Results and Prospects of Radiative and Electroweak Penguin Decays at Belle II

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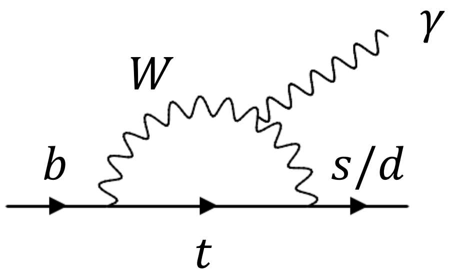
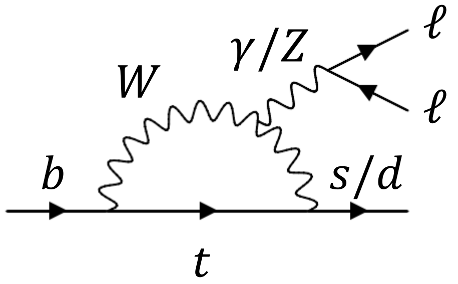
Belle II

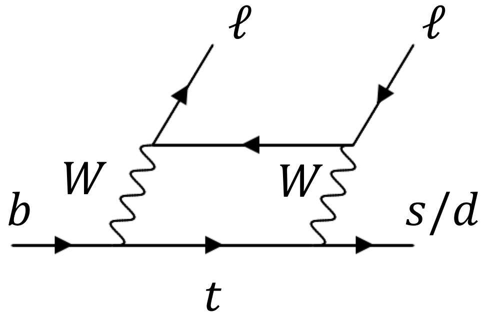
Introduction

- Flavour-changing neutral current (FCNC) $b \to s$ and $b \to d$ processes continue to be a great probe for new physics beyond the standard model.

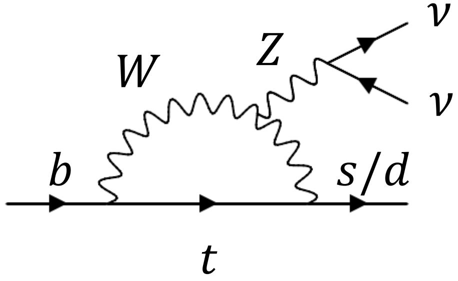


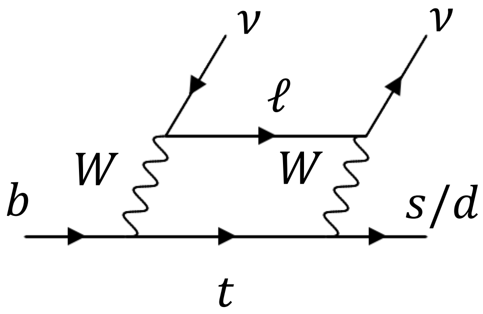
- Radiative and electroweak (EW) penguin decays are theoretically and experimentally clean because the final states include color single particle(s), γ, $\ell^+\ell^-$, $\nu\bar{\nu}$.





- The anomalies in $B \to K^{(*)}\ell^+\ell^-$ decays motivate further studies on this field.
[LHCb : 1, 2, 3] [Belle : 4]

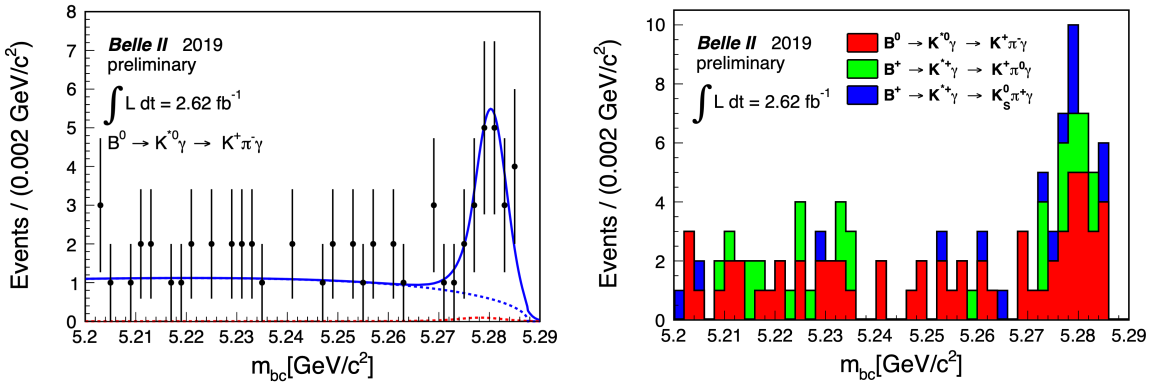




Radiative and EW Penguin decays at Belle II

Belle II program on the channels includes

- Time dependent CP violation in radiative decays.
  - New physics can induce much larger decay rate of $b_L \to s_R \gamma_R$ which introduce large mixed-induced CP violation.
  - Rediscovery of $B \to K^* \gamma$ at Belle II. Update with new dataset is in progress.
- Measurements on inclusive $B \to X_s \ell^+ \ell^-$ decays to shed further light on the anomalies of exclusive $B \to K^{(*)} \ell^+ \ell^-$.
- Discovery of the channels involving neutrino like $B \to K^{(*)} \nu \bar{\nu}$.



