$b \to s\gamma$ and $s\ell^+\ell^-$ at Belle II

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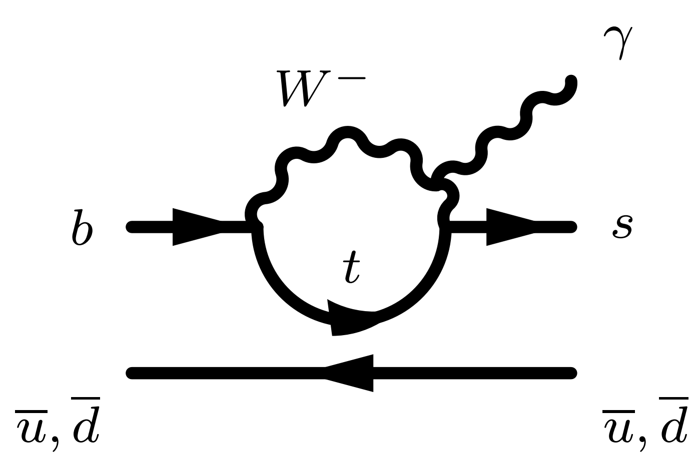
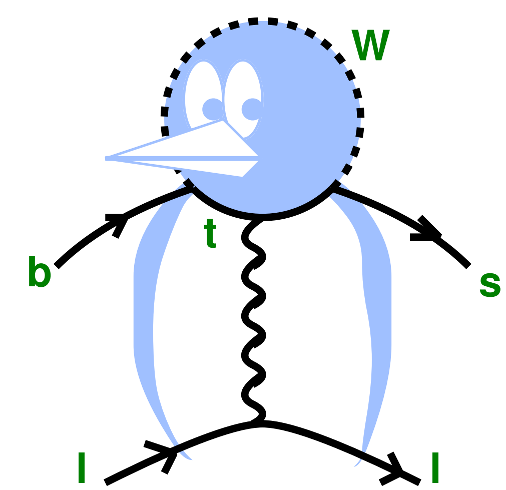
Introduction: $b \to s\gamma$ and $b \to s\ell^+\ell^-$

- Flavor changing neutral current (FCNC) $b \to s$ (d) transitions continue to be of great interest. These processes proceed via one-loop (penguin or box) diagrams and hence are highly suppressed in the SM
  → **BSM observability may be enhanced due to smaller SM background!**
- $b \to s\gamma$ and $b \to s\ell^+\ell^-$ decays are theoretically and experimentally clean.





$b \to s\gamma$ (Radiative Penguin)

$b \to s\ell^+\ell^-$ (EWK Penguin)

Br(b -> sγ) = (3.32 ± 0.15) x 10^{-4}
Br(b -> dγ) = (9.2 ± 3.0) x 10^{-6}

Br(B -> X_s $\ell^+\ell^-$) = (1.58 ±0.37) x 10^{-6} (1 GeV^2 < q^2 < 6 GeV^2)
Br(B -> X_s $\ell^+\ell^-$) = (0.48 ±1.0) x 10^{-6} (q^2>14.4 GeV^2)

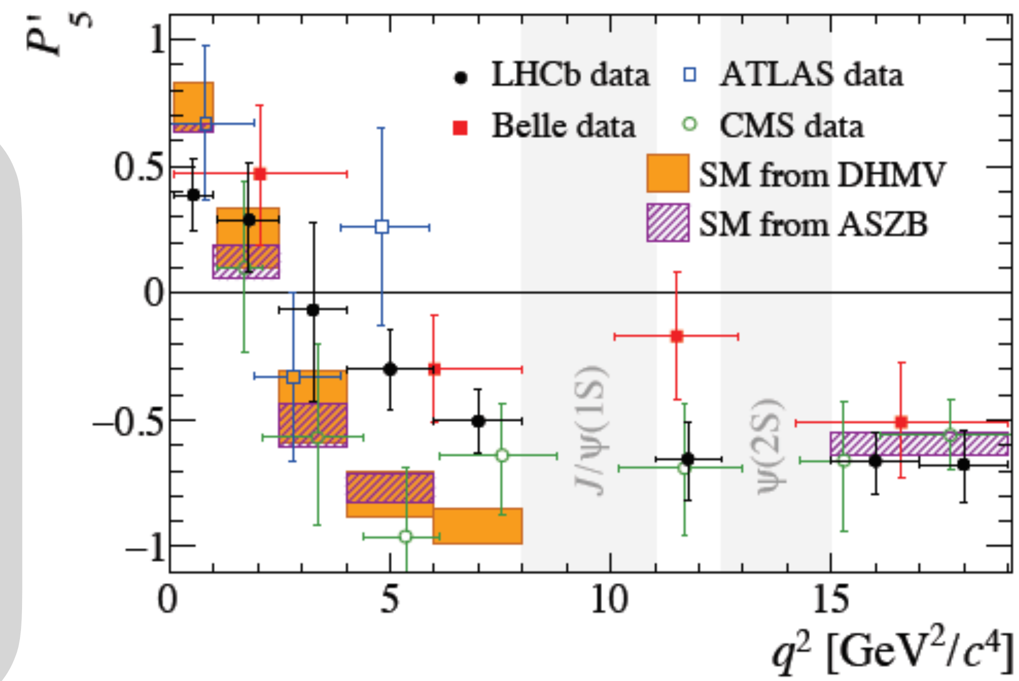
* q^2: dilepton invariant mass squired

Refs: PRL109.191801 (2012), PRD91(5)052004 (2015), JHEP06(2015)176, HFAG table (link)

Test of anomalies

- **Belle II will be able to provide independent tests of the anomalies** recently observed by the LHCb and Belle experiments in the angular analysis of ***B*** → ***K* ℓ⁺ℓ⁻ (P_5')*** as well as in the determination of $\boldsymbol{R_K}$ and $\boldsymbol{R_{K^*}}$

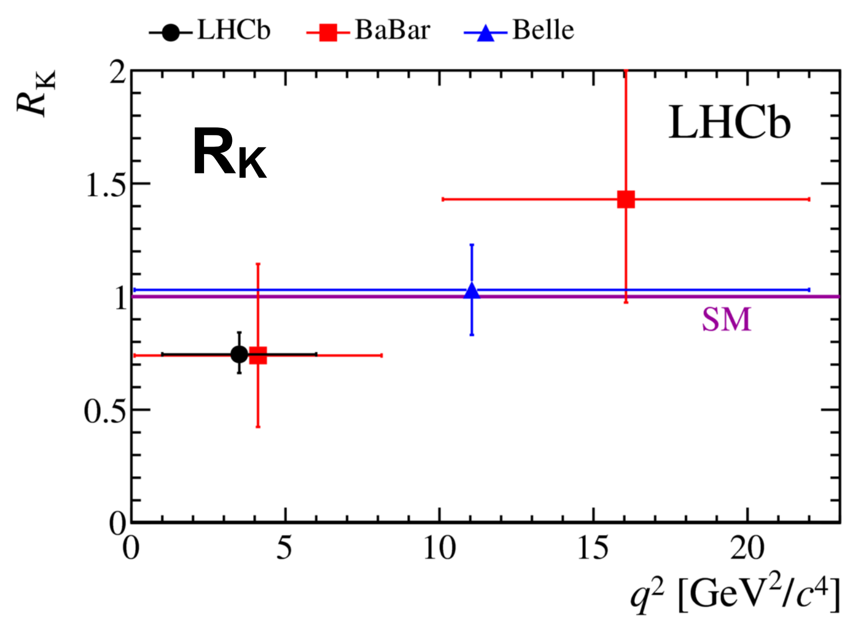
angular observable P_5'

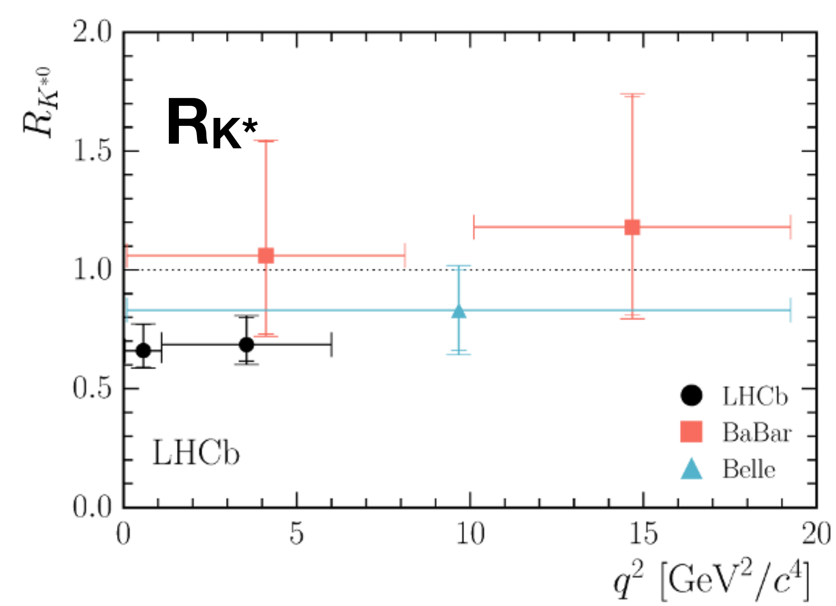


[*] lately LHCb had an update to P'₅, the excess going down a bit but still significant, see PRL125.011802(2020)

Lepton Flavor Universality test

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}\left[B \to K^{(*)}\mu^+\mu^-\right]}{\mathcal{B}\left[B \to K^{(*)}e^+e^-\right]},$$





Refs: PRL122.191801(2019), PRL118.111801(2017), PRL125.011802 (2020),JHEP08(2017)055

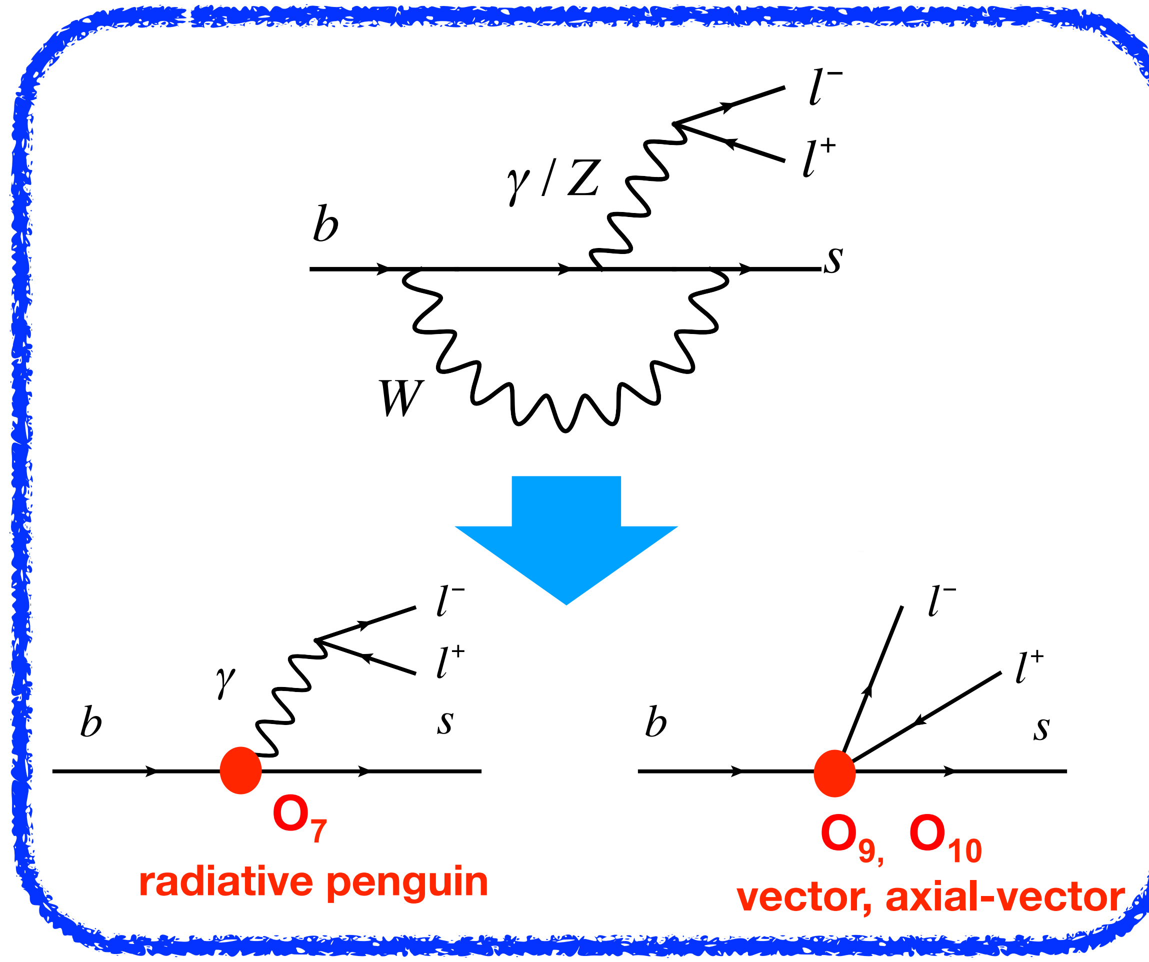
Theoretical framework

- Effective Hamiltonian describes the full theory at low energy (μ) **in model-independent way**:

$$\mathcal{H}_{\text{eff}} \sim \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

