Electroweak penguins and radiative B decays at Belle II

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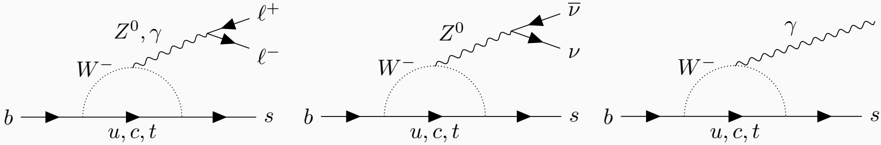
57th Rencontres de Moriond, 20.03.2023

Motivation

Why studying electroweak penguins and radiative B decays?

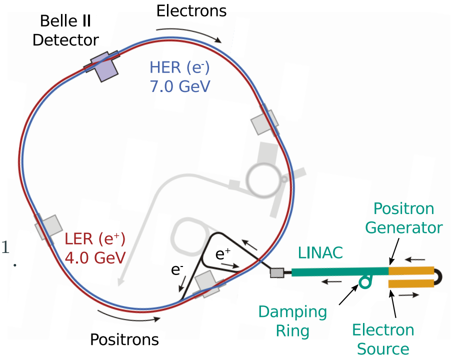
- Flavor-changing neutral-current transitions $b \to s$ forbidden at tree level in the standard model.
- Resulting B decays are rare (loop or box diagrams):
  - Branching fractions $\mathcal{B} \approx \mathcal{O}(10^{-7}) \sim \mathcal{O}(10^{-4})$.
- New physics may affect measured branching fractions and angular distributions of final-state particles.



The Belle II experiment

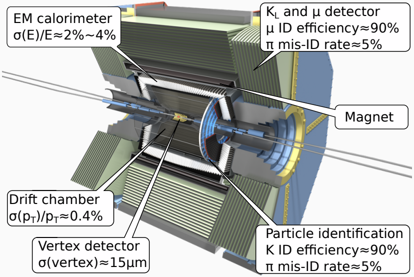
The SuperKEKB B factory

- e^+e^- collider in Tsukuba, Japan.
- $\sqrt{s} = 10.6\,\mathrm{GeV} = \mathrm{m}(\Upsilon(4S))$.
- $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) > 96\%$.
- $\int_{25.03.2019}^{22.06.2022} \mathcal{L}_{\sqrt{s}=\mathrm{m}(\Upsilon(4S))}\,\mathrm{dt} = 362\,\mathrm{fb}^{-1}$.
    - $N_{B\bar{B}} = 3.87 \times 10^8$.
    - Similar to Babar sample and half of Belle's.
- Maximum instantaneous luminosity: $4.7 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (world record).
- Target instantaneous luminosity: $6 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

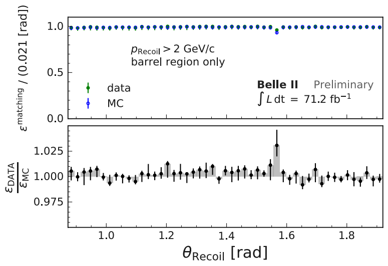


Strengths of Belle II for EW penguins and radiative B decays

- Belle II suited for measurements with neutral or missing energy.
  - Knowledge of initial energy-momentum in e^+e^- collisions.
  - Moderate backgrounds.
  - Close to 4π coverage.
  - Photons: high detection efficiency and good energy resolution.
- Good and similar identification of electrons and muons. [BELLE2-CONF-PH-2022-003]



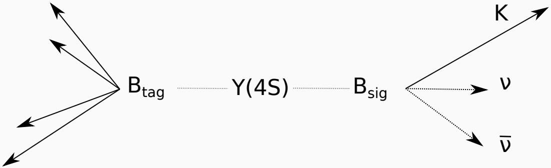
Photon-detection efficiency [BELLE2-NOTE-PL-2021-008]



Electroweak penguins and radiative *B* decays

Identifying $B\bar{B}$-meson production

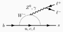
- Knowing that B mesons are produced in $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ events is valuable.
- When missing kinematic information in the signal decay ($B \to K\nu\bar{\nu}$, inclusive $B \to X_s\gamma$), accompanying B ($B_{\rm tag}$) is used to constrain the signal.



