Early physics prospects for radiative and electroweak penguin decays at Belle II

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Flavor Physics

Precision flavor physics

Compare precise experimental measurements of observables in B decays with theoretical predictions; interpret discrepancies in terms of new physics.

- Look for indirect effects of heavy unknown particles in low energy observables of B mesons.
- $b \to s(d)$ transitions are flavor changing neutral currents, loop + CKM suppression:
  - Rare, challenging to observe.
  - Exceptionally sensitive to virtual NP contributions.

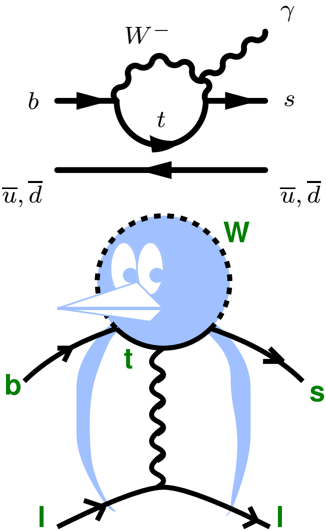


Figure 1: Radiative $b \to s\gamma$ (top) and electroweak $b \to s\ell^+\ell^-$ (bottom) penguins

Motivation

- Incorporate NP effects by modification of couplings between light fields in in effective Hamiltonian:

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \left(\sum_i \lambda^i_{\text{CKM}} C_i(\mu) Q_i(\mu) + \text{h.c.} \right) \tag{1}$$

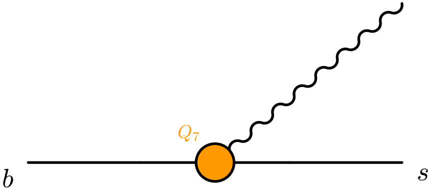
  - C_i: Wilson coefficients, encode high-energy contributions.
  - Q_i: Local operators constructed from light fields.

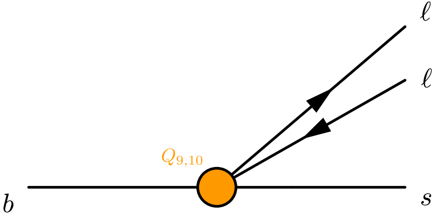
- NP modifies Wilson coefficients:

$$C_i = C_i^{\text{SM}} + C_i^{\text{NP}} \tag{2}$$

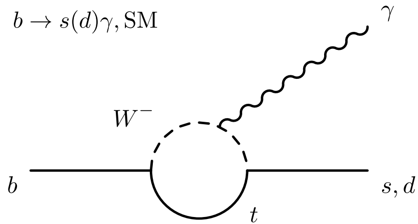
Motivation

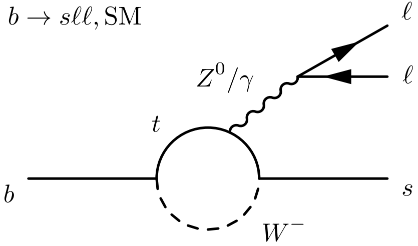
- Operators relevant to $b \to s(d)\gamma$, $b \to s\ell\ell$: Q_7, Q_9, Q_{10}. Approximate mediator exchange with local point interaction.
- Combined fits to different experimental measurements → model-independent constraints on C_i → constrain parameter space of NP models.