BELLE2-NOTE-PL-2019-021

Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathcal{B}(B \to K^{*+} \nu\bar{\nu})$	$< 40 \times 10^{-6}$	25%	9%
$\mathcal{B}(B \to K^{+} \nu\bar{\nu})$	$< 19 \times 10^{-6}$	30%	11%
$A_{CP}(B \to X_{s+d}\gamma)$ $[10^{-2}]$	$2.2 \pm 4.0 \pm 0.8$	1.5	0.5
$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$	0.11	0.035
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	0.23	0.07
$A_{FB}(B \to X_s \ell^+ \ell^-)$ $(1 < q^2 < 3.5\ \mathrm{GeV}^2/c^4)$	26%	10%	3%
$Br(B \to K^+ \mu^+ \mu^-)/Br(B \to K^+ e^+ e^-)$ $(1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$	28%	11%	4%
$Br(B \to K^{*+}(892)\mu^+ \mu^-)/Br(B \to K^{*+}(892) e^+ e^-)$ $(1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$	24%	9%	3%
$\mathcal{B}(B_s \to \gamma\gamma)$	$< 8.7 \times 10^{-6}$	23%	–
$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	–	< 0.8	–

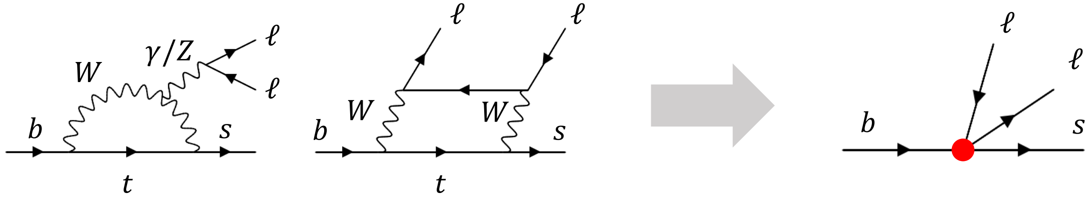
The Belle II Physics Book, PTEP 2019 (2019) 12
hereinafter referred to as B2TiP

In the SM,

- $b \to s\ell^+\ell^-$: C_7, C_9, and C_{10}.
- $C_7 \sim -0.3$, $C_9 \sim 4$, $C_{10} \sim -4$.
- Lepton Flavor Universality (LFU), $C_e = C_\mu$.

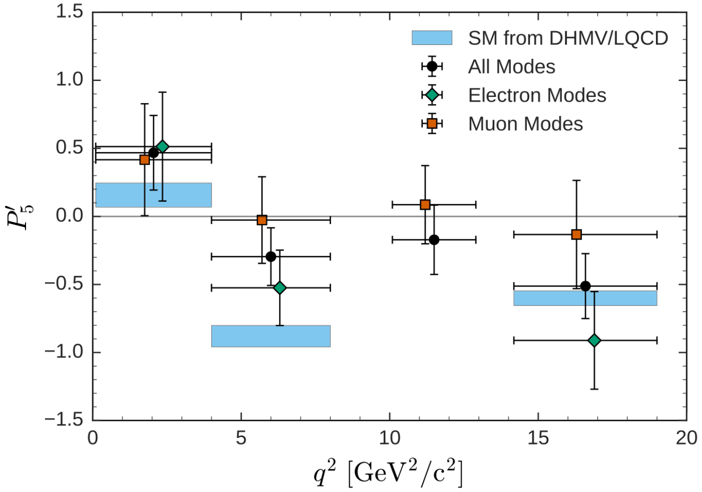
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

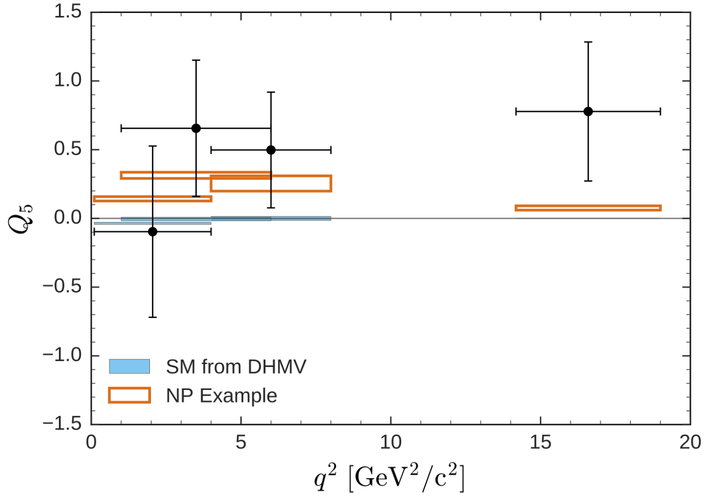
$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu},$$
$$\mathcal{O}_{9\ell} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell),$$
$$\mathcal{O}_{10\ell} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$



Anomalies in exclusive $B \to K^{(*)}\ell^+\ell^-$ imply smaller C_9, especially for $C_{9\mu}$.