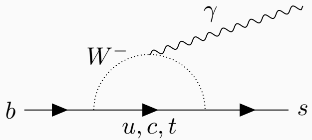
- Hadronic tagging: $B_{\rm tag}$ is reconstructed in a hadronic decay. [Comp Soft Big Sci 3, 6 (2019)]
  - Small tagging efficiency $\approx 0.1\% \sim 0.5\%$, full kinematic information.
- Inclusive tagging: no explicit reconstruction of $B_{\rm tag}$. [PRL 127 (2021) 18, 181802]
  - High tagging efficiency, limited kinematic information.

EW penguins and radiative B decay studies at Belle II

- A variety of $b \to s$ processes test the standard model in different ways.
  - In this talk.
  - Not in this talk.
- Larger branching fraction of $B \to X_s\gamma$ allows to study it with limited dataset.

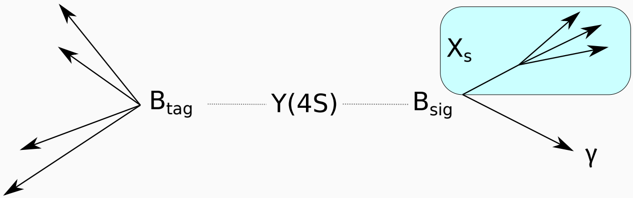
	Decay	$\mathcal{O}(\mathcal{B})$	Note	Dataset [fb^{-1}]	Documentation
	Fully inclusive $B \to X_s\gamma$	10^{-4}	hadronic tagging	189	[2210.10220]
	$B \to J/\psi(\ell^+\ell^-)K$	10^{-4}	control, *not* $b \to s$	189	[2207.11275]
	$B \to K^*(892)\ell^+\ell^-$	10^{-6}	-	189	[2206.05946]
	$B^+ \to K^+\nu\bar{\nu}$	10^{-6}	inclusive tagging	63	[PRL 127 (2021) 18, 181802]
	$B \to K^*(892)\gamma$	10^{-6}	-	63	[2110.08219]
	$B^+ \to K^+\ell^+\ell^-$	10^{-7}	-	63	[BELLE2-NOTE-PL-2021-005]
	Fully inclusive $B \to X_s\gamma$	10^{-4}	-	63	[BELLE2-NOTE-PL-2021-004]

Fully inclusive $B \to X_s\gamma$



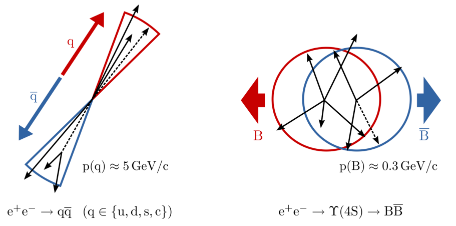
Fully inclusive $B \to X_s\gamma$ with hadronic tagging I [2210.10220]

- Sensitive to new physics (differently from $b \to s\ell\ell$).
- Unique to B factories.
- Fully inclusive $\to$ avoid form factor and fragmentation uncertainties.
- Sensitive to b-quark motion inside B. [PRL 127, 102001]
- Challenge: suppress and subtract large background contributions from $e^+e^- \to B\bar{B}$ and $e^+e^- \to q\bar{q}$ $(q = u, d, c, s)$.
- Hadronic-tagging used only once for $B \to X_s\gamma$, by Babar. [PRD 77 (2008) 051103]



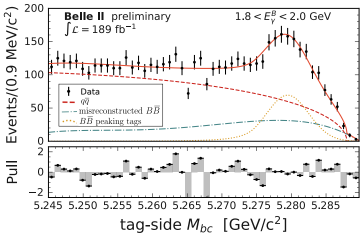
Fully inclusive $B \to X_s\gamma$ with hadronic tagging II [2210.10220]

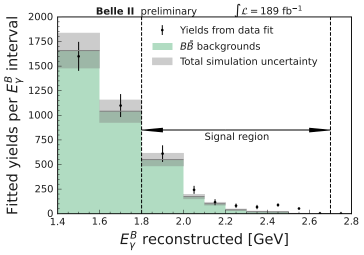
- Event selection strategy:
  - Reconstruct B_{tag} in a hadronic decay.
  - Select signal γ candidate with highest energy in B_{sig} frame (E_γ^B).
  - Suppress γ from π^0 and η decays with boosted-decision-tree classifier.
  - Suppress $e^+e^- \to q\bar{q}$ with boosted-decision-tree classifier.



