Radiative and electroweak penguin decays: results and prospects at Belle II

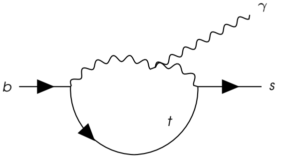
Soumen Halder
on behalf of the Belle II collaboration

10th June, 2020 (Wednesday)

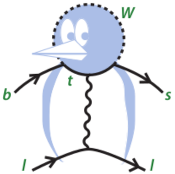
1. Beyond-the-Standard Model (BSM) searches via rare B decays
2. Belle II operation status
3. Analysis strategy
4. Radiative penguin B decays
5. Electroweak penguin B decays
6. Conclusion

BSM searches via rare B decays

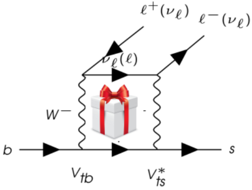
- $b \to s(d)$ is an FCNC transition which is not allowed at tree level in the standard model (SM)
  - $\to$ loop and CKM suppressed
- BSM particles can appear in loop, change branching fractions and/or other observables



$b \to s\gamma$ (radiative penguin)

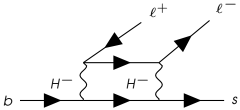


$b \to s\ell\ell$ (EW penguin)



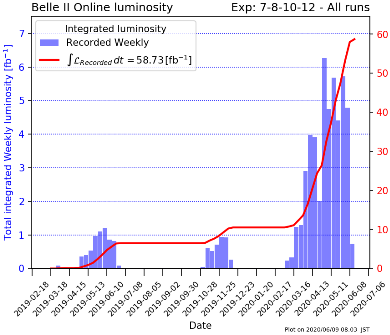
$b \to s\ell\ell$ (box diagram)

SM allowed processes

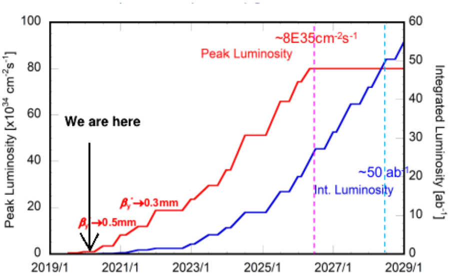


A possible BSM process

Belle II operation



Roadmap for data taking



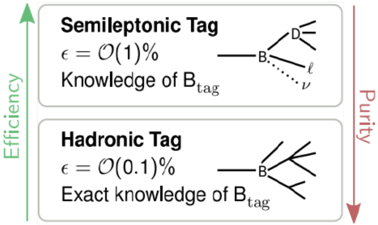
Roadmap for data taking

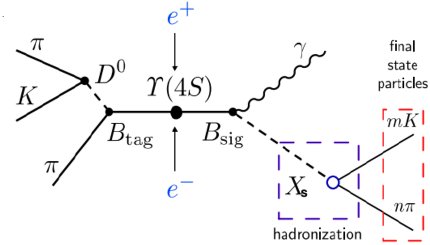
- Collected 0.5 fb^{-1} in 2018
- Recorded about 60 fb^{-1} since 2019
- Analyses performed on upto 8.7 fb^{-1} of data
- **Goal: integrate upto 50 ab^{-1} by 2029**

For more information on Belle II see Phillip Urquijo's talk

Analysis strategy

- Exclusive: Reconstruct a specific decay channel, say $B \to K^*\gamma$
- Inclusive: $B \to X_s\gamma$, where X_s is any strange final state
  - * Semi-inclusive or sum-of-exclusive: Reconstruct X_s from as many final states as possible
  - * Fully inclusive[1]





Hadronic tagged $B \to X_s\gamma$ event in center-of-mass frame

[1] For details look FEI talk by Slavomira Stefkova

1. Beyond-the-Standard Model (BSM) searches via rare *B* decays
2. Belle II operation status
3. Analysis strategy
4. Radiative penguin B decays
5. Electroweak penguin B decays
6. Conclusion