C_i: Wilson coefficient, encode high energy contributions

O_i: local operators with different Lorentz structures



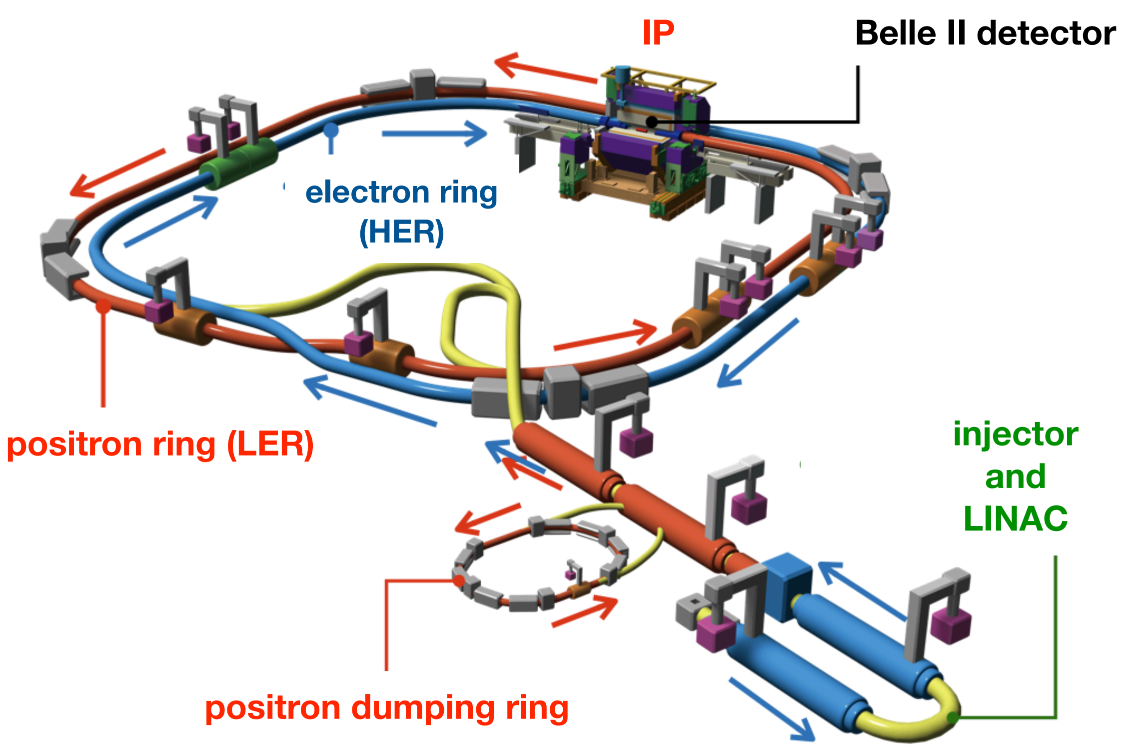
- Contributions from new physics will modify SM contributions or introduce new operators.

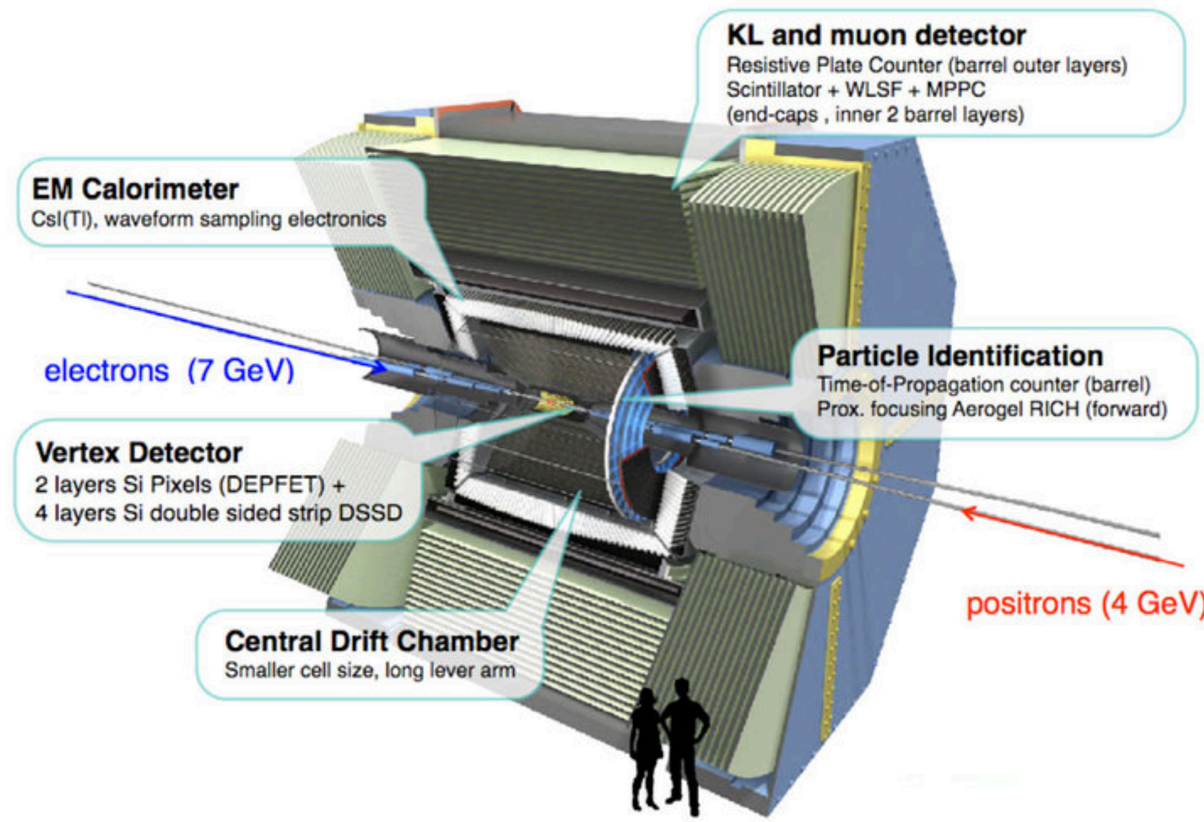
$$\Delta\mathcal{H}_{\text{eff}} = \frac{c_{NP}}{\Lambda_{NP}}\mathcal{O}_{NP}$$

$$\mathcal{O}_9 \propto (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell);$$
$$\mathcal{O}_{10} \propto (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell);$$
$$\mathcal{O}_7 \propto m_b(\bar{s}\sigma_{\mu\nu} P_R b)F^{\mu\nu}.$$

- $b \to s\gamma$ and $b \to s\ell^+\ell^-$ are sensitive to C_7, C_9, and C_{10}
- Combined fits with different measurements will obtain model-independent constraints on C_i and hence constrain BSM models