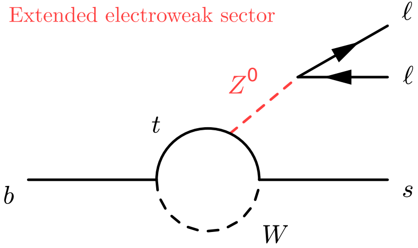




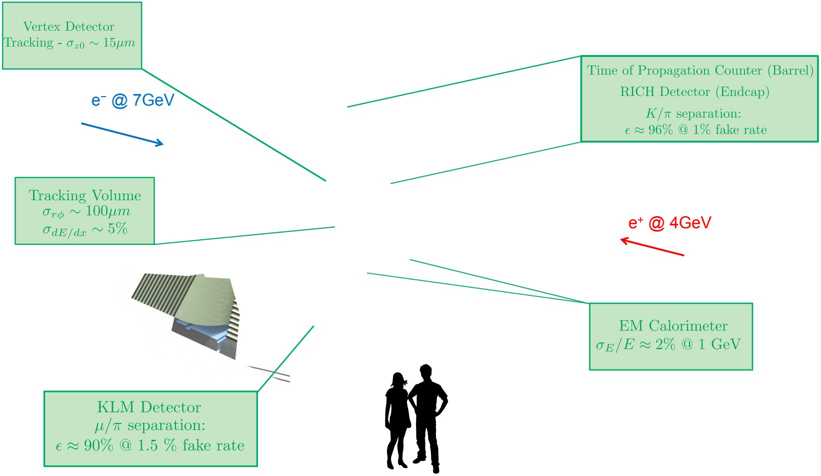
Motivation


$b \to s(d)\gamma, \mathrm{SM}$


$b \to s\ell\ell, \mathrm{SM}$


Extended electroweak sector

Belle II Detector



Vertex Detector
Tracking - $\sigma_{z0} \sim 15\mu m$

e⁻ @ 7GeV

Time of Propagation Counter (Barrel)
RICH Detector (Endcap)
K/π separation:
$\epsilon \approx 96\%$ @ 1% fake rate

Tracking Volume
$\sigma_{r\phi} \sim 100\mu m$
$\sigma_{dE/dx} \sim 5\%$

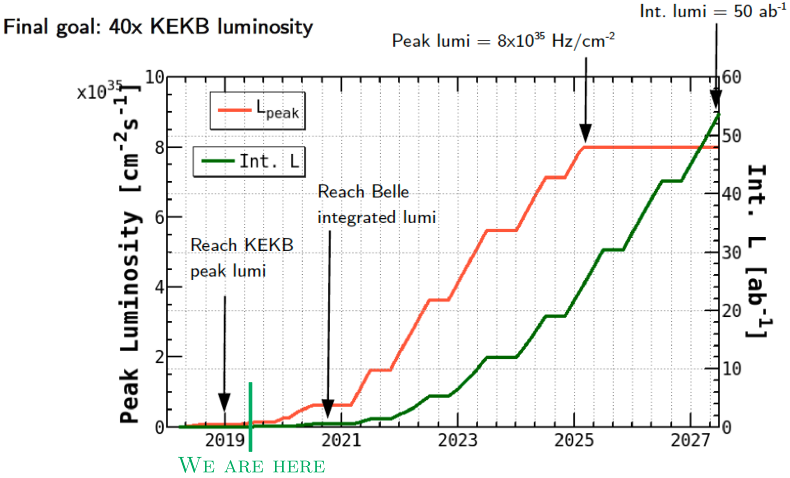
e⁺ @ 4GeV

EM Calorimeter
$\sigma_E/E \approx 2\%$ @ 1 GeV

KLM Detector
μ/π separation:
$\epsilon \approx 90\%$ @ 1.5 % fake rate

Data-Taking

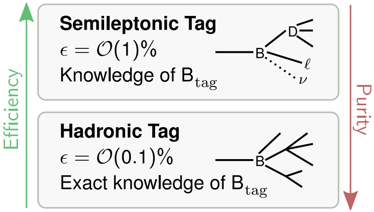
- Target: 50×10^9 $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ events by 2027.
- Large statistics → high precision measurements of important penguin decay observables. $\mathcal{B}(b \to s\gamma), \mathcal{B}(b \to s\ell\ell), R_{X_s}$, etc.



Analysis Strategies

Fully Inclusive

- Semi-leptonic tag: reconstruct B_{tag} in SL decay mode.
- Fully hadronic tag: reconstruct B_{tag} in hadronic decay mode.
- Low $\epsilon_{\text{SIG}} \rightarrow$ statistically limited.
- Systematics from neutral hadrons faking photons.



Semileptonic Tag

$\epsilon = \mathcal{O}(1)\%$

Knowledge of B_{tag}

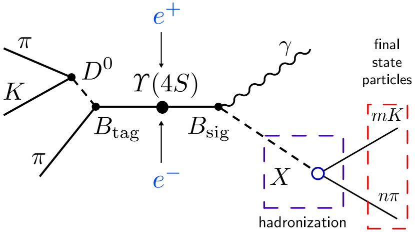
Hadronic Tag

$\epsilon = \mathcal{O}(0.1)\%$

Exact knowledge of B_{tag}

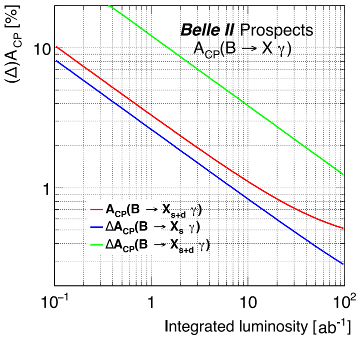
Semi-Inclusive

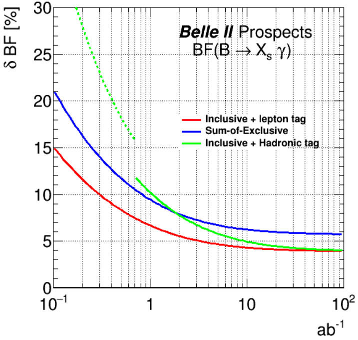
- Reconstruct hadronic X in as many distinct final states as possible (≈ 40).
- Determine flavor, charge.
- Distinguish $b \rightarrow s$ and $b \rightarrow d$.
- Systematics from fragmentation + excluded final states.