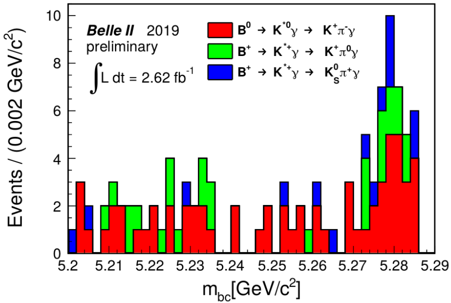
First penguin decay observed at Belle II ($B \to K^*\gamma$)

Motivation

- Evidence (3.1σ) for isospin violation from recent measurement
  $\Delta_{0+} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)} = [+6.2 \pm 1.5(\text{stat}) \pm 0.6(\text{syst}) \pm 1.2(f_{+-}/f_{00})]\%$
  (PRL 119 (2017) 191802)
- Possible window for BSM physics? (PRD 88 (2013) 094004)
- At Belle II isospin violation can be observed $> 5\sigma$ precision with 5 ab^{-1}

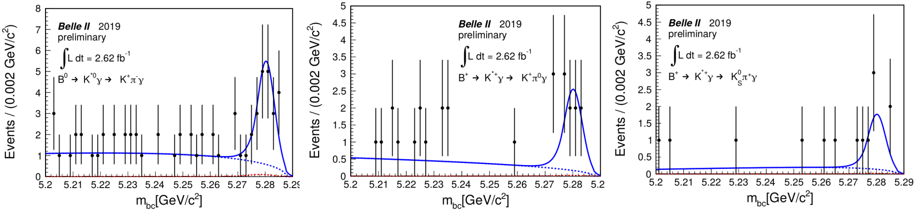
Analysis procedure $\to$ BELLE2-NOTE-PL-2019-021

- Search for $B \to K^*\gamma$ using three decay modes
- Dominant $q\bar{q}$ events suppressed with a FastBDT multivariate classifier (arXiv:1609.06119).
- $\Delta E (= E_B^* - E_{\text{beam}}) \in [-0.2, 0.08]$ GeV
- Clear peak in the beam-energy-constrained mass $M_{\text{bc}}(= \sqrt{E_{\text{beam}}^{*2} - p_B^{*2}})$ distribution near the nominal B mass



Signal extraction of $K^*\gamma$ process

- Fit the M_{bc} distribution to extract signal yield



	signal yield ((stat. error only))	significance
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	19.1 ± 5.2	4.4σ
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	9.8 ± 3.4	3.7σ
$B^+ \to K^{*+}[K_s^0\pi^+]\gamma$	6.6 ± 3.1	2.1σ

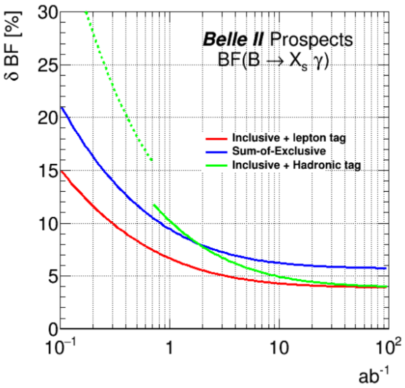
- Yield agrees with the expectation from world-average branching fraction
- Combined significance exceeds 5σ

Rediscovery of radiative penguin decay at Belle II

Inclusive branching fraction measurement

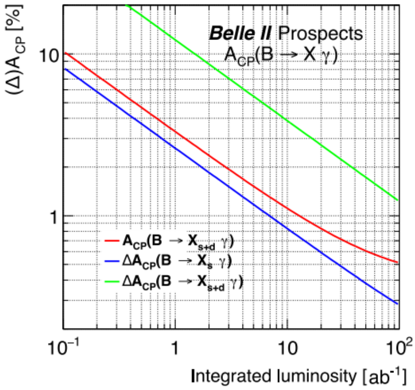
- Theoretically more reliable than exclusive
  - $\mathcal{B}^{SM}(B \to X_s\gamma) = (3.36 \pm 0.23) \times 10^{-4}$ for $E_\gamma > 1.6$ GeV (PRL 114 (2015) 22)
- In effective field theory it puts a strong constraint on the Wilson coefficient C_7
- Measurements (eg. arxiv:1608.02344) are consistent with SM and limited by systematic uncertainty