- Angular observable P_5' in $B \to K^*\ell^+\ell^-$.
  - $Q_5 = P_5'^{\mu} - P_5'^{e}$.
- LFU violation, R_K, R_{K^*}.

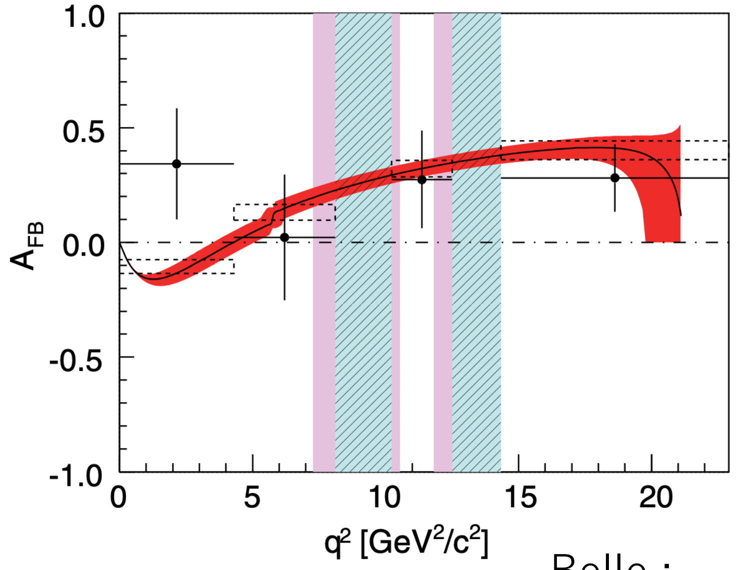




Belle : PRL 118 (2017) 111801

Inclusive $B \to X_s \ell^+ \ell^-$

- Hadronic uncertainties are under better control than exclusive $b \to s\ell^+\ell^-$.
- Sum-of-exclusive method : Reconstruct as many final states as possible.
- Experimentally challenging due to large backgrounds.
  - All observables are highly statistics limited.

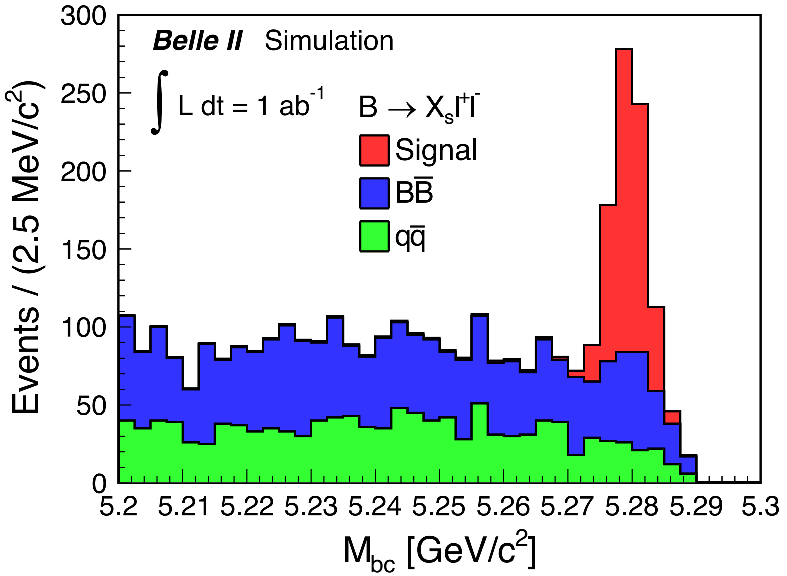


Belle : Phys. Rev. D 93, 032008

Belle II is the unique experiment to perform an analysis of $B \to X_s \ell^+ \ell^-$ with large statistics.

$B \to X_s \ell^+ \ell^-$ in Belle II

- Sum-of-exclusive method
  - X_s is reconstructed from
    - $Kn\pi$ $(n \leq 4)$ and $3K$.
    - at most one K_S^0, π^0.
    - $M_{X_s} < 2.0$ GeV/c^2.
  - Background
    - Dominated by $B(\to X\ell\nu)\bar{B}(\to X\ell\nu)$.
    - Mis-identified $B \to Km\pi$ has to be understood.
  - Sensitivity of BF and A_{FB} is a few % level in 50 ab^{-1}.