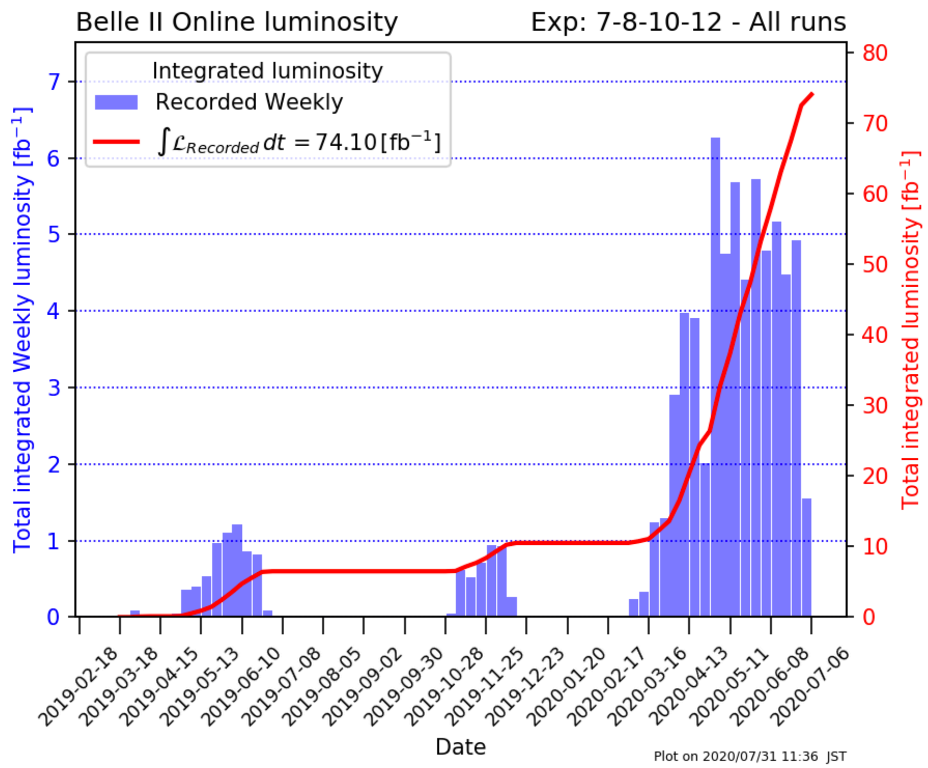
SuperKEKB and Belle II detector

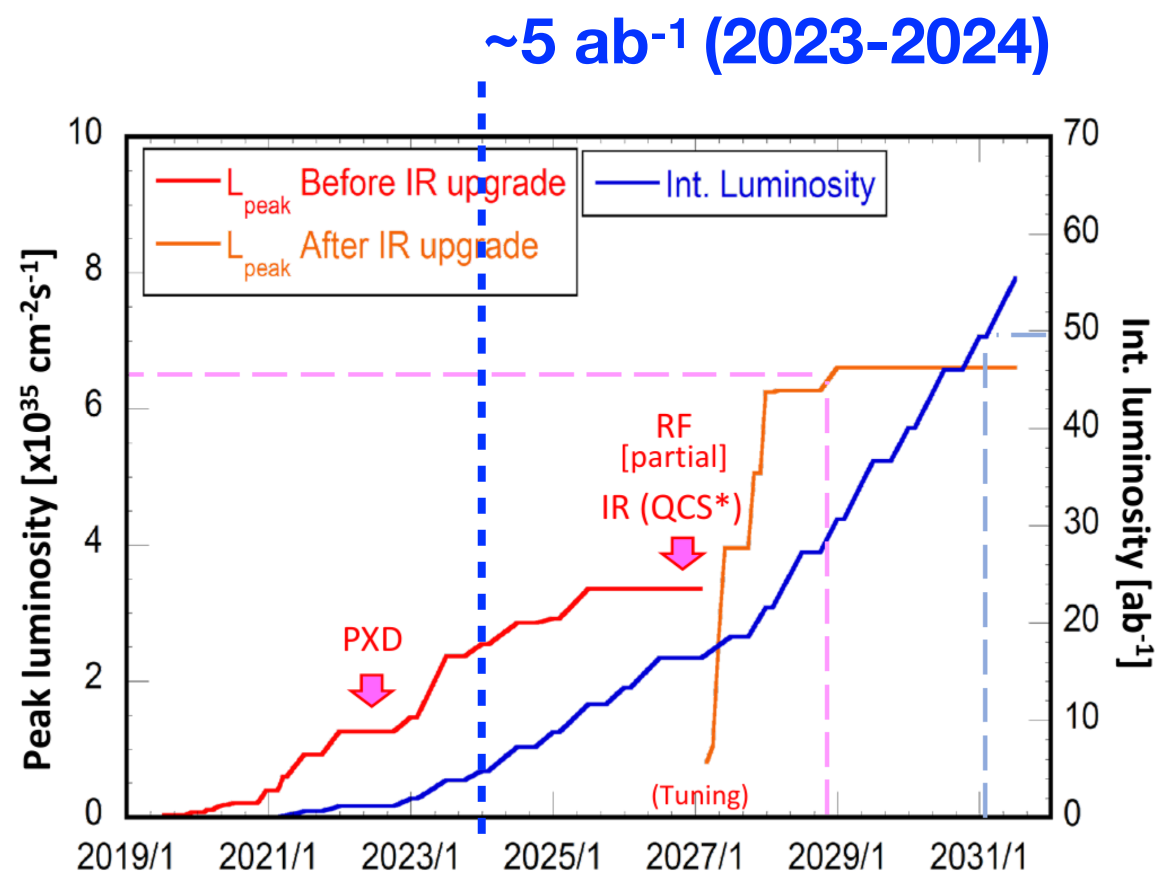




- SuperKEKB (KEK, Japan) aims for collecting **50 ab^{-1}** of data, which is **~50 times larger** than KEKB/Belle experiment.
- Belle II detector composed of vertex detector, drift chamber, PID counters, EM calorimeter and muon detector was designed to cope with higher background and high trigger rate **~30 kHz**.

Operation status





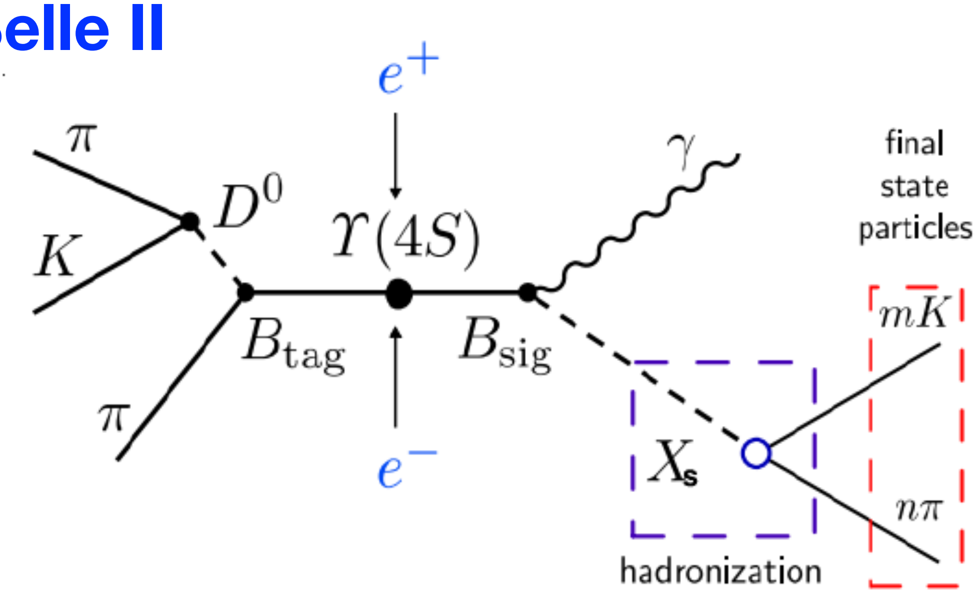
- Belle II achieved peak luminosity of **2.4 x 10^{34} /cm^2/sec** (old record at KEKB was 2.1x10^{34} /cm^2/sec) and integrated ~1 fb^{-1}/day on average in June 2020 (maximum 1.3 fb^{-1}/day). Total **74 fb^{-1}** data has been collected so far.
- Toward the goal of 6 x 10^{35} /cm^2/sec and 50 ab^{-1}, further upgrade to detector and accelerator is planned

Analysis strategy

- Exclusive mode:
  reconstruct a specific decay channel
- Inclusive mode:
  (1) **sum-of-exclusive**: reconstruct X_s from as many excl. channels as possible
  (2) **fully inclusive**: all possible X_s final states considered

Higher (~2 times) tagging efficiency at Belle II

reco. method	tagging	effi.	S/B
sum-of-exclusive	none	high	moderate
fully-inclusive	had. B	very low	very good
	SL B	very low	very good
	L	moderate	good
	none	very high	very bad



- Energy difference (ΔE) and beam constrained mass (M_{bc}) are key variables:

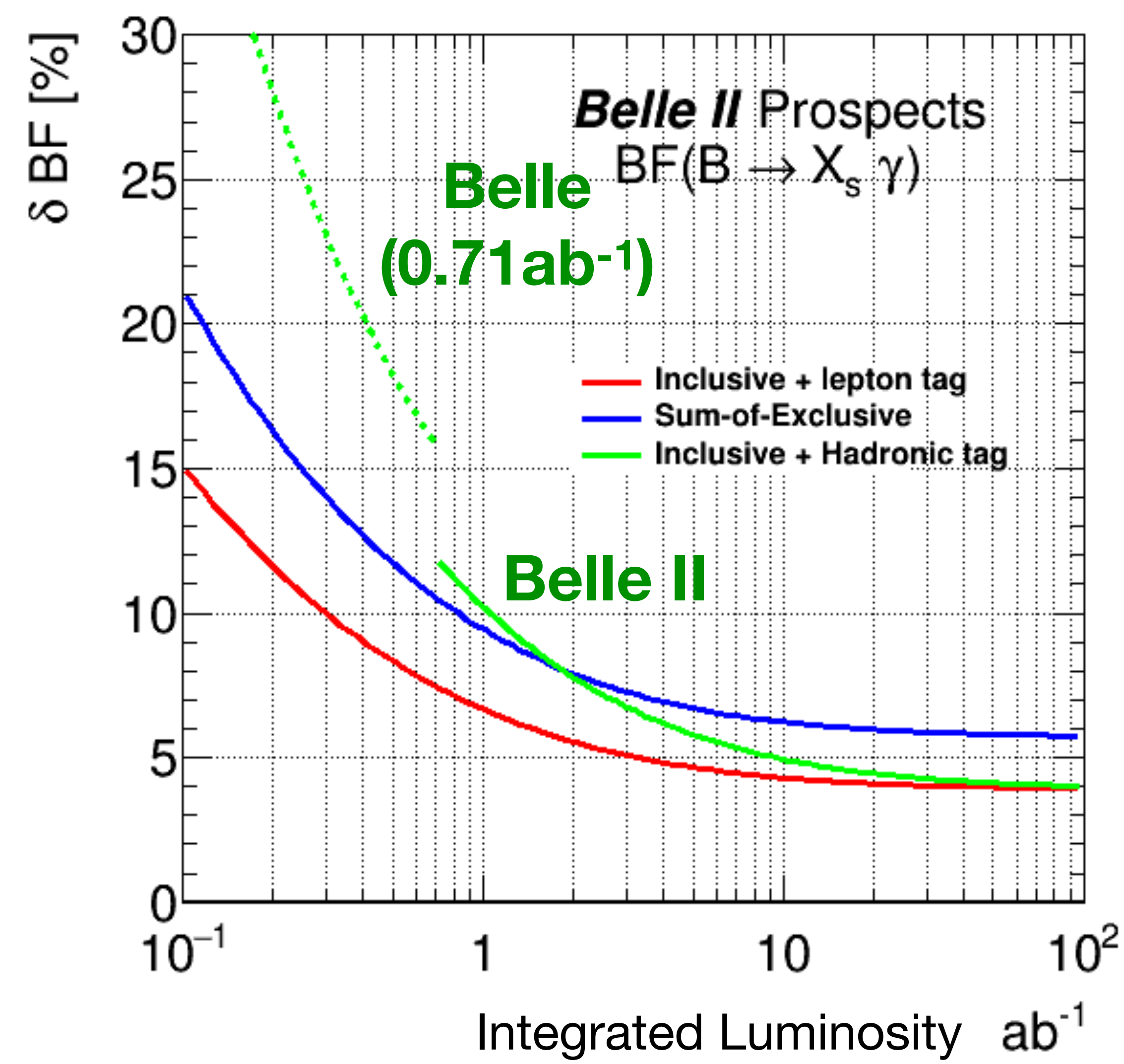
$$\Delta E = E_B - E_{\rm beam} \quad M_{\rm bc} = \sqrt{E^2_{\rm beam} - p^2_B} \quad \textbf{where} \quad E_{\rm beam} = \frac{E_{e-} + E_{e+}}{2}$$

*** in center of mass frame**

$B \to X_s \gamma$

- **Inclusive measurement can be only performed at Belle II !!**
- $B \to X_s \gamma$ offers strongest constraint on Wilson coefficient C_7
- For *BF*, ~6% (3.2%) precision with 5 ab^{-1} (50 ab^{-1}) data:

- **Fully inclusive (green and red):** reduce systematics by better modeling neutral hadrons faking photons
- **Sum-of-exclusive:** increase the number of models to reduce the systematic from X_s hadronization
- Belle II sensitivity in green considering improvement in hadronic tagging



Belle II Physics Book: https://arxiv.org/abs/1808.10567

$B \to X_s \gamma$ — CP and isospin observables

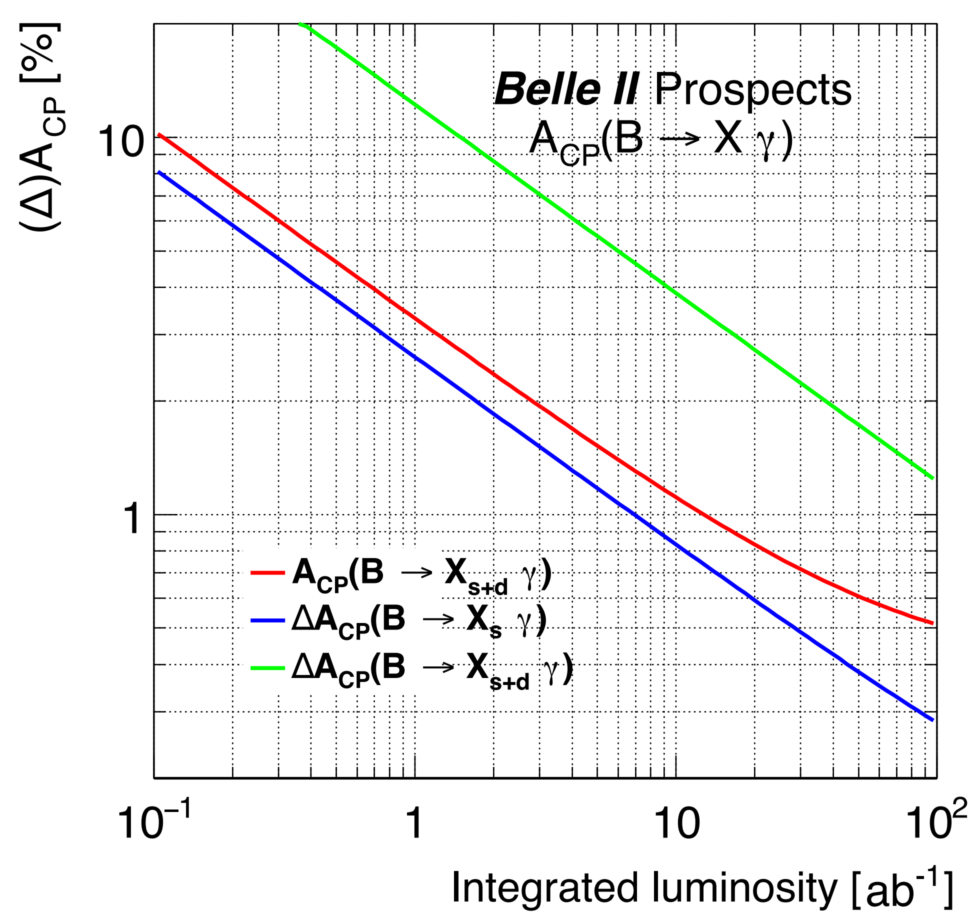
- Three important observables, ***A_{CP}*, *ΔA_{CP}*, and *Δ_{0+}***, are expected to be determined to < 5% (< a few %) level at 5 ab^{-1} (50 ab^{-1})

$$A_{\mathrm{CP}} = \frac{\Gamma\left[\bar{B} \to X_s\gamma\right] - \Gamma\left[B \to X_{\bar{s}}\gamma\right]}{\Gamma\left[\bar{B} \to X_s\gamma\right] + \Gamma\left[B \to X_{\bar{s}}\gamma\right]} \qquad \Delta_{0+} = \frac{\Gamma\left[B^0 \to X_s\gamma\right] - \Gamma\left[B^\pm \to X_s\gamma\right]}{\Gamma\left[B^0 \to X_s\gamma\right] + \Gamma\left[B^\pm \to X_s\gamma\right]}$$

$$\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}\left[B^\pm \to X_s^\pm\gamma\right] - A_{\mathrm{CP}}\left[B^0 \to X_s^0\gamma\right]$$