- Goal for Belle II
  - Fully inclusive - reduce systematics by better modelling of neutral hadrons faking photons
  - Sum-of-exclusive - increase the number of modes to reduce the systematic from X_s hadronization
  - Hadronic tagging method - increased purity so that the $E_\gamma^{\text{threshold}}$ can be reduced



Inclusive direct CP violation

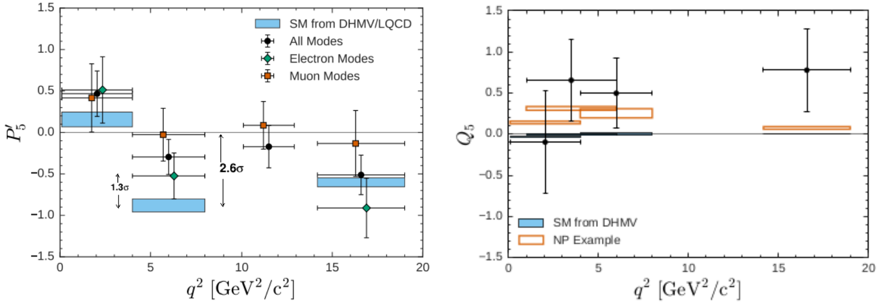
- $A_{CP}^{X_{s+d}\gamma} = \frac{\Gamma(\bar{B}\to X_{s+d}\gamma)-\Gamma(B\to X_{\bar{s+d}}\gamma)}{\Gamma(\bar{B}\to X_{s+d}\gamma)+\Gamma(B\to X_{\bar{s+d}}\gamma)} \sim \mathcal{O}(\Lambda_{QCD}/m_b)$
  - → Deviation from zero indicates BSM physics (PRL 106 (2011) 141801)
  - → $A_{CP}^{X_{s+d}\gamma} = (2.2 \pm 3.9\,(\text{stat}) \pm 0.9\,(\text{syst}))\%$ (arxiv:1608.02344)
- $\Delta A_{CP}(B \to X_s\gamma) = A_{CP}(B^+ \to X_s^+\gamma) - A_{CP}(B^0 \to X_s^0\gamma) \propto Im(C_{8g}/c_{7\gamma}) \to$ zero in SM
  - → $\Delta A_{CP} = (3.69 \pm 2.65\,(\text{stat}) \pm 0.76\,(\text{syst}))\%$ (PRD 99 (2019) 3)
- Goal for Belle II
  - Reduce statistical uncertainty
  - Systematic uncertainty due to detector asymmetry could be reduced using control samples
  - More measurements at Belle II of A_{CP} in rare charmless decays, that can fake the inclusive signal → Room for improvement using more realistic peaking background study



1. Beyond-the-Standard Model (BSM) searches via rare *B* decays
2. Belle II operation status
3. Analysis strategy
4. Radiative penguin B decays
5. Electroweak penguin B decays
6. Conclusion

Angular analysis: $B \to K^* \ell^+ \ell^-$

- Angular observables $P'_{i=4,5,6,8}$ are suggested to be theoretically robust (JHEP 05 (2013) 137)
- Sensitive to Wilson coefficients C_7, C_9 and C_{10}
- Lepton flavour universality (LFU) test with $Q_i = P_i^{\mu} - P_i^{e}$

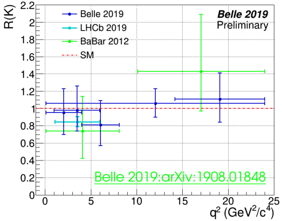


Distribution of P'_5 (left) and Q'_5(right) in Belle measurement

- Belle measurement (PRL 118, 111801) uncertainty is statistically dominated
- Sensitivity to P'_5 with full Belle II data in the 4-8 GeV^2/c^2 bin will be around 0.04 (PTEP 2020(2020) 2)

Lepton flavor universality test

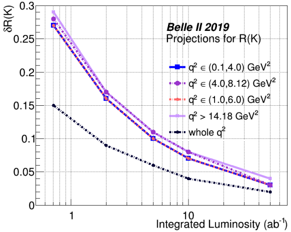
$$R_H[q_0^2, q_1^2] = \frac{\int_{q_0^2}^{q_1^2} dq^2 \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}}{\int_{q_0^2}^{q_1^2} dq^2 \frac{d\Gamma(B \to He^+e^-)}{dq^2}}$$