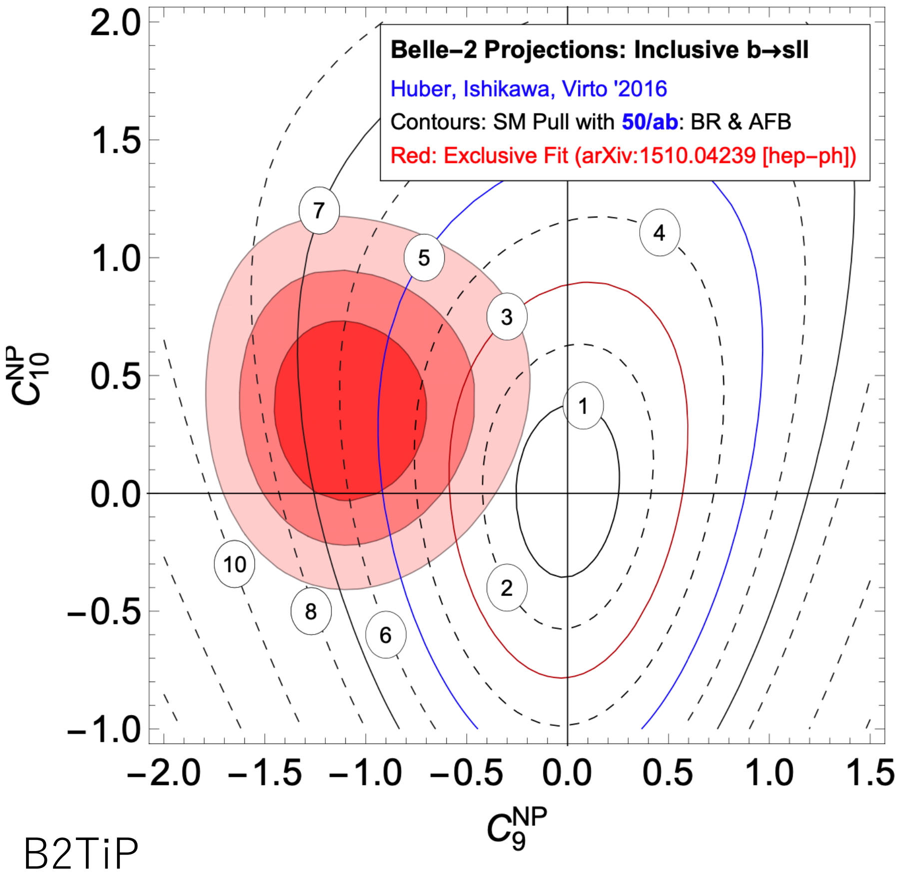
BELLE2-NOTE-PL-2020-007

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

B2TiP

- Fully inclusive method will be explored with dedicated simulation studies.

Interplay of inclusive and exclusive $b \to s\ell^+\ell^-$



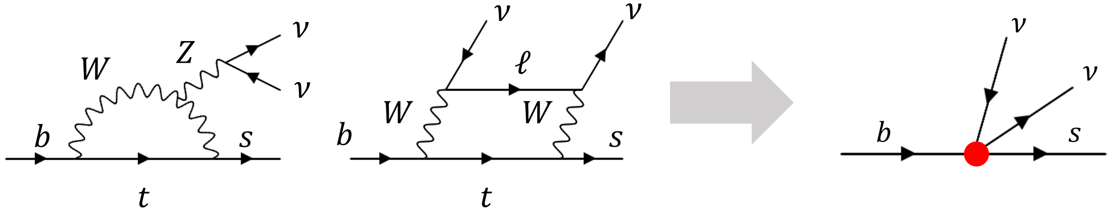
B2TiP

An analysis of inclusive $B \to X_s \ell^+\ell^-$ with 50 ab^{-1} will exclude the SM by 5σ if the true values of C_9 and C_{10} are at the current best-fit.

- Hadronic uncertainties in the inclusive and exclusive decays are independent. Complementary information can be provided.
- Full angular analysis, not only A_{FB}, can be performed with large statistics.

$b \to s\nu\bar{\nu}$

- Theoretically cleaner than $b \to s\ell^+\ell^-$ due to the absence of photon mediated contribution.
  - In the SM, only O_L is relevant.
- Experimentally, the decay has never been observed.
  - Two neutrinos cannot be detected.



$$\mathcal{O}_L = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

Mode	Upper limit
$B^+ \to K^+\nu\bar{\nu}$	$< 5.5 \times 10^{-5}$
$B^0 \to K^0_s\nu\bar{\nu}$	$< 9.7 \times 10^{-5}$
$B^+ \to K^{*+}\nu\bar{\nu}$	$< 4.0 \times 10^{-5}$
$B^0 \to K^{*0}\nu\bar{\nu}$	$< 5.5 \times 10^{-5}$