$b \to s(d)\gamma$

- Inclusive $B \to X_s\gamma$ theoretically and experimentally clean.
- $\mathcal{B}(B \to X_s\gamma)$ represents strongest constraint on NP in C_7.
    - Percent-level precision achievable with full dataset.
- A_{CP}, ΔA_{CP}, Δ_{0+} expected to be determined to sub-percent precision with full dataset.





$b \to s(d)\gamma$

- $b \to d\gamma$ transition largely experimentally untested, especially important.
  - Only accessible through sum-of-exclusives method.
  - Increase in luminosity → addition of previously missing high-multiplicity modes → reduced systematics.
  - Improved PID expected to significantly improve S/B.
- $\mathcal{B}(B \to X_d\gamma)$ expected to reach 14%.
- A_{CP}, Δ_{0+} expected ≈ 4% precision.

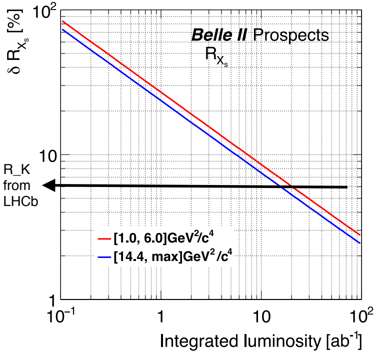
reco. method	tagging	effi.	S/B	q	p_B	A_{CP}	Δ_{0+}	ΔA_{CP}
sum-of-exclusive	none	high	moderate	s or d	yes	yes	yes	yes
fully-inclusive	had. B	very low	very good	s and d	yes	yes	yes	yes
	SL B	very low	very good	s and d	no	yes	yes	yes
	L	moderate	good	s and d	no	yes	no	no
	none	very high	very bad	s and d	no	no	no	no

$b \to s\ell\ell$

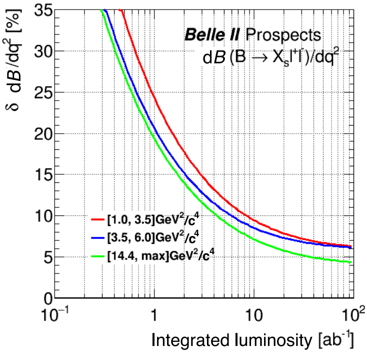
- Inclusive $B \to X_q\ell\ell$ analysis possible at Belle II.
    - Complement LHCb + cross-check exclusive $b \to q\ell\ell$ anomalies.
- Test lepton flavor universality via inclusive ratio R_{Xs}
    - Percent-level precision achievable with full dataset.

mumu/ee ratio for the inclusive decay B—>Xsll

- Low radiation length in tracking volume → very good e^+e^- resolution.

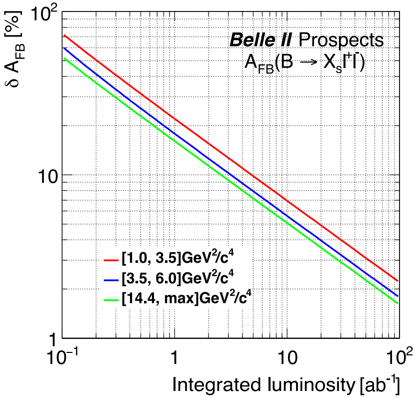


R_K from LHCb



$b \to s\ell\ell$

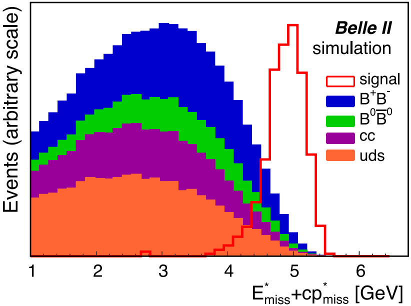
- Complete angular analysis of $b \to s\ell\ell$ possible at Belle II.
  - Initially semi-inclusive, fully-inclusive possible in long-term.
- Measurements of A_{FB} (2-3% precision) expected to tightly constrain C_9, C_{10}.
- Roughly same sensitivity to $B \to K^*\ell\ell$ channels as LHCb.
  - Independent verification of P_5', R_K, R_{K^*}.
  - Possible to confirm R_K anomaly with 20 ab^{-1} of data at 5σ.



Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K ($[1.0, 6.0]$ GeV^2)	28%	11%	3.6%
R_K (> 14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ($[1.0, 6.0]$ GeV^2)	26%	10%	3.2%
R_{K^*} (> 14.4 GeV^2)	24%	9.2%	2.8%
R_{X_s} ($[1.0, 6.0]$ GeV^2)	32%	12%	4.0%
R_{X_s} (> 14.4 GeV^2)	28%	11%	3.4%

$B \to K^{(*)}\nu\bar{\nu}$

- Probe dark sector coupling and $b \to s$ transition.
  - Or any exotic final state with missing energy signature.
- Expected $\mathcal{B}_{K^{(*)}\nu\nu}$ sensitivity $\approx 10\%$ with 50 ab^{-1}.
- Clean environment → identify signal peak in missing 4-momentum in CM frame, $E^*_{\text{miss}} + cp^*_{miss}$.



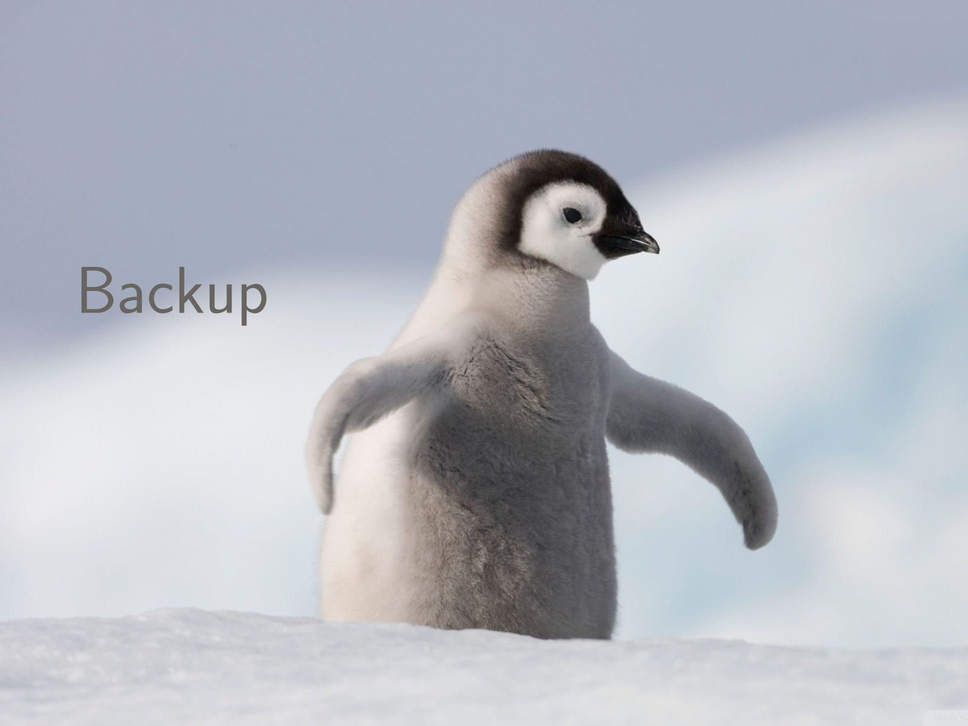
Observables	Belle $0.71\,\text{ab}^{-1}$ $(0.12\,\text{ab}^{-1})$	Belle II $5\,\text{ab}^{-1}$	Belle II $50\,\text{ab}^{-1}$
$\text{Br}(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$\text{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\text{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0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

Summary

- Belle II uniquely positioned to measure important penguin observables to high precision.
- Clean environment at Belle II grants access to unique observables.
- Uncertainties mostly orthogonal to LHCb - complementary analyses, independent verification.
- Strong model-independent constraints on NP through C_7, C_9, C_{10} with full 50 ab^{-1} target data sample.