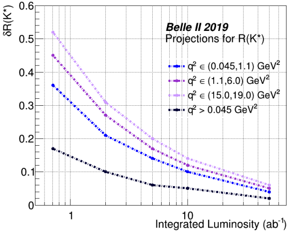


- In SM gauge bosons couple equally to different lepton flavours
- Precise prediction of R_H ratios in SM

Advantage for Belle II

- Electron and muon modes have similar efficiency
- Both low and high q^2 regions will be measured
- All $R_{K(*)}$ and R_{X_s} are possible at Belle II



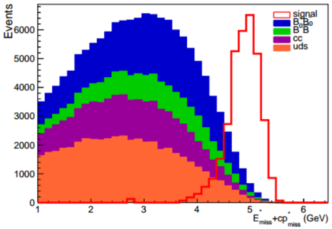


If 2.7σ deviation is real, Belle II should be able to make a 5σ discovery with 20 ab^{-1}

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

- Theoretically cleaner w.r.t $b \to s\ell^+\ell^-$
  - No photon mediated (Q_7) contribution
  - BF allows to extract form factors to high accuracy
- Clean observable: K^* longitudinal polarisation fraction (F_L).
  - $F_L^{\text{SM}} = 0.47 \pm 0.03$
  - Sensitive to BSM right-handed-current $\to Q_R^\nu$ (JHEP 04 (2009) 022)
- Interesting in dark matter context (JHEP 03 (2012) 090)

⇒ Measurement in Belle (PRD 87, 111103) and BaBar (PRD 82, 112002) provided UL on the BF



Distributions of missing 4-momentum in the CM frame with hadronic tag for $B^0 \to K^{*0}[K^+\pi^-]\nu\bar{\nu}$ (Belle II MC with arbitrary signal normalisation (PTEP 2020(2020) 2))

Belle II prospects

- Expect to observe $B \to K^*\nu\bar{\nu}$ decays with ≈ 5 ab^{-1}
- 10% BF measurement possible with 50 ab^{-1}
- Sensitivity on F_L with 50 ab^{-1} is about 0.08 for both $K^{*0/+}\nu\bar{\nu}$

Conclusion

- Belle II is collecting data and has recorded 55 fb^{-1}.
- Clean environment at Belle II grants access to unique observables in rare B decays
- We have made a beginning with the rediscovery of a radiative *B* decay
- We expect to provide model-independent constraints on BSM physics, thanks to the large data sample of Belle II

Backup

BSM searches via radiative or EWP B decays

$$\mathcal{H}_{\text{eff}} = \sum_i \lambda^i_{CKM} C_i(\mu) Q_i(\mu) + \text{h.c}$$

- $C_i(\mu)$ Short distance contribution (physics above EW scale)
- $Q_i(\mu)$ Local operators constructed from fields below EW scale, encode large distance contribution

NP can contribute through,

- $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$
- Generate new operators not present in SM

Few SM operators

- $Q_7 = \frac{e}{16\pi^2} m_b (\bar{q}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$
- $Q_8 = \frac{g_s}{16\pi^2} m_b (\bar{q}_L \sigma^{\mu\nu} T^a b_R) G^a_{\mu\nu}$
- $Q_9 = \frac{e}{16\pi^2} (\bar{q}_L \gamma_\mu b_L) \sum_\ell (\bar{\ell} \gamma^\mu \ell)$
- $Q_{10} = \frac{e}{16\pi^2} (\bar{q}_L \gamma_\mu b_L) \sum_\ell (\bar{\ell} \gamma^\mu \gamma_5 \ell)$
- $Q_\nu = \frac{e}{16\pi^2} (\bar{q}_L \gamma_\mu b_L) \sum_\ell (\bar{\nu_{\ell L}} \gamma^\mu \nu_{\ell L})$

beyond SM operator

- $Q^{L(R)}_{\nu\ell} = \frac{e}{16\pi^2} (\bar{q}_{L(R)} \gamma_\mu b_{L(R)}) (\bar{\nu_{\ell L}} \gamma^\mu \nu_{\ell L})$

- For $b \to s\gamma$ processes C_7
- For $b \to s\gamma$ processes C_7,C_9 and C_{10}
- For $b \to s\nu\bar{\nu}$ Q_ν
  is sensitive.