Belle : Phys. Rev. D87 (2013) 111103

$$\mathrm{BR}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SM}} = (3.98 \pm 0.43 \pm 0.19) \times 10^{-6},$$
$$\mathrm{BR}(B^0 \to K^{*0}\nu\bar{\nu})_{\mathrm{SM}} = (9.19 \pm 0.86 \pm 0.50) \times 10^{-6},$$
$$F_L^{\mathrm{SM}} = 0.47 \pm 0.03\,,$$

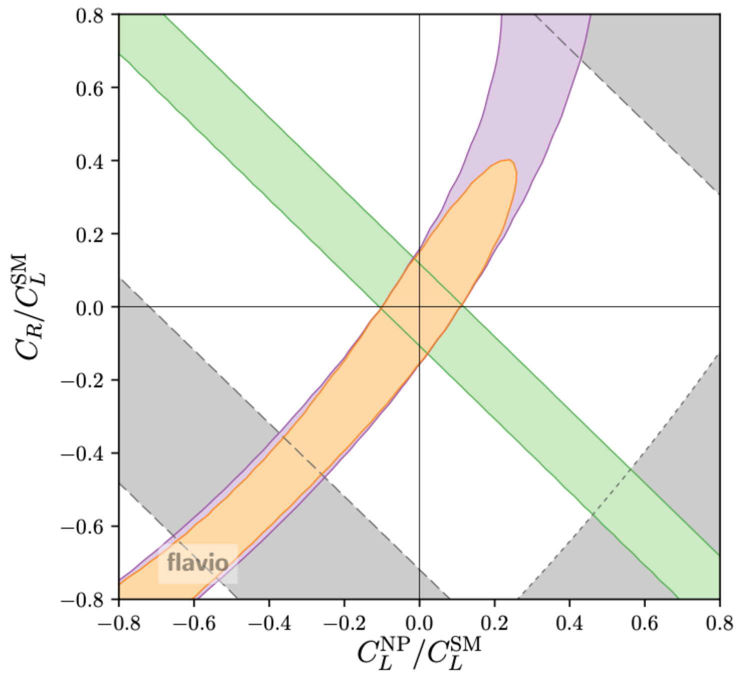
Buras, Girrbach-Noe, Niehoff and Straub, JHEP 02 184 (2015)

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

Belle II can observe the $B \to K^{(*)}\nu\bar{\nu}$ at early stage (several ab^{-1}).

- Hadronic and Semi-leptonic tagging with FEI [T. Keck et al. Comput. Softw. Big. Sci. (2019)3: 6].
- Sensitivity on the BF is 10% level with 50 ab^{-1}.
- The longitudinal polarization fraction $F_L(K^*)$ can be measured with 20% precision.
- Combining measurements of $B \to K\nu\bar{\nu}$ and $K^*\nu\bar{\nu}$ will exclude a large portion of the allowed parameter space.

New analysis method with current data in progress for publication.



Belle + BaBar $B \to K\nu\nu$ 90% CL excluded
Belle + BaBar $B \to K^*\nu\nu$ 90% CL excluded
Belle II $B \to K\nu\nu$ 68% CL allowed
Belle II BR($B \to K^*\nu\nu$) 68% CL allowed
Belle II $B \to K^*\nu\nu$ 68% CL allowed ← Both BF and F_L

B2TiP

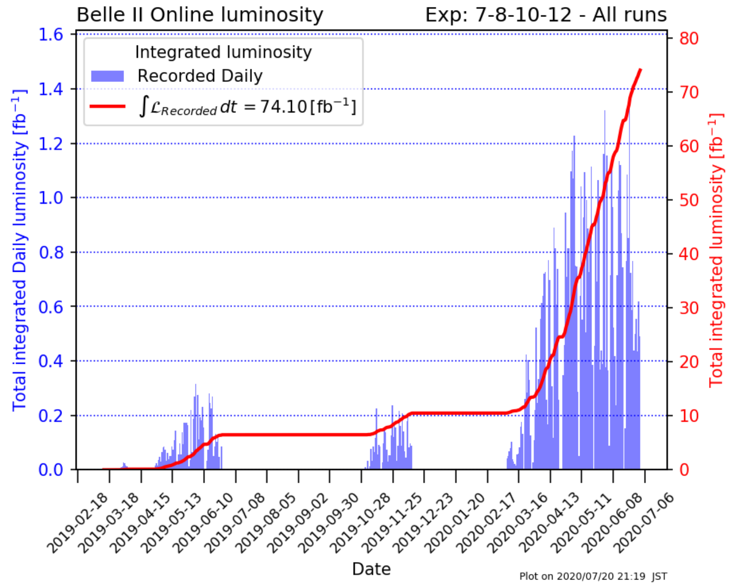
$$\mathcal{O}_L = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)\,,$$