*** *ΔA_{CP}* ~0 in the SM**

- **Precision driven by sample size —** experimental systematic uncertainties can be reduced as well as theoretical uncertainty on hadronic form-factors.
- ***$A_{CP}(B \to X_{s+d}\gamma)$*** is sensitive to BSM thanks to small theory unc. (while *$A_{CP}(B \to X_s\gamma)$* has been theory unc limited)

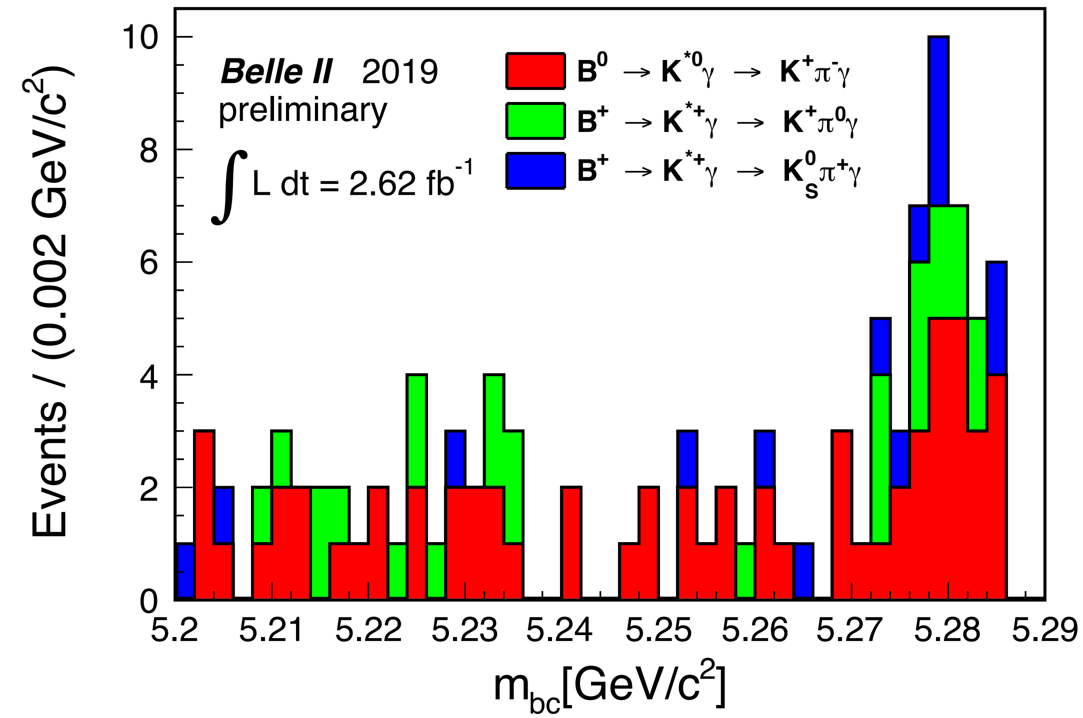


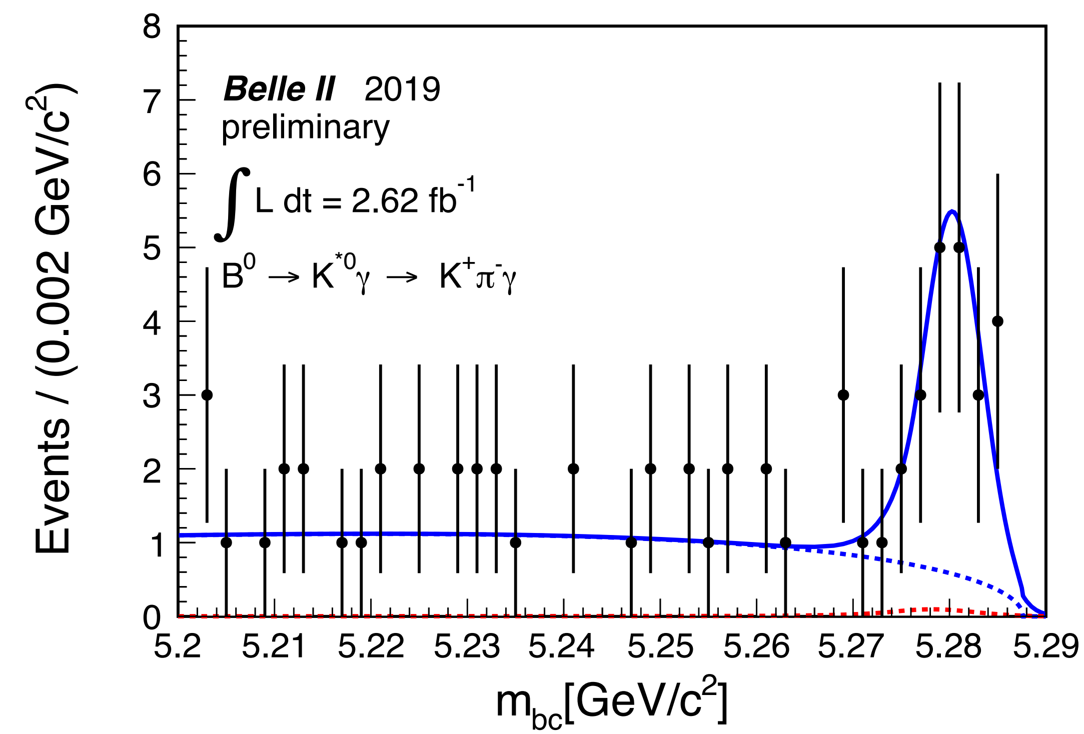
Re-discovery of radiative penguin decay

- Search for $B \to K^*\gamma$ using three decays: $K^+\pi^0\gamma$, $K^0_S\pi^+\gamma$, $K^+\pi^-\gamma$
- Dominant $q\bar{q}$ events suppressed with multivariate classifier (FastBDT)
- **Combined significance more than 5σ**

	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
$B^+ \to K^{*+}[K^0_S\pi^+]\gamma$	6.6 ± 3.1	2.1σ

- Time dependent CPV can be measured in $B^0 \to K^*(K^0_S\pi^0)\gamma$ channel ($b_L \to s_R\gamma_R$)

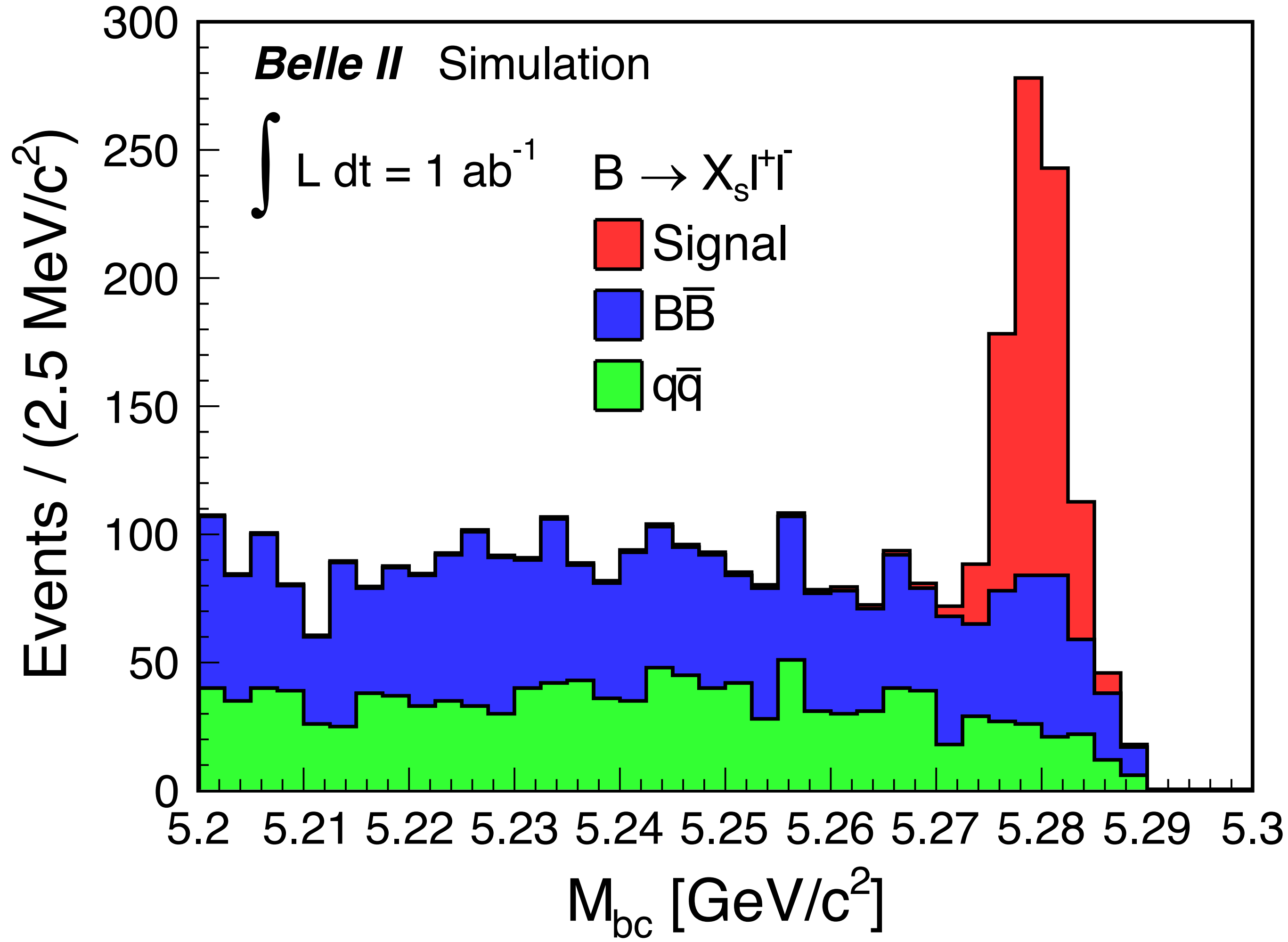




$B \to X_s \ell^+ \ell^-$ — simulation study

Belle II is capable of performing inclusive measurement!

