ Study of $B^+ \to K^+\ell^+\ell^-$ BELLE2-NOTE-PL-2021-014

→ Search for $B^+ \to K^+\nu\bar{\nu}$ with the inclusive tagging method arXiv:2104.12624 (Accepted to PRL!)

- The result on $B^+ \to K^+\nu\bar{\nu}$ based on a novel inclusive tagging approach already has an impact on the global picture of these decays

- Belle II has recorded 213 fb^{-1} of data by 2021 summer

- 3× larger sample ready to be analysed while aiming for 400 fb^{-1} by 2022 summer (50 ab^{-1} over 10 years)

- Interesting results are coming in the near future with more and more channels and improved analysis techniques!

Stay tuned!

Extra Slides

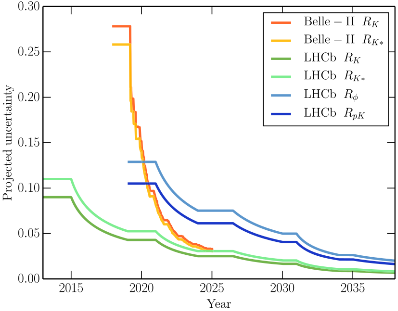
Summary of the Sensitivities: $B \to K^*\gamma$

Observables	Belle $0.71\,\mathrm{ab}^{-1}$ ($0.12\,\mathrm{ab}^{-1}$)	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\Delta_{0+}(B \to K^*\gamma)$	2.0%	0.70%	0.53%
$A_{CP}(B^0 \to K^{*0}\gamma)$	1.7%	0.58%	0.21%
$A_{CP}(B^+ \to K^{*+}\gamma)$	2.4%	0.81%	0.29%
$\Delta A_{CP}(B \to K^*\gamma)$	2.9%	0.98%	0.36%
$S_{K^{*0}\gamma}$	0.29	0.090	0.030

Summary of the Sensitivities: $B \to X_s\gamma$

Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B \to X_s\gamma)_{\mathrm{inc}}^{\mathrm{lep\text{-}tag}}$	5.3%	3.9%	3.2%
$\mathrm{Br}(B \to X_s\gamma)_{\mathrm{inc}}^{\mathrm{had\text{-}tag}}$	13%	7.0%	4.2%
$\mathrm{Br}(B \to X_s\gamma)_{\mathrm{sum\text{-}of\text{-}ex}}$	10.5%	7.3%	5.7%
$\Delta_{0+}(B \to X_s\gamma)_{\mathrm{sum\text{-}of\text{-}ex}}$	2.1%	0.81%	0.63%
$\Delta_{0+}(B \to X_{s+d}\gamma)_{\mathrm{inc}}^{\mathrm{had\text{-}tag}}$	9.0%	2.6%	0.85%
$A_{CP}(B \to X_s\gamma)_{\mathrm{sum\text{-}of\text{-}ex}}$	1.3%	0.52%	0.19%
$A_{CP}(B^0 \to X_s^0\gamma)_{\mathrm{sum\text{-}of\text{-}ex}}$	1.8%	0.72%	0.26%
$A_{CP}(B^+ \to X_s^+\gamma)_{\mathrm{sum\text{-}of\text{-}ex}}$	1.8%	0.69%	0.25%
$A_{CP}(B \to X_{s+d}\gamma)_{\mathrm{inc}}^{\mathrm{lep\text{-}tag}}$	4.0%	1.5%	0.48%
$A_{CP}(B \to X_{s+d}\gamma)_{\mathrm{inc}}^{\mathrm{had\text{-}tag}}$	8.0%	2.2%	0.70%
$\Delta A_{CP}(B \to X_s\gamma)_{\mathrm{sum\text{-}of\text{-}ex}}$	2.5%	0.98%	0.30%
$\Delta A_{CP}(B \to X_{s+d}\gamma)_{\mathrm{inc}}^{\mathrm{had\text{-}tag}}$	16%	4.3%	1.3%

Summary of the Sensitivities: R_K



J. Phys. G: Nucl. Part. Phys. **46** (2019)023001

Summary of the Sensitivities: $B^+ \to K^+\nu\bar{\nu}$

Observables	Belle $0.71\,\text{ab}^{-1}$ $(0.12\,\text{ab}^{-1})$	Belle II $5\,\text{ab}^{-1}$	Belle II $50\,\text{ab}^{-1}$
$\text{Br}(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$\text{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\text{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0}\nu\bar{\nu})$	–	–	0.079
$F_L(B^+ \to K^{*+}\nu\bar{\nu})$	–	–	0.077
$\text{Br}(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5
$\text{Br}(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 1.1	–