$$\mathcal{O}_R = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)\,.$$

Conclusion

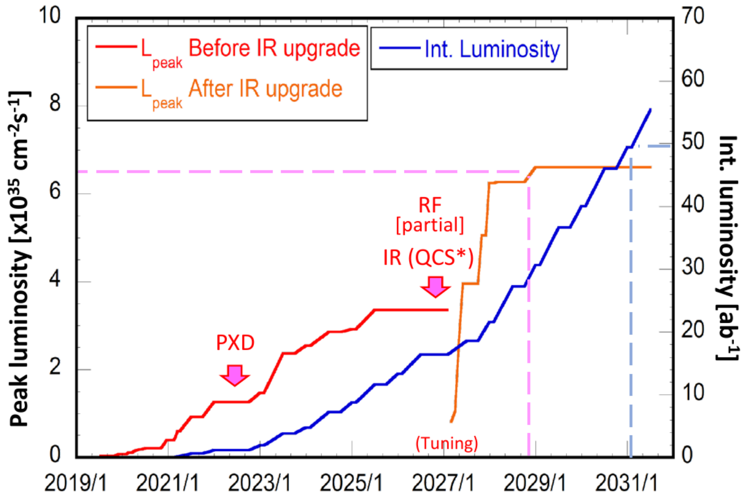
Belle II collected 74.10 fb^{-1} integrated luminosity

- ~10 times more in this summer than last year.
- Measurements in various processes have been started.
  - Rediscovery of $B \to K^*\gamma$.
- First results in $b \to s\ell^+\ell^-$ and $b \to s\nu\bar{\nu}$ in progress.



Goal : L = 50 ab^{-1} by ~2030

- Confirm or exclude the anomalies with $B \to X_s\ell^+\ell^-$.
- Discover $B \to K^{(*)}\nu\bar{\nu}$ at early stage and precise measurements will be performed.



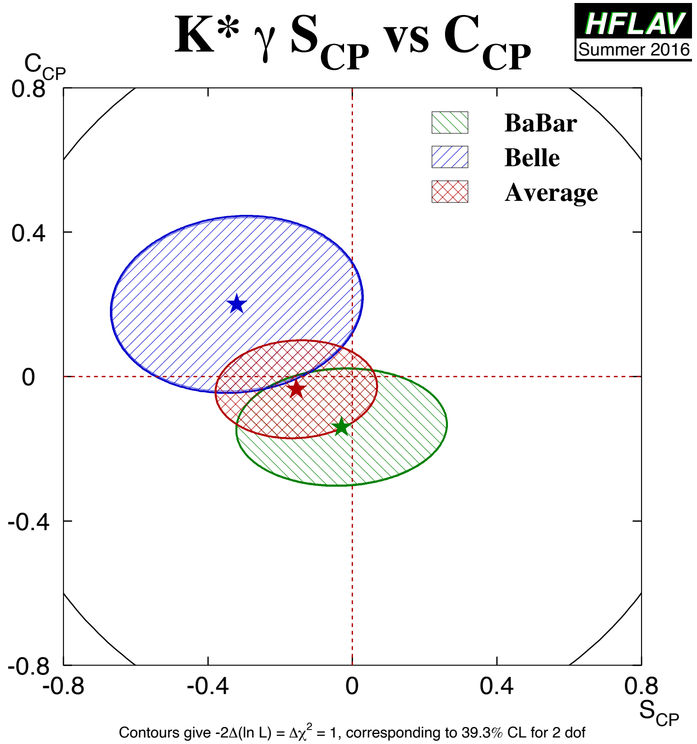
Yo Sato (Tohoku University)

Time dependent CP violation in $b \to s(d)\gamma$

- $b_L \to s_R\gamma_R$ is helicity suppressed (m_s/m_b) compared to $b_R \to s_L\gamma_L$.
- Interference between $B \to f_{CP}\gamma_R$ and $B \to \bar{B} \to f_{CP}\gamma_R$ arises from only the helicity suppressed $b_L \to s_R\gamma_R$ decay.
- SM : $S^{SM}_{K^0_S\pi^0\gamma} \sim -s\frac{m_s}{m_b}\sin 2\phi_1 = -(2.3 \pm 1.6)\%$.
- Current world average : $S^{exp}_{K^0_S\pi^0\gamma} = -0.16 \pm 0.22$.
- New physics can enhance the $b_L \to s_R\gamma_R$ decay rate.

Experimentally,

- $B \to K^*\gamma$ has the largest BF. At several ab-1, tension from SM will be observed if the true values are at world average.
- $B \to \rho\gamma$ will be explored with high statistics.