Fully inclusive $B \to X_s\gamma$ with hadronic tagging III [2210.10220]

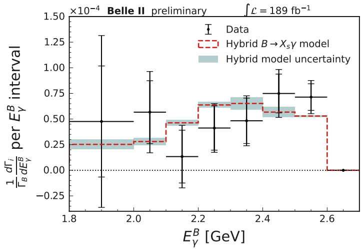
- Perform simultaneous fit of tag-side $M_{\rm bc}$ in bins of E_γ^B to determine $B\bar{B}$ yields.
  - Tag-side $M_{\rm bc} \equiv \sqrt{(\sqrt{s}/2)^2 - p^{*2}_{B_{\rm tag}}}$.
- Resulting $B\bar{B}$ yields include:
  - Events with a $B \to X_{s+d}\gamma$ decay.
  - Other correctly-tagged $B\bar{B}$ processes.
- Size of remaining $B\bar{B}$ background estimated from simulation.
- $B\bar{B}$ background subtracted from data in bins of E_γ^B to determine the signal yield.





Fully inclusive $B \to X_s\gamma$ with hadronic tagging IV [2210.10220]

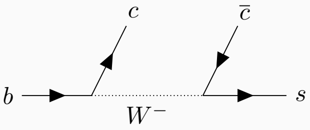
- After background subtraction, results integrated for multiple E_γ^B thresholds.
- Background mis-modelling dominates systematic uncertainties.



E_γ^B threshold [GeV]	$\mathcal{B}(B \to X_s\gamma)$ [10^{-4}]	Experiment	L [fb^{-1}]	Signal Yield	Reference
1.8	$\mathbf{3.54 \pm 0.78 \pm 0.83}$	Belle II	189	$\mathbf{343 \pm 122}$	[2210.10220]
2.0	$\mathbf{3.06 \pm 0.56 \pm 0.47}$	Belle II	189	$\mathbf{285 \pm 68}$	[2210.10220]
1.9	$3.66 \pm 0.85 \pm 0.60$	BaBar	210		PRD 77 (2008) 051103
1.6	3.49 ± 0.19	World average			PDG 2022

- Result competitive with the only other hadronic-tagging measurement (BaBar), and consistent with world average (including all tagging techniques).

$B \to J/\psi(\ell^+\ell^-)K$ as control for $B \to K\ell^+\ell^-$

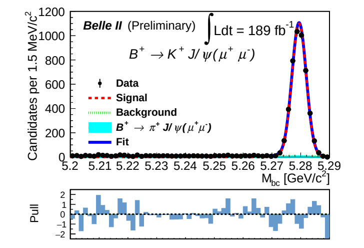


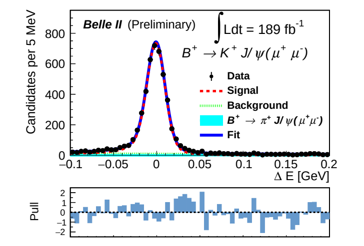
$B \to J/\psi(\ell^+\ell^-)K$ as control for $B \to K\ell^+\ell^-$ [2207.11275]

- $B \to J/\psi K$ involves a $b \to c$ transition, but is a control channel for $B \to K\ell^+\ell^-$ studies.
- Reconstruct $B \to J/\psi\,(\ell^+\ell^-)K$ with $\ell = e,\ \mu$.
- Measure signal yield with 2D fit:
  - M_{bc}
  - $\Delta E \equiv E_B^* - \sqrt{s}/2$.
- Compute $R_K(J/\psi) \equiv \frac{\mathcal{B}(B\to J/\psi(\mu^+\mu^-)K)}{\mathcal{B}(B\to J/\psi(e^+e^-)K)}$.

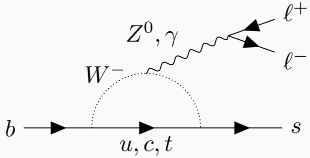
Mode	$N_{J/\psi\to\mu^+\mu^-}$	$N_{J/\psi\to e^+e^-}$	$R_K\,(J/\psi)$
$B^+ \to J/\psi K^+$	4578 ± 62	3706 ± 62	$1.009 \pm 0.022 \pm 0.008$
$B^0 \to J/\psi K^0_S$	1343 ± 37	1052 ± 33	$1.042 \pm 0.042 \pm 0.008$

- Lepton ID systematic uncertainty (<1%) smaller than Belle's [JHEP 03 (2021) 105].