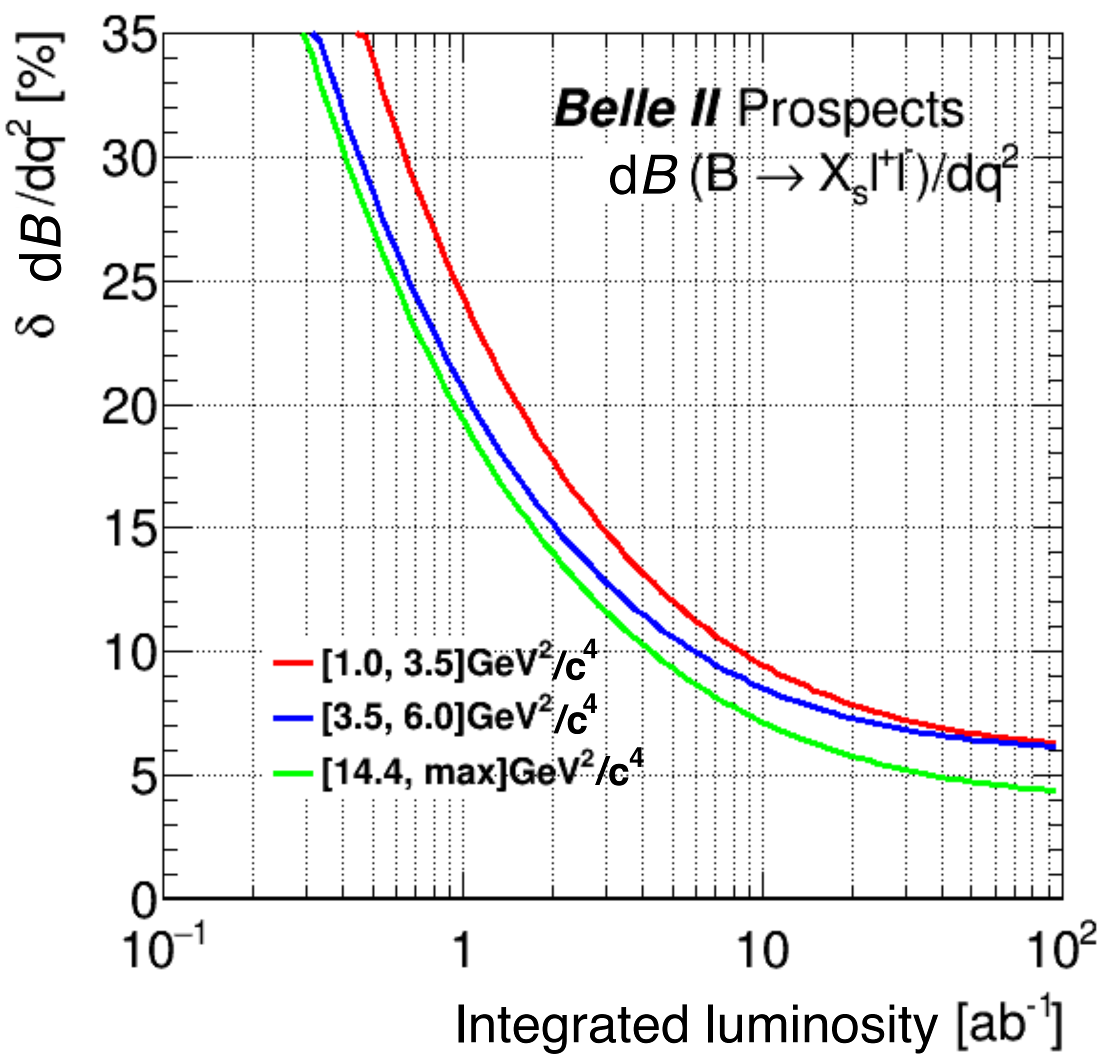
- Higher ΔE resolution (than $X_s\gamma$)
- **Sum-of-exclusive mode:**
  - X_s reconstruction: $Kn\pi$ (n≦4) and $3K$
  - at most one K_s^0, π^0
  - $M_{Xs} < 2.0$ GeV

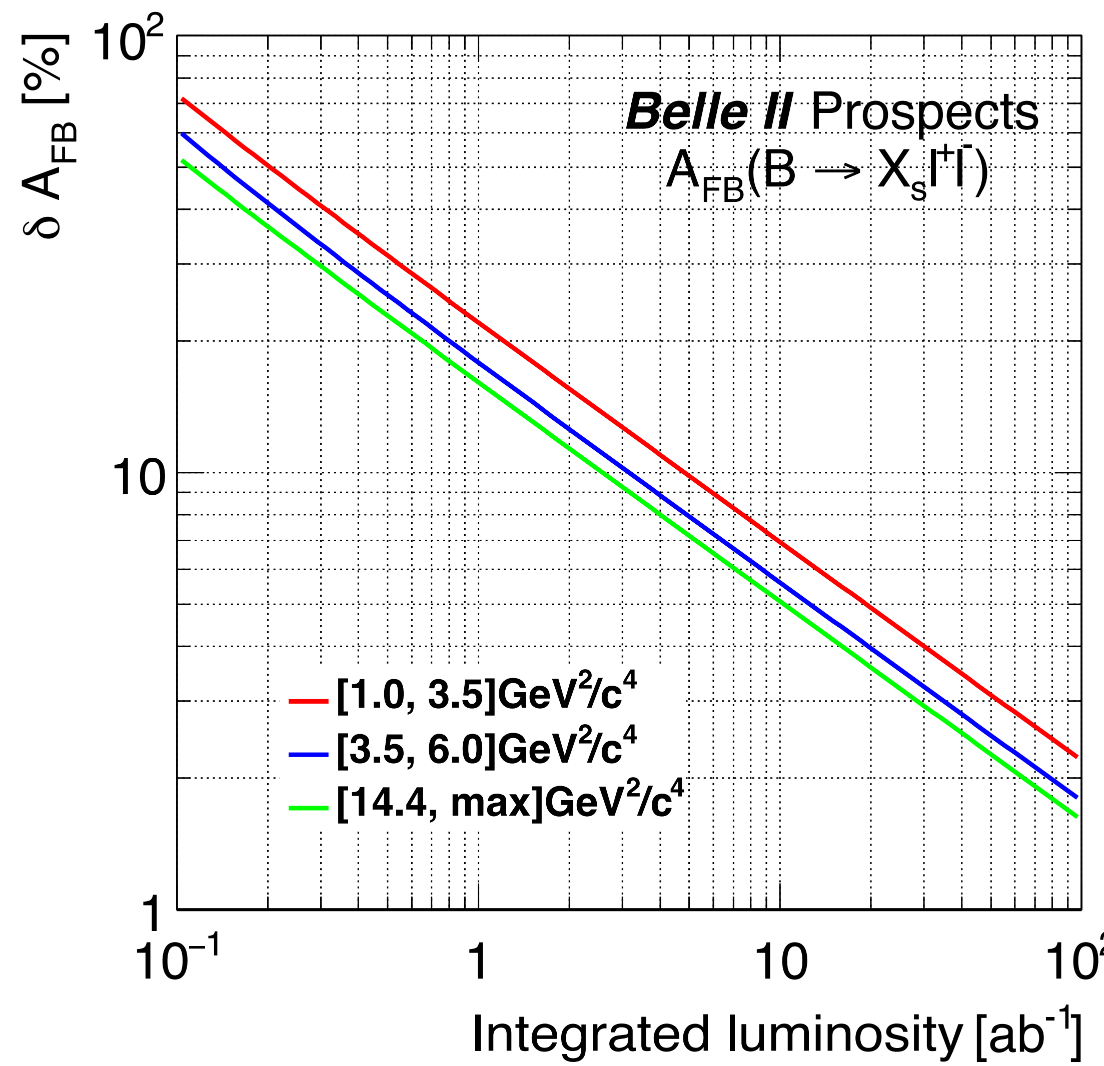


- Background:
  - dominated by B(→Xℓν)B(→Yℓν) — it can be suppressed with missing energy and vertex information
  - mis-ID B →Kmπ to be understood

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

- In addition to BF, ***A_{FB}*** is also an important measurement to constrain ***C_9*** and ***C_{10}*** — Smaller systematic uncertainty than exclusive mode
- Uncertainty on ***BF*** will be dominated by systematics at ~15 ab^{-1}, while ***A_{FB}*** measurement will be still statistically dominated at 50 ab^{-1}
- A_{CP} and $\Delta_{CP}(A_{FB})$ will also be measured

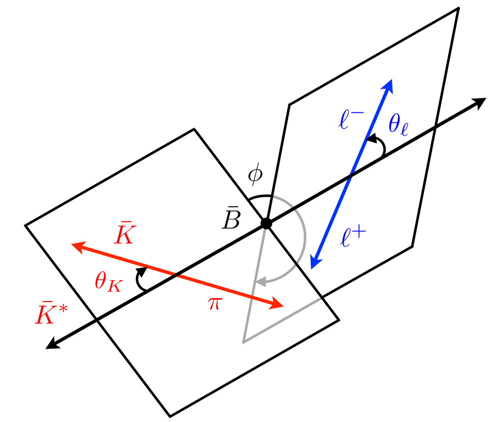




Angular analysis — $B \to K^* \ell^+ \ell^-$ at Belle II

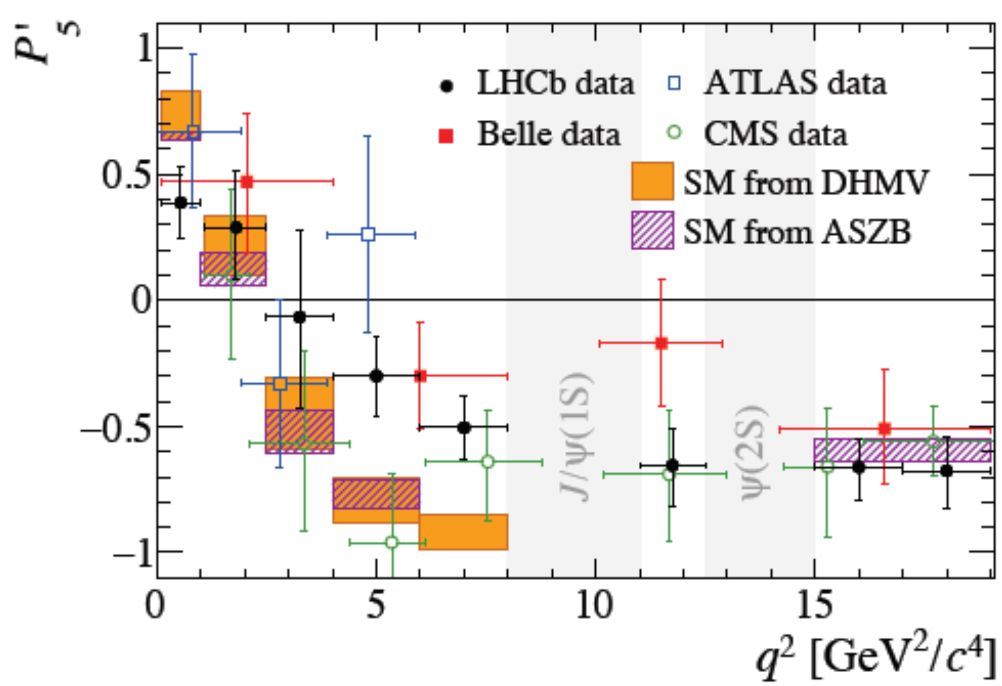
- Angular observables $P'_{i=4,5,6,8}$ are theoretically interesting and sensitive to ***C_7*, *C_9* and *C_{10}***

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



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

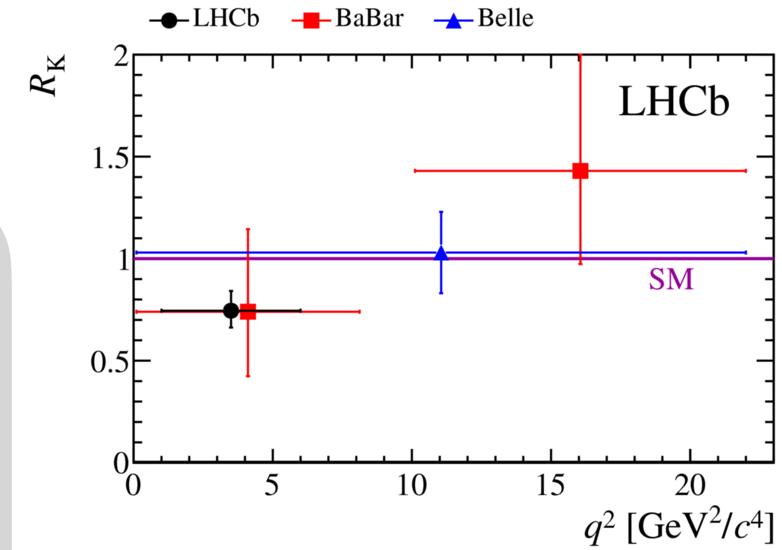
- Precise measurement of $B \to K^* \ell^+\ell^-$ in the low-q^2 and high-q^2 at Belle II will provide important cross-check to the anomaly in $B \to K^*\mu^+\mu^-$
- Sensitivity of ~5 ab^{-1} of Belle II data (~2023) will be comparable to 4.7 fb^{-1} of LHCb