Int. Lum. ab^{-1}	Stat(S)	Stat(A)
2	0.15	0.10
10	0.07	0.05
50	0.031	0.021

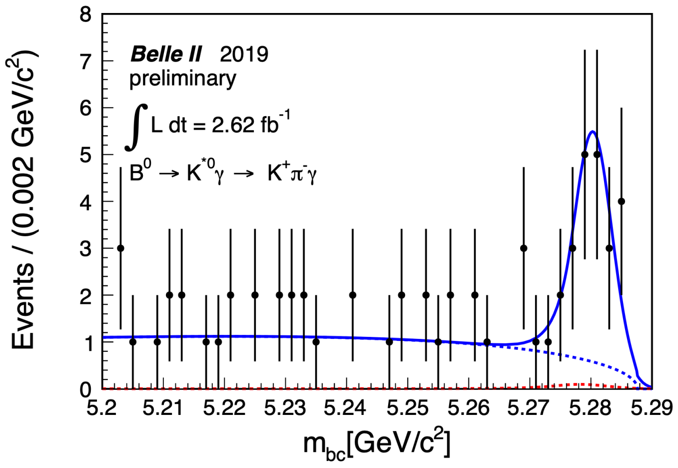
Sensitivity on S and $A(C)$ for $B \to K^*\gamma$ at Belle II, B2TiP

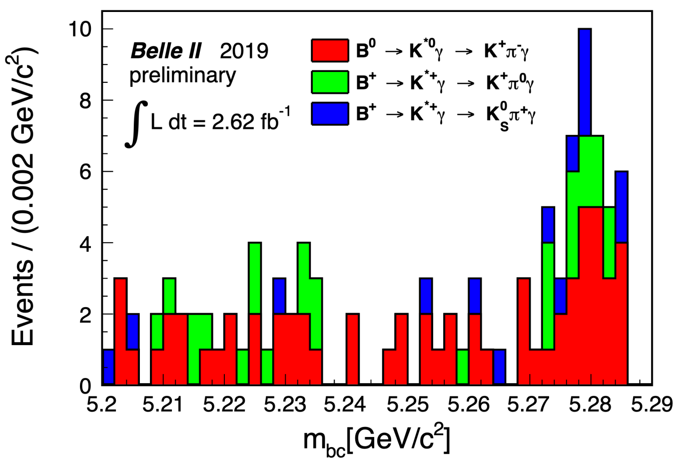
Results of $B \to K^*\gamma$ at Belle II

Search for $B \to K^*\gamma$ decay using three decay modes.

- Clear peak is observed in the beam-constrained mass $M_{bc} = \sqrt{E_{\text{beam}}^{*2} - p_B^{*2}}$ distribution.
- Signal yields agree with world average branching fraction.
- Combined significance exceeds 5σ.

Rediscovery of radiative penguin decay at Belle II.





	Signal yield (stat. error)	Significance
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	19.2 ± 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

BELLE2-NOTE-PL-2019-021

Full angular analysis of $B \to X_s \ell^+ \ell^-$

The double differential decay rate for $B \to X_s \ell^+ \ell^-$.

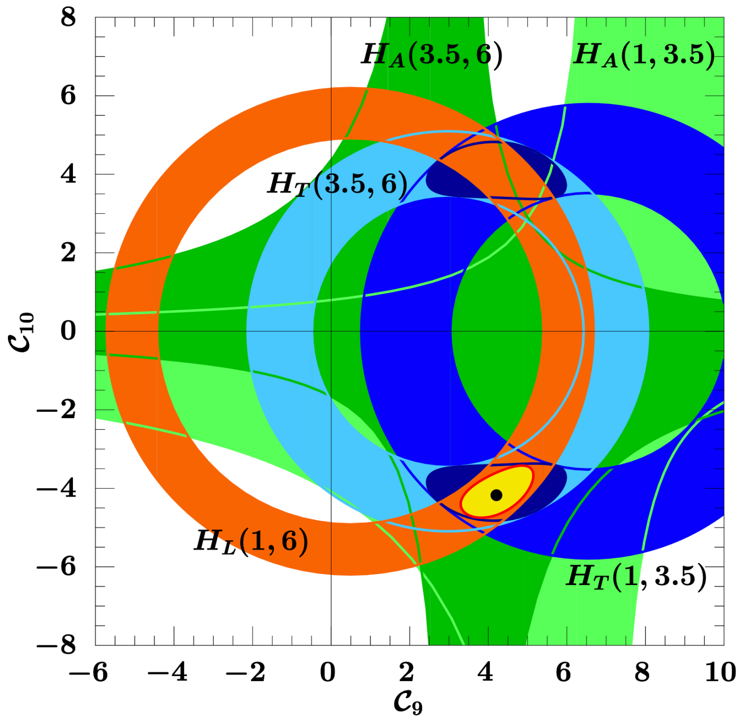
$$\frac{d^2\Gamma}{dq^2\,dz} = \frac{3}{8}\left[(1+z^2)H_T(q^2) + 2zH_A(q^2) + 2(1-z^2)H_L(q^2)\right].$$

$q^2 = (p_{\ell^+} + p_{\ell^-})^2$, $z = \cos\theta$ (θ is the angle between ℓ^- and B in the di-lepton center-of-mass frame).

$$\frac{d\Gamma}{dq^2} = H_T(q^2) + H_L(q^2)\,,$$
$$\frac{dA_{\rm FB}}{dq^2} = \frac{3}{4}H_A(q^2)\,.$$

Helicity decomposition gives third observables. Third independent constraint can be set.