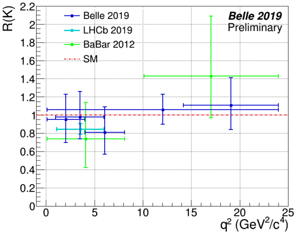
Radiative penguin B decay

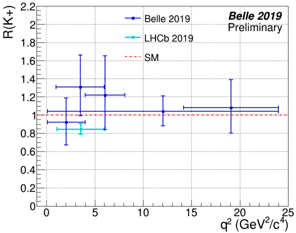
Sensitivities of observables for the radiative inclusive B decay. A photon energy threshold of $E_\gamma > 1.9GeV (E_\gamma > 2.0GeV)$ is assumed for the $B \to X_{s\gamma} (B \to X_{d\gamma})$ analysis. Some sensitivities at Belle are extrapolated to 0.71 ab^{-1}. In the case of the branching ratios the quoted uncertainties are relative ones, while for what concerns Δ_{0+}, A_{CP} and ΔA_{CP} they are absolute numbers. [2]

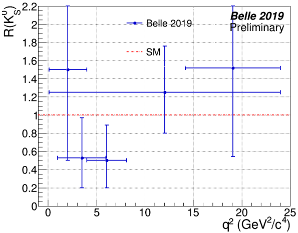
Observables	Belle 0.71(0.12)ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B \to X_{s\gamma})^{\text{lep-tag}}_{\text{inc}}$	5.3%	3.9%	3.2%
$Br(B \to X_{s\gamma})^{\text{had-tag}}_{\text{inc}}$	13%	7.0%	4.2%
$Br(B \to X_{s\gamma})_{\text{sum-of-ex}}$	10.5%	7.3%	5.7%
$\Delta_{0+}(B \to X_{s\gamma})_{\text{sum-of-ex}}$	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%
$A_{CP}(B^0 \to X^0_{s\gamma})_{\text{sum-of-ex}}$	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%

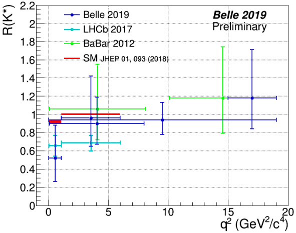
[2] PTEP 2020(2020) 2

Lepton universality test

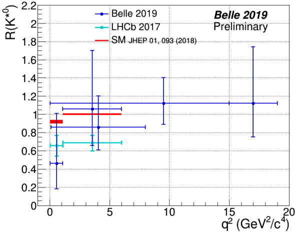




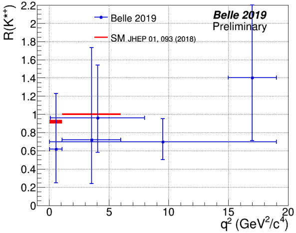




(d) R_{K*}



(e) R_{K*0}



(f) R_{K*+}

Angular analysis: $B \to K^*\ell^+\ell^-$

For $\bar{B}^0 \to \bar{K}^{*0}[K^-\pi^+]\mu^+\mu^-$,

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi} I(q^2,\theta_K,\theta_\ell,\phi)$$

The corresponding expression for the CP-conjugated mode is $B^0 \to K^{*0}[K^+\pi^-]e^+e^-$,

$$\frac{1}{d\bar{\Gamma}/dq^2}\frac{d^4\bar{\Gamma}}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi} \bar{I}(q^2,\theta_K,\theta_\ell,\phi)$$

,
where $\bar{I}(q^2,\theta_K,\theta_\ell,\phi)$ is obtained by, $I^{(a)}_{1,2,3,4,7} \to \bar{I}^{(a)}_{1,2,3,4,7}$ and $I^{(a)}_{5,6,8,9} \to -\bar{I}^{(a)}_{5,6,8,9}$.