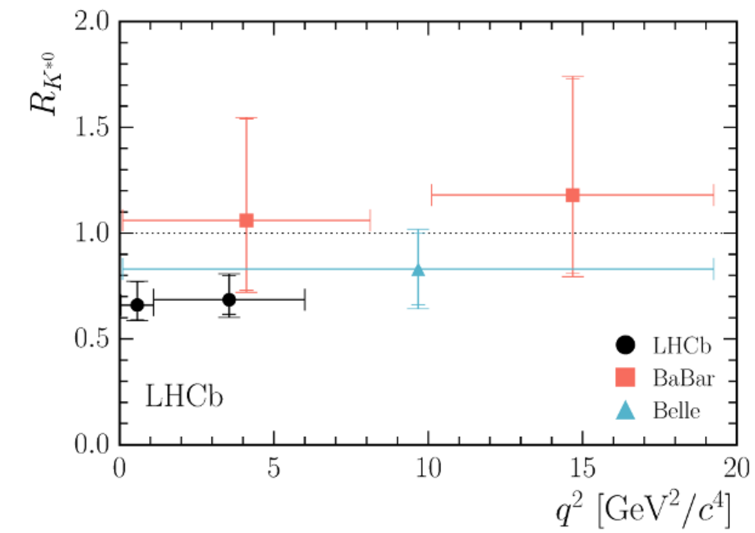


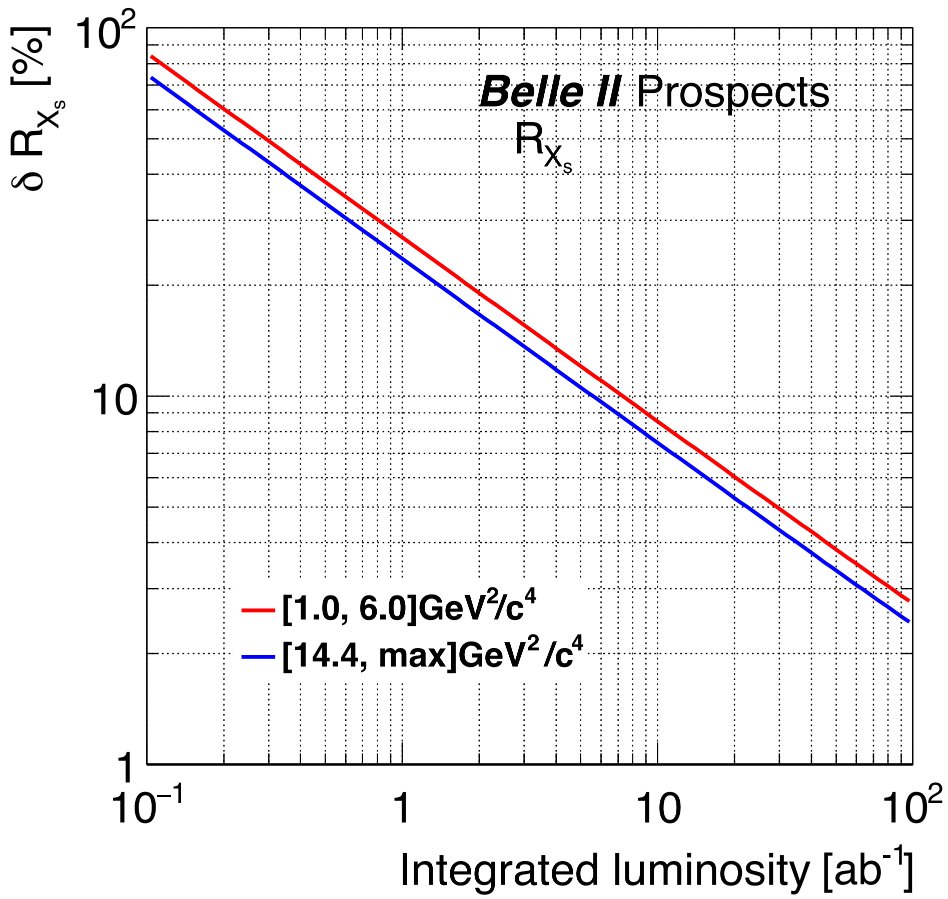
Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
P'_5 ([1.0, 2.5] GeV^2)	0.47	0.17	0.054
P'_5 ([2.5, 4.0] GeV^2)	0.42	0.15	0.049
P'_5 ([4.0, 6.0] GeV^2)	0.34	0.12	0.040
P'_5 (> 14.2 GeV^2)	0.23	0.088	0.027

Lepton Flavor Universality

- $R_{K(*)}$ anomalies will be cross-checked at Belle II
  - Similar reco efficiency/purity for electron and muon
  - Sensitive to both low- and high-q^2
  - In addition to $R_{K(*)}$, R_{Xs} can also be measured







$$R_{X_s} \equiv \frac{\mathcal{B}[B \to X_s \mu^+ \mu^-]}{\mathcal{B}[B \to X_s e^+ e^-]}$$

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%

$Q_5 = P_5'^{\mu} - P_5'^{e}$

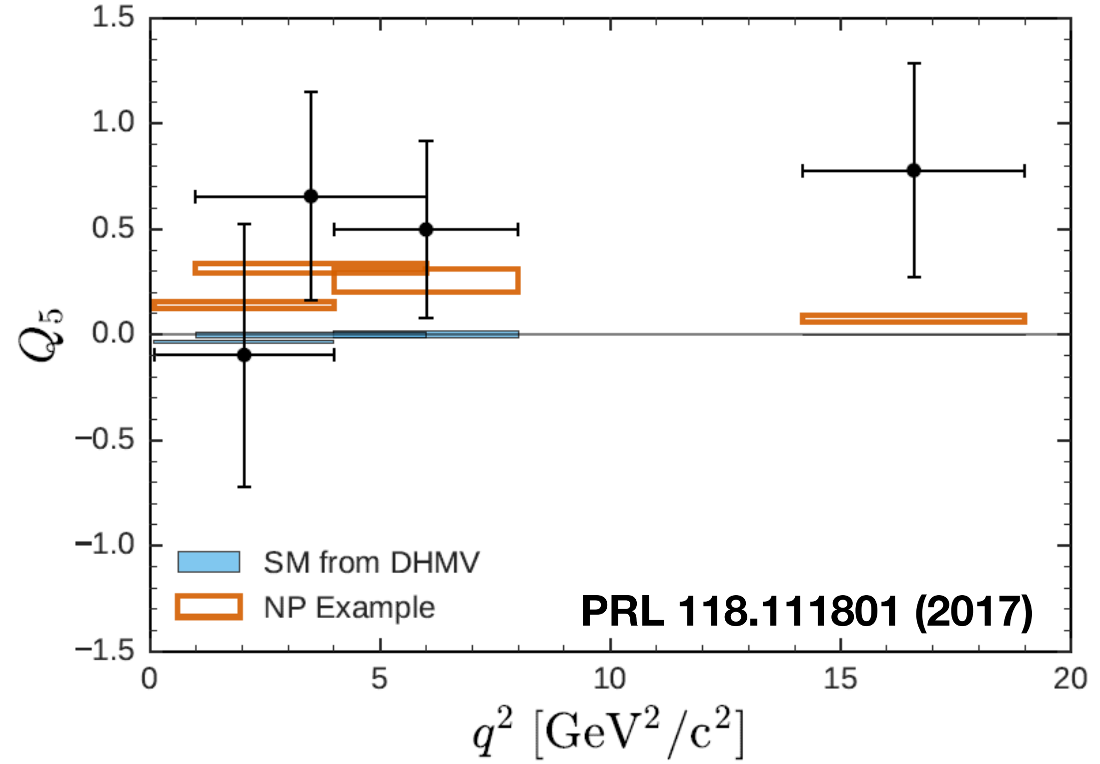
- Further lepton universality test can be performed by looking at other observables such as Q_5 (or ΔA_{FB}) in $B \to K^* \ell^+\ell^-$ channel

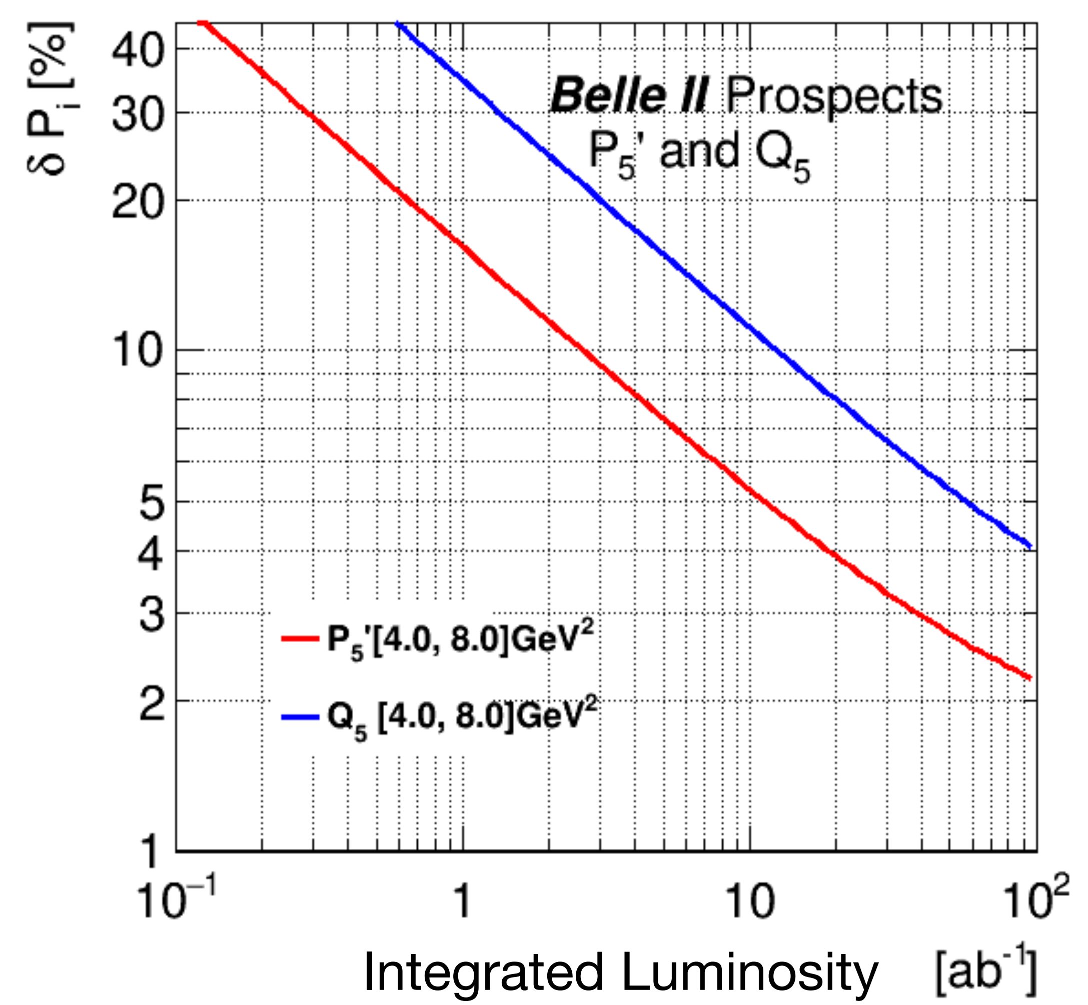
$$Q_i = P_i^{\mu} - P_i^{e}$$

$$\Delta_{A_{\rm FB}} = A_{\rm FB}(B \to K^* \mu^+\mu^-) - A_{\rm FB}(B \to K^* e^+e^-)$$