Lee, Ligeti Stewart and Tackmann, PRD 75, 034016 (2007)

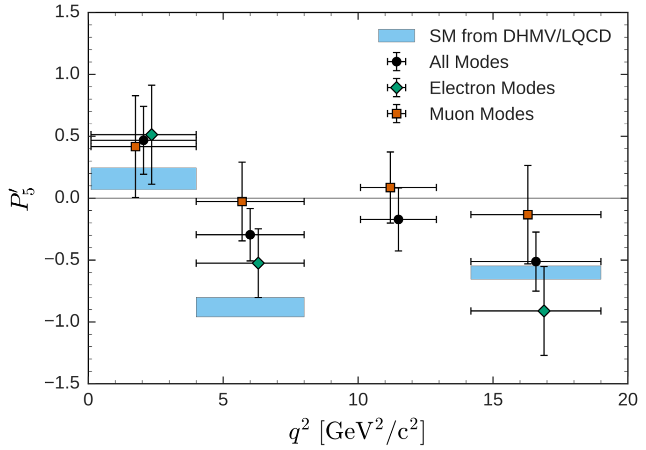


Exclusive $B \to K^* \ell^+ \ell^-$ at Belle II

- The uncertainty on P_5' in $q^2 \in [4,6]\ \mathrm{GeV}^2$ bin using both electron and muon modes at ~5 ab^{-1} will be comparable to the 4.7 fb^{-1} LHCb result that used the muon mode only.
- Precise measurement of $B \to K^* e^+ e^-$ in the low-q^2 and high-q^2 region at Belle II, provides important information to the anomaly in $B \to K^* \mu^+ \mu^-$.

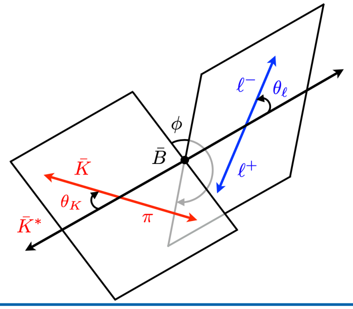
Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
P_5' ([1.0, 2.5] GeV^2)	0.47	0.17	0.054
P_5' ([2.5, 4.0] GeV^2)	0.42	0.15	0.049
P_5' ([4.0, 6.0] GeV^2)	0.34	0.12	0.040
P_5' (> 14.2 GeV^2)	0.23	0.088	0.027

B2TiP



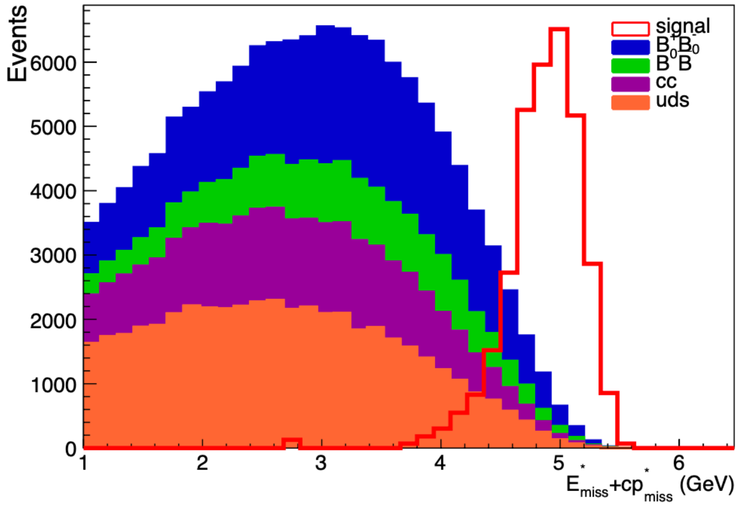
$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}.$$



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

- By reconstructing the other B meson (tag-side) and using the initial state of e^+e^-, the missing energy and momentum can be used to distinguish signal from backgrounds.
- Tagging efficiency
  - Hadronic tag : O(0.1)%.
  - Semi-leptonic tag : O(1)%.
- Analysis with new tagging method gives comparable sensitivity with current data set.
  - Inclusive tag : Higher tagging efficiency.



Missing $E + p$ in the CM frame for $B^0 \to K^{*0}[K^+\pi^-]\nu\bar{\nu}$. Backgrounds correspond to 1 ab^{-1}, while the signal normalization is arbitrary. B2TiP

References of page2

[1] LHCb Collaboration, JHEP 08 (2017) 055

[2] LHCb Collaboration, Phys.Rev.Lett. 122 (2019) 19, 191801

[3] LHCb Collaboration, Phys.Rev.Lett. 125 (2020) 1, 011802

[4] Belle Collaboration, Phys.Rev.Lett. 118 (2017) 11, 111801