Now define [a] $S_i^{(a)} = (I_i^{(a)} + \bar{I}_i^{(a)})/\frac{d(\Gamma+\bar{\Gamma})}{dq^2}$ and $A_i^{(a)} = (I_i^{(a)} - \bar{I}_i^{(a)})/\frac{d(\Gamma+\bar{\Gamma})}{dq^2}$

Define[b] $P'_{i=4,5,6,8} = \frac{S_{j=4,5,6,8}}{\sqrt{F_L(1-F_L)}}$

[a] JHEP 01 (2009) 019
[b] JHEP 05 (2013) 137

$I(q^2,\theta_\ell,\theta_{K^*},\phi) = [I_1^s \sin^2\theta_{K^*} + I_1^c \cos^2\theta_{K^*} + (I_2^s \sin^2\theta_{K^*} + I_2^c \cos^2\theta_{K^*})\cos 2\theta_\ell + ..$

where, θ_{K^*} is angle between K^{*0} ($\bar{K}^{*0}$) and $K^+(K^-)$ in $B(\bar{B})$ rest frame,
θ_ℓ is angle between $\ell^+(\ell^-)$ and the direction of di-lepton system in the $B(\bar{B})$ rest frame

Angular analysis: $B \to K^* \ell^+ \ell^-$

TABLE I. Fit results for P_4' and P_5' for all decay channels and separately, for the electron and muon modes. The first uncertainties are statistical and the second systematic.

q^2 in GeV$^2/c^2$	P_4'	$P_4^{e\prime}$	$P_4^{\mu\prime}$	P_5'	$P_5^{e\prime}$	$P_5^{\mu\prime}$
[1.00, 6.00]	$-0.45^{+0.23}_{-0.22} \pm 0.09$	$-0.72^{+0.40}_{-0.39} \pm 0.06$	$-0.22^{+0.35}_{-0.34} \pm 0.15$	$0.23^{+0.21}_{-0.22} \pm 0.07$	$-0.22^{+0.39}_{-0.41} \pm 0.03$	$0.43^{+0.26}_{-0.28} \pm 0.10$
[0.10, 4.00]	$0.11^{+0.32}_{-0.31} \pm 0.05$	$0.34^{+0.41}_{-0.45} \pm 0.11$	$-0.38^{+0.50}_{-0.48} \pm 0.12$	$0.47^{+0.27}_{-0.28} \pm 0.05$	$0.51^{+0.39}_{-0.46} \pm 0.09$	$0.42^{+0.39}_{-0.39} \pm 0.14$
[4.00, 8.00]	$-0.34^{+0.18}_{-0.17} \pm 0.05$	$-0.52^{+0.24}_{-0.22} \pm 0.03$	$-0.07^{+0.32}_{-0.31} \pm 0.07$	$-0.30^{+0.19}_{-0.19} \pm 0.09$	$-0.52^{+0.28}_{-0.26} \pm 0.03$	$-0.03^{+0.31}_{-0.30} \pm 0.09$
[10.09, 12.90]	$-0.18^{+0.28}_{-0.27} \pm 0.06$	...	$-0.40^{+0.33}_{-0.29} \pm 0.09$	$-0.17^{+0.25}_{-0.25} \pm 0.01$	...	$0.09^{+0.29}_{-0.29} \pm 0.02$
[14.18, 19.00]	$-0.14^{+0.26}_{-0.26} \pm 0.05$	$-0.15^{+0.41}_{-0.40} \pm 0.04$	$-0.10^{+0.39}_{-0.39} \pm 0.07$	$-0.51^{+0.24}_{-0.22} \pm 0.01$	$-0.91^{+0.36}_{-0.30} \pm 0.03$	$-0.13^{+0.39}_{-0.35} \pm 0.06$

Belle Result (PRL 118, 111801)