- First measurement of Q_5 at Belle (2017) — Belle II will be able to measure it with much higher accuracy

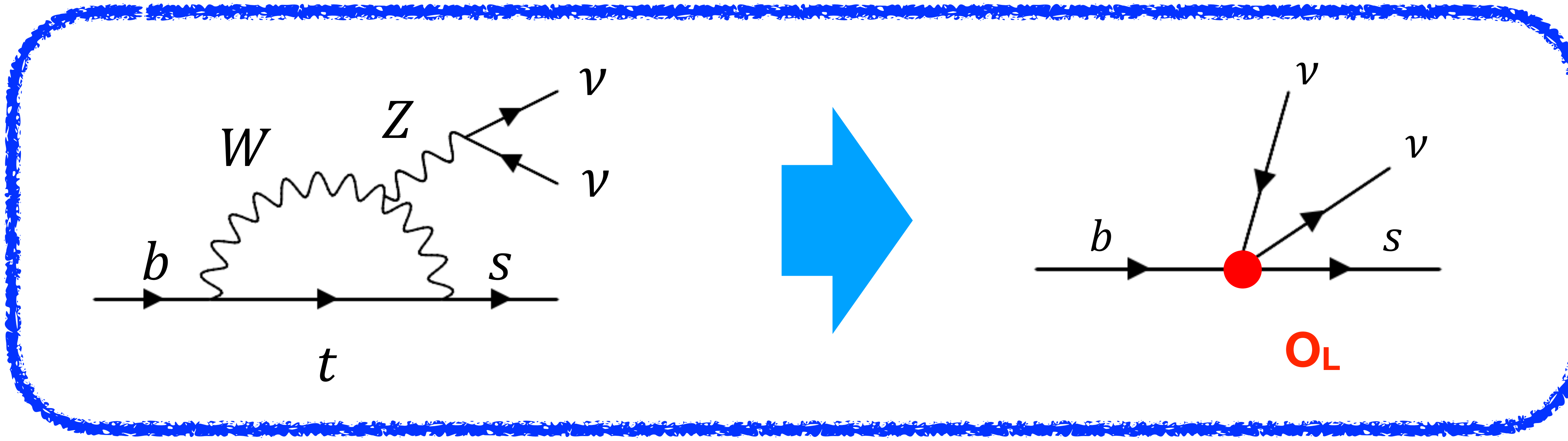
Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
Q_5 ($[1.0, 2.5]\,\mathrm{GeV}^2$)	0.47	0.17	0.054
Q_5 ($[2.5, 4.0]\,\mathrm{GeV}^2$)	0.42	0.15	0.049
Q_5 ($[4.0, 6.0]\,\mathrm{GeV}^2$)	0.34	0.12	0.040
Q_5 ($> 14.2\,\mathrm{GeV}^2$)	0.23	0.088	0.027





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

- Theoretically and experimentally cleaner than $b\to s\ell^+\ell^-$ thanks to no photon mediated contribution



- The decay has never been observed yet

  Theoretical prediction:

$$\mathcal{B}\left[B^+ \to K^+\nu\bar{\nu}\right] = (4.7 \pm 0.6) \times 10^{-6}$$
$$\mathcal{B}\left[B^0 \to K^{*0}\nu\bar{\nu}\right] = (9.5 \pm 1.1) \times 10^{-6}$$

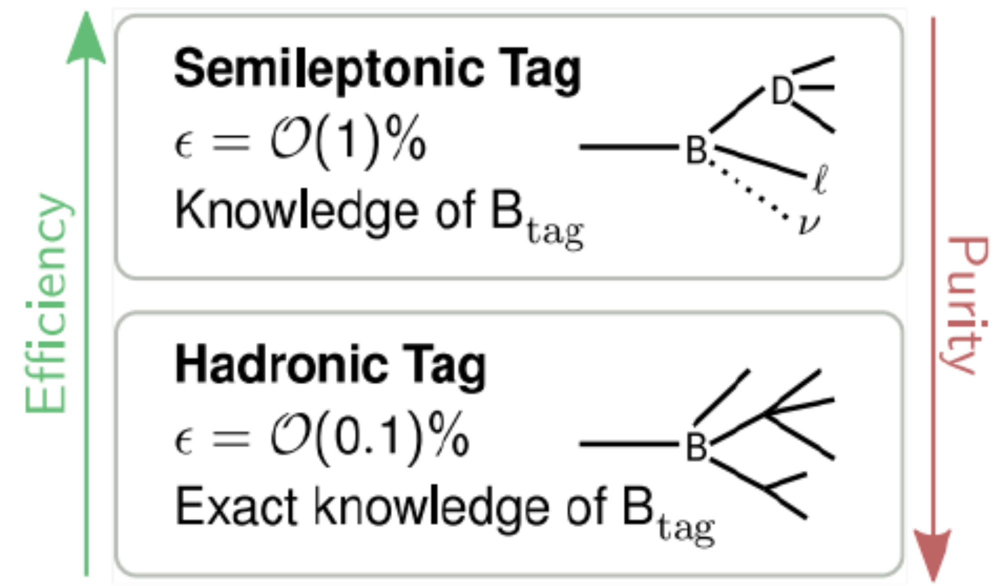
[JHEP02 (2015)184]

- **Belle II is expected to observe $B\to K^{(*)}\nu\bar{\nu}$ with 5 ab^{-1} if it's at the SM rate:**
  - 10% *BF* measurement at 50 ab^{-1}

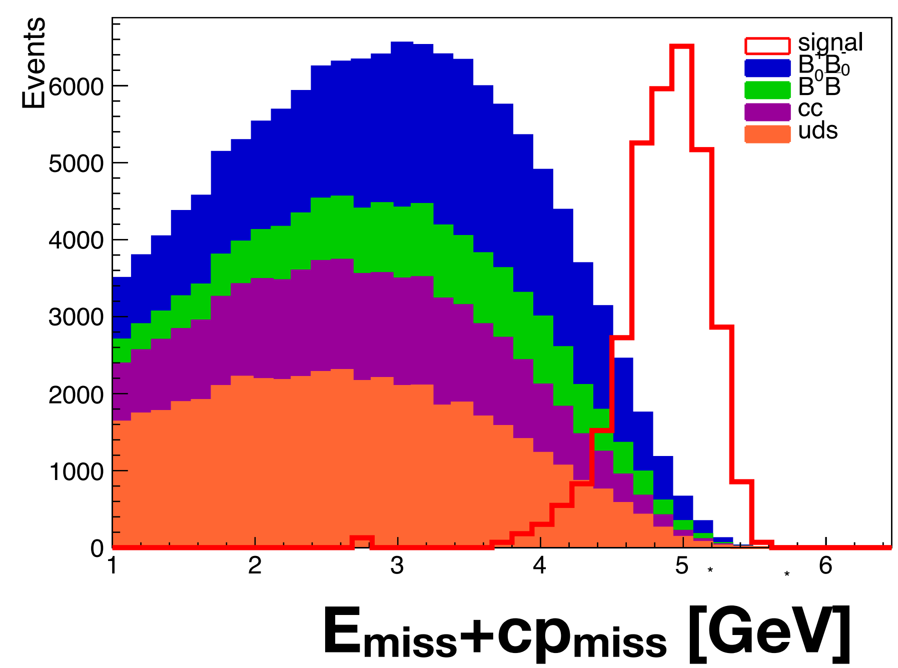
$B \to K^{(*)} \nu \bar{\nu}$

- Since there're two neutrinos in the final state, the other B meson needs to be fully reconstructed (**Full Event Interpretation***)

  — hadronic (low eff) and semi-leptonic (higher eff) tagging



- Distributions of missing 4-momentum in the CM frame with hadronic tag. Bkg norm corresponds to 1 ab^{-1}, while the signal norm arbitrary.



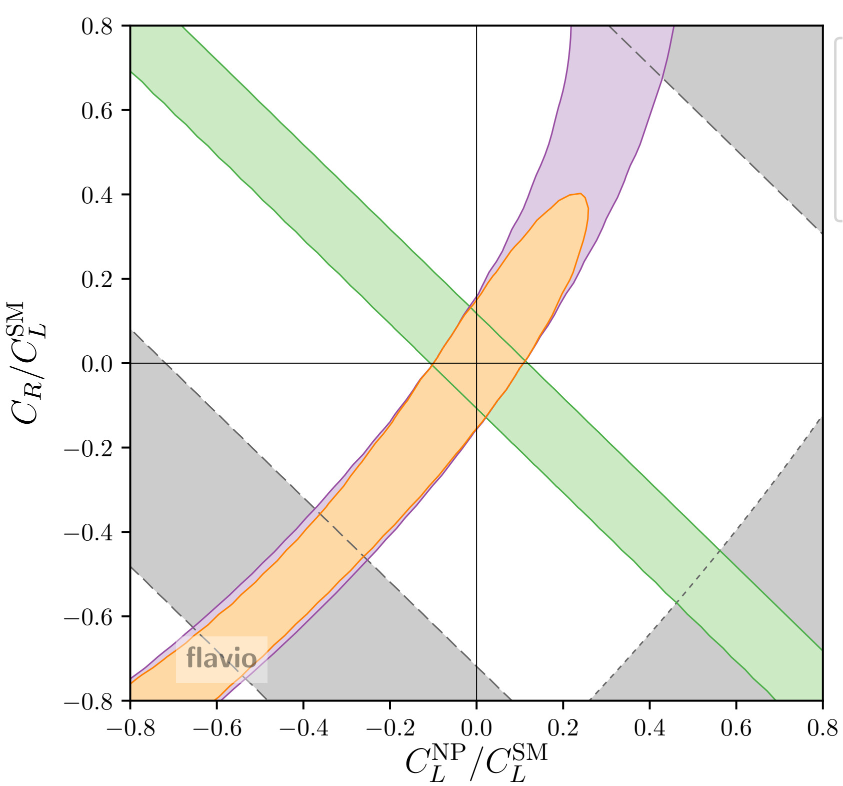
Ref: [*] 10.1007/s41781-019-0021-8

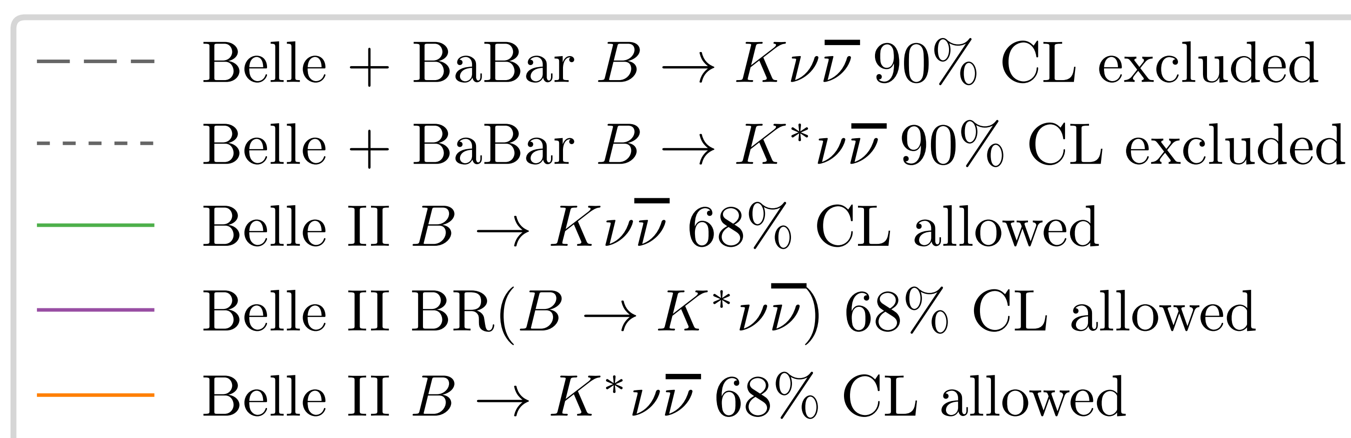
$B \to K^{(*)} \nu\bar{\nu}$

- In addition to BF, fraction of longitudinal polarization (***F_L***) is sensitive to BSM
- Full Belle II sensitivity to ***F_L*** (~0.47 ± 0.03 in SM) is about 0.08 for $K^{*0/+}\nu\bar{\nu}$