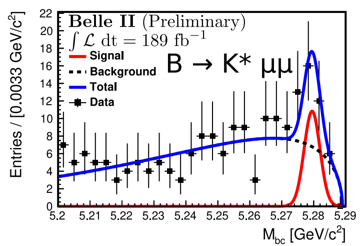
$B \to K^*(892)\ell^+\ell^-$

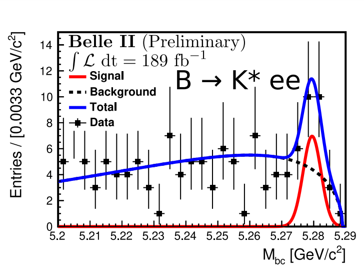


- Reconstruct $K^* \to K^+\pi^-$, $K^+\pi^0$, $K_S^0\pi^+$ and $\ell^+\ell^-$ ($\ell = e,\ \mu$).
- Veto dilepton-mass regions containing $B \to J/\psi K^*$, $\psi(2S)K^*$, γK^*.
- Suppress background with boosted tree.
- Measure signal yield with $(M_{\rm bc}, \Delta E)$ fit.

Observable	Signal Yield	Measured value $[10^{-6}]$	PDG $[10^{-6}]$
$\mathcal{B}(B \to K^*\mu^+\mu^-)$	22 ± 6	$1.19 \pm 0.31^{+0.08}_{-0.07}$	1.06 ± 0.09
$\mathcal{B}(B \to K^*e^+e^-)$	18 ± 6	$1.42 \pm 0.48 \pm 0.09$	1.19 ± 0.20

- Similar performance for e^+e^- and $\mu^+\mu^-$ modes.





Summary

- Electroweak penguins and radiative B decays offer multiple opportunities to search for new physics.
- Fully inclusive $B \to X_s\gamma$:
  - First $b \to s\gamma$ measurement with hadronic tagging from Belle/Belle II.
  - Competitive with the only other hadronic-tagging measurement.
- $B \to K^*(892)\ell^+\ell^-$, $B \to J/\psi(\ell^+\ell^-)K$:
  - Good and similar identification of electrons and muons.
  - Prepare the ground for precision measurements of rare decays at Belle II when more data will be collected.

Belle II contributions to Moriond 2023

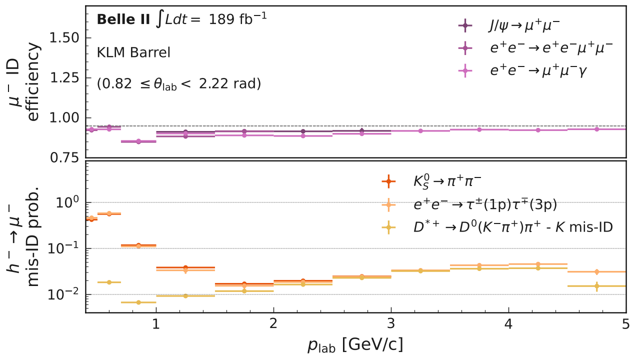
- Sascha Dreyer: *Dark sector and tau physics results at Belle II.*
- Sagar Hazra: *Hadronic B decays and charm at Belle II.*
- Kazuki Kojima: *Belle II results related to $b \to c$ anomalies.*
- Cyrille Praz: *Electroweak penguins and radiative B decays at Belle II.*
- Christoph Schwanda: *Semileptonic B decays at Belle II.*
- Michele Veronesi: *Time-dependent CP violation results at Belle II.*

Thank you for your attention.

Backup

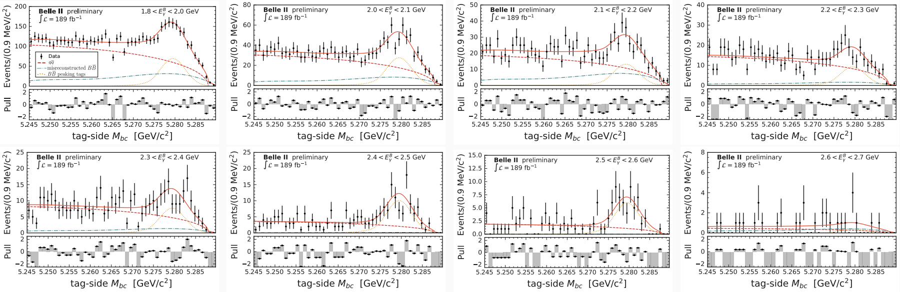
Electron and muon identification performance [BELLE2-CONF-PH-2022-003]

- Good and similar identification of electrons and muons at Belle II.