$4.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$		$6.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$	
P_1	$0.088 \pm 0.235 \pm 0.029$	P_1	$-0.071 \pm 0.211 \pm 0.020$
P_2	$0.105 \pm 0.068 \pm 0.009$	P_2	$0.207 \pm 0.048 \pm 0.013$
P_3	$-0.090 \pm 0.139 \pm 0.006$	P_3	$-0.068 \pm 0.104 \pm 0.007$
P_4'	$-0.312 \pm 0.115 \pm 0.013$	P_4'	$-0.574 \pm 0.091 \pm 0.018$
P_5'	$-0.439 \pm 0.111 \pm 0.036$	P_5'	$-0.583 \pm 0.090 \pm 0.030$
P_6'	$-0.293 \pm 0.117 \pm 0.004$	P_6'	$-0.155 \pm 0.098 \pm 0.009$
P_8'	$0.166 \pm 0.127 \pm 0.004$	P_8'	$-0.129 \pm 0.098 \pm 0.005$

LHCb Result (arxiv:2003.04831)

Lepton flavor universality test

- LHCb result $R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$ for $q^2 \in [1.0, 6.0]\mathrm{GeV}^2/c^4$ (PRL 122, 191801)
- Belle result, 2.7σ deviation in 3rd bin (arxiv 1908.01848)

$$R_K = \begin{cases} 0.95\ ^{+0.27}_{-0.24} \pm 0.06 & q^2 \in (0.1, 4.0) \quad \mathrm{GeV}^2/c^4, \\ 0.81\ ^{+0.28}_{-0.23} \pm 0.05 & q^2 \in (4.0, 8.12) \quad \mathrm{GeV}^2/c^4, \\ 0.98\ ^{+0.27}_{-0.23} \pm 0.06 & q^2 \in (1.0, 6.0) \quad \mathrm{GeV}^2/c^4, \\ 1.11\ ^{+0.29}_{-0.26} \pm 0.07 & q^2 > 14.18 \quad \mathrm{GeV}^2/c^4. \end{cases}$$

Electroweak penguin B decays

The Belle II sensitivities to $B \to K^{(*)}\ell^+\ell^-$ observables that allow to test lepton flavour universality. Some numbers at Belle are extrapolated to 0.71 ab^{-1}

Observables	Belle 0.71(0.12)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%

The Belle II sensitivities of the angular observables in $B \to K^{(*)}\ell^+\ell^-$. Some numbers at Belle are extrapolated to 0.71 ab^{-1}

Observables	Belle 0.71(0.12)ab^{-1}	Belle II 5ab^{-1}	Belle II 50 ab^{-1}
$P'_5([1.0, 2.5]GeV^2)$	0.47	0.17	0.054
$P'_5([2.5, 4.0]GeV^2)$	0.42	0.15	0.049
$P'_5([4.0, 6.0]GeV^2)$	0.34	0.12	0.040
$P'_5([> 14.2]GeV^2)$	0.23	0.088	0.027

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

Sensitivities to the modes involving neutrinos in the final states. We assume that 5ab^{-1} of data will be taken on the $\Upsilon(5S)$ resonance at Belle II. Some numbers at Belle are extrapolated to $0.71\text{ab}^{-1}(0.12\text{ab}^{-1})$ for the $B_{u,d}(B_s)$ decay.

Observables	Belle $0.71(0.12)\text{ab}^{-1}$	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	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

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

Defining F_L: JHEP 04 (2009) 022

$\frac{d\Gamma_L}{ds_B} = 3m_B^2|A_0|^2$, $\frac{d\Gamma_L}{ds_B} = 3m_B^2|A_0|^2$
where $s_B = q^2/m_B^2$ and q is invariant mass of $\nu\bar{\nu}$
$\frac{d^2\Gamma}{ds_B d\cos\theta} = \frac{3}{4}\frac{d\Gamma_T}{ds_B}\sin^2\theta + \frac{3}{2}\frac{d\Gamma_L}{ds_B}\cos^2\theta$
where θ is the angle between the K^* flight direction in the B rest frame and the K flight direction in the $K\pi$ rest frame. $\frac{d\Gamma_L}{ds_B}$ and $\frac{d\Gamma_T}{ds_B}$ can be extracted using Angular analysis.
$\frac{d\Gamma}{ds_B} = \frac{d\Gamma_T}{ds_B} + \frac{d\Gamma_L}{ds_B}$
$\Rightarrow F_L = \frac{d\Gamma_L}{ds_B}$ and $F_T = 1 - F_L$