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 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

Constraint on Wilson coefficients: C_R and C_L^{NP}



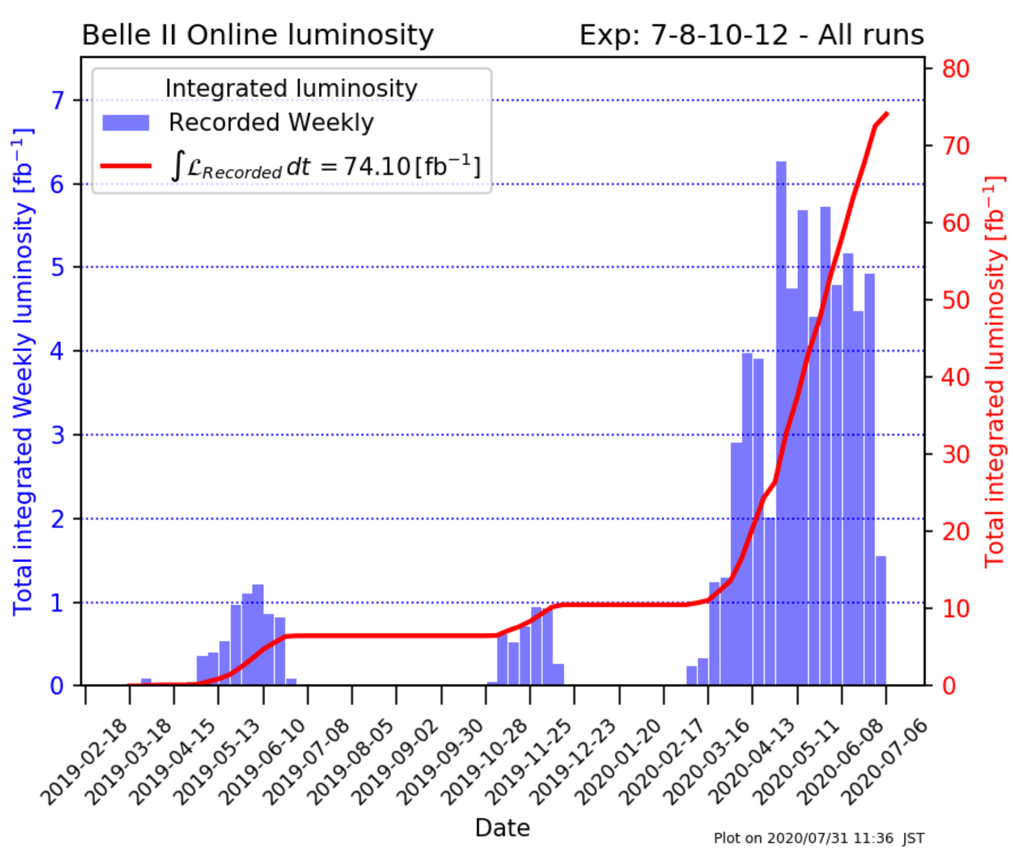


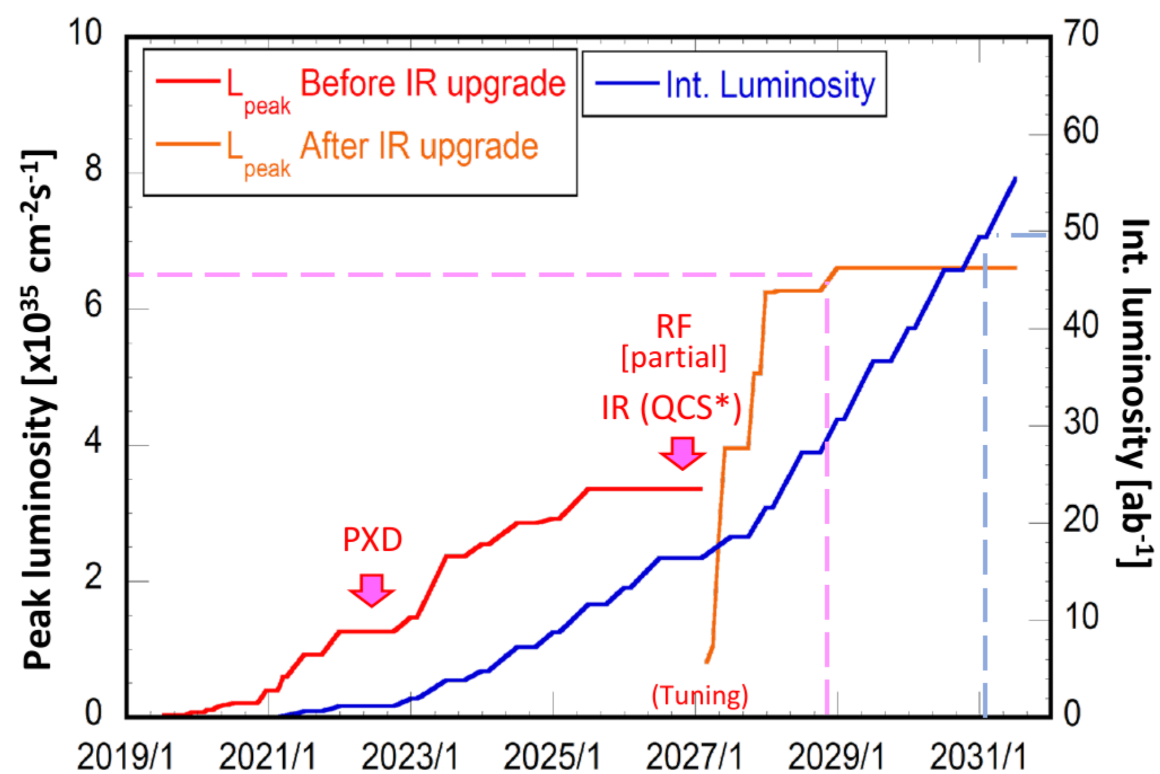
$$\mathcal{O}_L = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

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

Summary

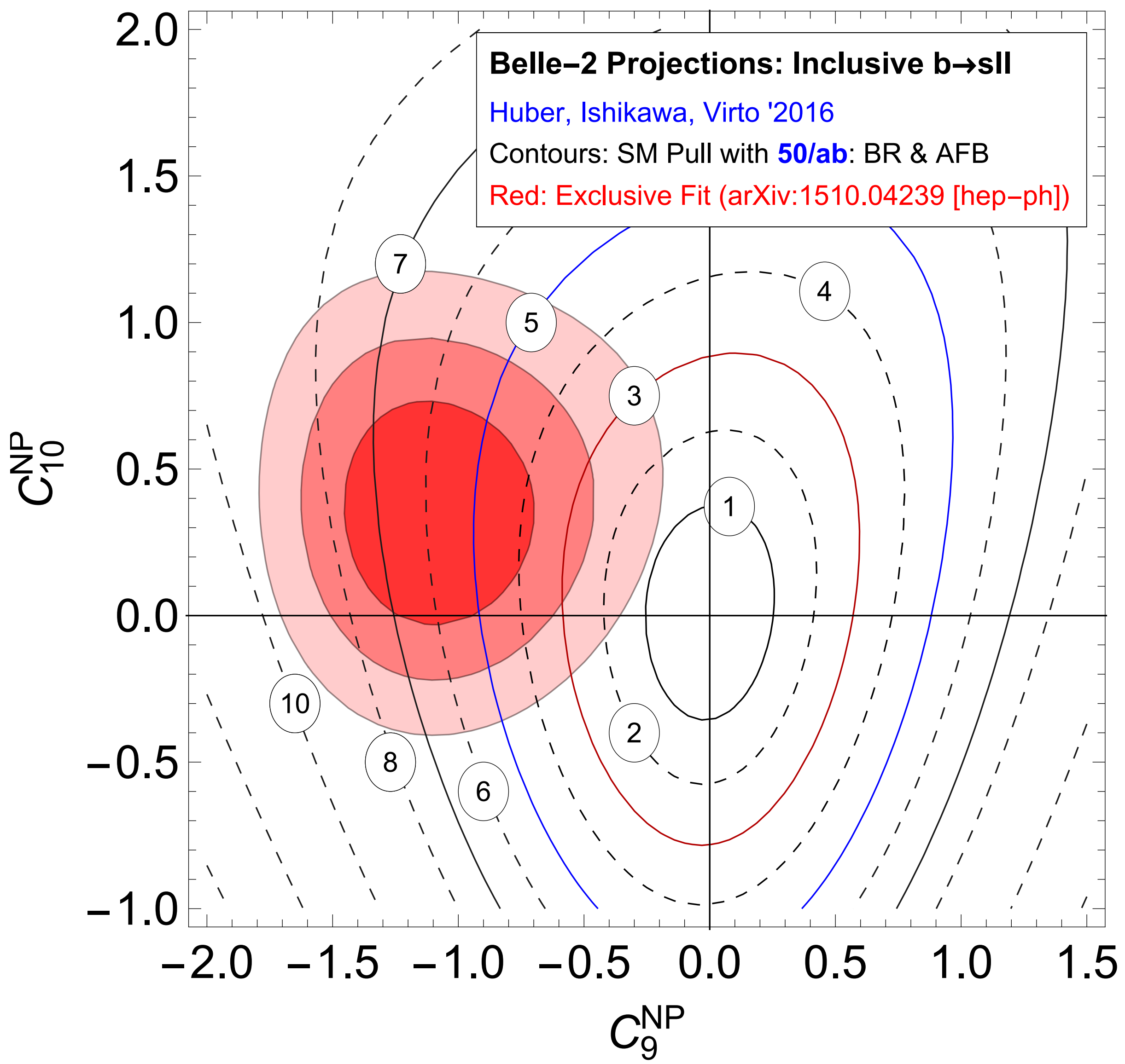
- Belle II has been running well collecting 74 fb^{-1} data even during COVID19 pandemic.
- Many interesting results ($B \to X_s\gamma$, $B \to X_s\ \ell^+\ell^-$, $K^*\nu\bar{\nu}$) will be out in the area of radiative and EWK penguin searches — **Stay tuned!**





Backup

Interplay between incl. and excl.



- Hadronic uncertainties in the inclusive and exclusive measurements are independent, and hence the difference between the two may be explained by these uncertainties (e.g. charm loop contribution)
- Belle II is capable of doing both measurements!

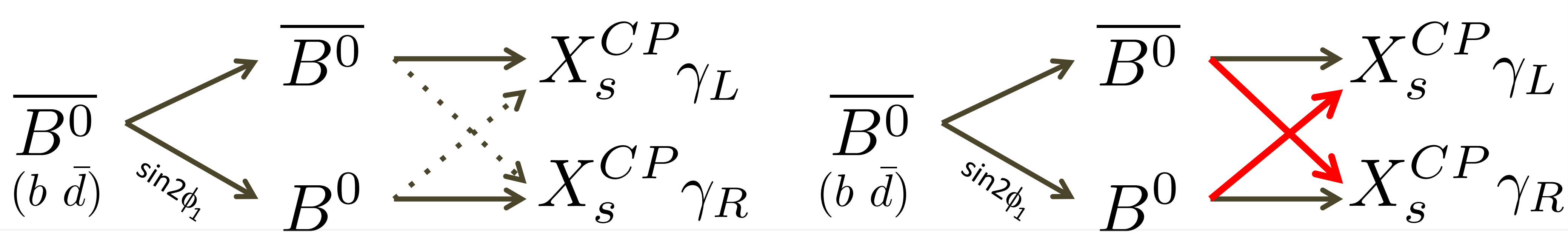
TCPV in $K^* (K_S\pi^0)\gamma$

- In the SM, γ is mostly left-handed and right-handed γ is suppressed by $O(m_s/m_b)$.

$$|S_{CP}| \approx \frac{2m_s}{m_b}\sin 2\phi_1 \quad \sim \text{a few } \%$$

- However, the right-handed may be induced by BSM effect and mix with the left-handed. If the hadronic system is in CP eigenstate, large TCPV can be seen

Large mixing in BSM scenarios



Sensitivity of $B \to X_s \ell^+ \ell^-$

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%