	Prospects	Precision by 2022
$b \to s(d)\gamma$	Improved Precision in $\mathcal{B}_{s\gamma}$ ($\mathcal{B}_{d\gamma}$)	4% (20%)
$b \to s\ell\ell$	Measure $R(X_s)$ (A_{FB})	$\approx$ 11% (8%)
$B \to K^{(*)}\ell\ell$	Verify R_K (R_{K^*}) anomalies	$\approx$ 11% (10%)
$b \to K^{(*)}\nu\nu$	Observe if at expected SM rate	$\approx$ 26%

Backup



$b \to s(d)\gamma$

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B \to X_s\gamma)^{\text{lep-tag}}_{\text{inc}}$	5.3%	2022 3.9%	3.2%
$\mathrm{Br}(B \to X_s\gamma)^{\text{had-tag}}_{\text{inc}}$	13%	7.0%	4.2%
$\mathrm{Br}(B \to X_s\gamma)_{\text{sum-of-ex}}$	10.5%	7.3%	5.7%
$\Delta_{0+}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.1%	0.81%	0.63%
$\Delta_{0+}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	9.0%	2.6%	0.85%
$A_{CP}(B \to X_s\gamma)_{\text{sum-of-ex}}$	1.3%	0.52%	0.19%
$A_{CP}(B^0 \to X_s^0\gamma)_{\text{sum-of-ex}}$	1.8%	0.72%	0.26%
$A_{CP}(B^+ \to X_s^+\gamma)_{\text{sum-of-ex}}$	1.8%	0.69%	0.25%
$A_{CP}(B \to X_{s+d}\gamma)^{\text{lep-tag}}_{\text{inc}}$	4.0%	1.5%	0.48%
$A_{CP}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	8.0%	2.2%	0.70%
$\Delta A_{CP}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.5%	0.98%	0.30%
$\Delta A_{CP}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	16%	4.3%	1.3%
$\mathrm{Br}(B \to X_d\gamma)_{\text{sum-of-ex}}$	30%	20%	14%
$\Delta_{0+}(B \to X_d\gamma)_{\text{sum-of-ex}}$	30%	11%	3.6%
$A_{CP}(B^+ \to X^+_{u\bar{d}}\gamma)_{\text{sum-of-ex}}$	42%	16%	5.1%
$A_{CP}(B^0 \to X^0_{d\bar{d}}\gamma)_{\text{sum-of-ex}}$	84%	32%	10%
$A_{CP}(B \to X_d\gamma)_{\text{sum-of-ex}}$	38%	14%	4.6%
$\Delta A_{CP}(B \to X_d\gamma)_{\text{sum-of-ex}}$	93%	36%	11%

$b \to s\ell\ell$

Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B \to X_s\ell^+\ell^-)$ ($[1.0, 3.5]\,\mathrm{GeV}^2$)	29%	13%	6.6%
$\mathrm{Br}(B \to X_s\ell^+\ell^-)$ ($[3.5, 6.0]\,\mathrm{GeV}^2$)	24%	11%	6.4%
$\mathrm{Br}(B \to X_s\ell^+\ell^-)$ ($> 14.4\ \mathrm{GeV}^2$)	23%	10%	4.7%
$A_{\mathrm{CP}}(B \to X_s\ell^+\ell^-)$ ($[1.0, 3.5]\,\mathrm{GeV}^2$)	26%	9.7 %	3.1 %
$A_{\mathrm{CP}}(B \to X_s\ell^+\ell^-)$ ($[3.5, 6.0]\,\mathrm{GeV}^2$)	21%	7.9 %	2.6 %
$A_{\mathrm{CP}}(B \to X_s\ell^+\ell^-)$ ($> 14.4\ \mathrm{GeV}^2$)	21%	8.1 %	2.6 %
$A_{\mathrm{FB}}(B \to X_s\ell^+\ell^-)$ ($[1.0, 3.5]\,\mathrm{GeV}^2$)	26%	9.7%	3.1%
$A_{\mathrm{FB}}(B \to X_s\ell^+\ell^-)$ ($[3.5, 6.0]\,\mathrm{GeV}^2$)	21%	7.9%	2.6%
$A_{\mathrm{FB}}(B \to X_s\ell^+\ell^-)$ ($> 14.4\ \mathrm{GeV}^2$)	19%	7.3%	2.4%
$\Delta_{\mathrm{CP}}(A_{\mathrm{FB}})$ ($[1.0, 3.5]\,\mathrm{GeV}^2$)	52%	19%	6.1%
$\Delta_{\mathrm{CP}}(A_{\mathrm{FB}})$ ($[3.5, 6.0]\,\mathrm{GeV}^2$)	42%	16%	5.2%
$\Delta_{\mathrm{CP}}(A_{\mathrm{FB}})$ ($> 14.4\ \mathrm{GeV}^2$)	38%	15%	4.8%

Figure 2: Belle II sensitivites to $b \to s\ell\ell$ observables subject to hadronic mass requirement $M_{X_s} < 2.0$ GeV.