$B \to X_s\gamma$ with hadronic tagging: tag-side $M_{\rm bc}$ [2210.10220]

- Perform simultaneous fit of tag-side $M_{\rm bc}$ in bins of E_γ^B to determine $B\bar{B}$ yields.



$B \to X_s\gamma$ with hadronic tagging: uncertainties [2210.10220]

- The uncertainties are expressed in units of 10^{-4}.

E_γ^B [GeV]	$\frac{1}{\Gamma_B}\frac{d\Gamma_i}{dE_\gamma^B}(10^{-4})$	Statistical	Systematic	Fit procedure	Signal efficiency	Background modelling	Other
$1.8-2.0$	0.48	0.54	0.64	0.42	0.03	0.49	0.09
$2.0-2.1$	0.57	0.31	0.25	0.17	0.06	0.17	0.07
$2.1-2.2$	0.13	0.26	0.16	0.13	0.01	0.11	0.01
$2.2-2.3$	0.41	0.22	0.10	0.07	0.05	0.04	0.02
$2.3-2.4$	0.48	0.22	0.10	0.06	0.06	0.02	0.05
$2.4-2.5$	0.75	0.19	0.14	0.04	0.09	0.02	0.09
$2.5-2.6$	0.71	0.13	0.10	0.02	0.09	0.00	0.04

$B \to J/\psi(\ell^+\ell^-)K$: uncertainties [2207.11275]

- Relative systematic uncertainties (in %).

Source	$\mathcal{B}(B \to KJ/\psi)$				R_K		A_I	
	K^+	K^+	K_S^0	K_S^0	K^+	K^0		
	e^+e^-	$\mu^+\mu^-$	e^+e^-	$\mu^+\mu^-$			e^+e^-	$\mu^+\mu^-$
Number of $B\overline{B}$ events	1.5	1.5	1.5	1.5	–	–	–	–
PDF shape	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1
Electron identification	0.6	–	0.6	–	0.6	0.6	–	–
Muon identification	–	0.4	–	0.4	0.4	0.4	–	–
Kaon identification	0.2	0.2	–	–	–	–	0.1	0.1
K_S^0 reconstruction	–	–	3.0	3.0	–	–	1.5	1.5
Tracking efficiency	0.9	0.9	1.2	1.2	–	–	0.4	0.4
Simulation sample size	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
$\Upsilon(4S)$ branching fraction	2.6	2.6	2.6	2.6	–	–	2.6	2.6
(τ_{B^+}/τ_{B^0})	–	–	–	–	–	–	0.2	0.2
Total	3.2	3.2	4.4	4.4	0.8	0.8	3.0	3.0

$B \to K^*(892)\ell^+\ell^-$: uncertainties [2206.05946]

- Relative systematic uncertainties (in %).

Source	Systematic (%)
Kaon identification	0.4
Pion identification	2.5
Muon identification	$^{+1.9}_{-0.8}$
Electron identification	$^{+0.9}_{-0.5}$
K_S^0 identification	2.0
π^0 identification	3.4
Tracking	$1.2 - 1.5$
MVA selection	$1.3 - 1.7$
Simulated sample size	< 0.5
Signal cross feed	$< 1\%$
Signal PDF shape	$0.5 - 1.0\%$
$\mathcal{B}(\Upsilon(4S) \to B^+B^-)[(\mathcal{B}(\Upsilon(4S) \to B^0\overline{B^0}))$	1.2
Number of $B\overline{B}$ pairs	2.9
Total	$^{+6.7}_{-6.0}$

Long-shutdown activity and plans

Belle II stopped taking data in Summer 2022 for a long shutdown

- replacement of beam-pipe
- replacement of photomultipliers of the central PID detector (TOP)
- installation of 2-layered pixel vertex detector
- improved data-quality monitoring and alarm system
- completed transition to new DAQ boards (PCIe40)
- accelerator improvements: injection, non-linear collimators, monitoring
- replacement of aging components
- additional shielding and increased resilience against beam bckg

Currently working on pixel detector installation:
==> shipping to KEK in ~mid March
==> final tests at KEK scheduled in April

On track to resume data taking next winter with new pixel detector