$b \to s\ell\ell$ transitions at Belle II, status and prospects

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on behalf of the Belle II collaboration

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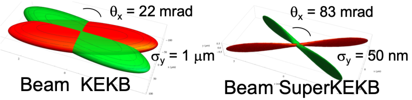
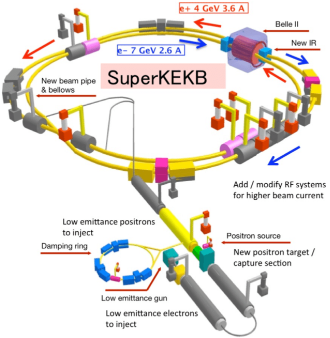
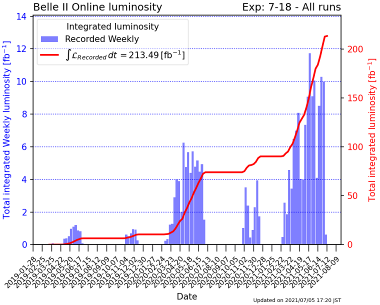
Anomalies and Precision in the Belle II Era - Workshop
6-8 September 2021

SuperKEKB

- Asymmetric e^+-e^- collider with center-of-mass energy at $B\bar{B}$ threshold, 10.58 GeV.
- Aims to collect 50 ab^{-1} (50 $\times$ Belle) of data sample by 2031.
- Plan to deliver collision at a peak luminosity of 6.5×10^{35} cm^{-2}s^{-1} (30 times that of KEKB) by;
  - reducing beam size by 20 times.
  - increasing beam current by 1.5 times.



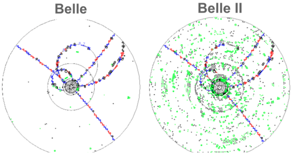


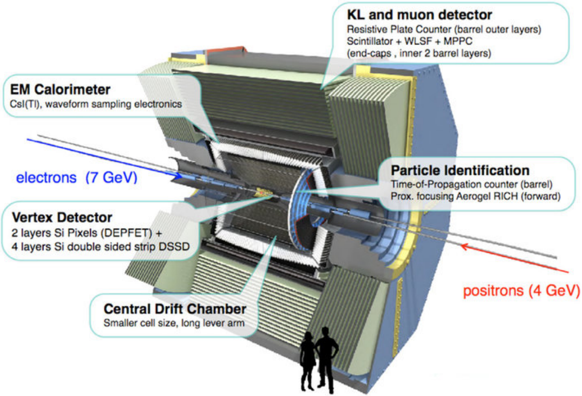


- Recorded luminosity: 213.49 fb^{-1} till summer 2021.
- Set world record: Highest instantaneous luminosity of $L = 3.1 \times 10^{34}$ cm^{-2}s^{-1}: Entering the regime of a "Super B factory".

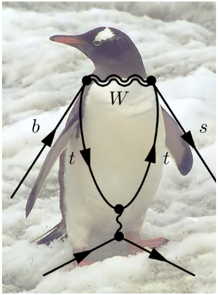
Belle II detector

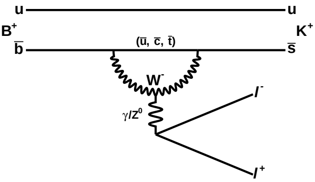
- Designed to operate with a performance similar or better than Belle.
- New detector (only the structure, the super conducting magnets and the crystals of the calorimeter are re-utilized).
- Increases beam background ($\times 10 - 20$)
    - Upgraded trigger system and sub-detectors.

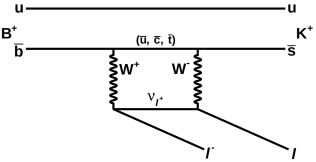




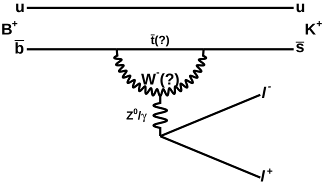
- Rare decay $B \to K^{(*)}\ell^+\ell^-$ involves $b \to s$ quark level transition, which are flavor changing neutral currents. These processes occur through penguin loop and box diagrams in standard model (SM).







- These decays are highly suppressed and have very small BRs ($\mathcal{O}$ (10^{-7})).
- They are very sensitive to new physics [PRD 69, 074020 (2004), JHEP 12, 040 (2007)].
- New physics can contribute by enhancing or suppressing the decay rates or modifying the angular distribution of the final state particles [PRD 96, 055008 (2017), PRD 96, 093006 (2017), JHEP 01, 093 (2018)].



Lepton-flavor-universality (R_K & R_{K^*})

$$R_{K^{(*)}} = \frac{B \to K^{(*)}\mu^+\mu^-}{B \to K^{(*)}e^+e^-}$$

- SM gauge bosons don't discriminate between different lepton flavors.
- SM prediction is very accurate. $R^{(SM)}_{K^{(*)}} = 1 \pm \mathcal{O}\left(10^{-2}\right)$ [Eur. Phys. J. C76, 440 (2016)].
- LHCb reported a series of anomalies with several modes, $B^0 \to K^{*0}\ell^+\ell^-$, $B^+ \to K^+\ell^+\ell^-$, $\Lambda_b \to pK\ell^+\ell^-$.
- LHCb [arXiv:2103.11769] shows 3.1σ deviation with 9 fb^{-1} in $q^2 \in [1.1, 6]$ GeV$^2/c^4$ in $R_{K^+} = 0.846^{+0.042+0.013}_{-0.039-0.012}$.
- LHCb [JHEP 08 (2017) 055] R_{K^*} values are compatible with SM predictions at levels of $2.1 - 2.3\sigma$ for low $q^2 \in [0.045 - 1.1]$ GeV$^2/c^4$ and $2.4 - 2.5\sigma$ at central $q^2 \in [1.1, 6.0]$ GeV$^2/c^4$ for a data sample of 3fb^{-1}.

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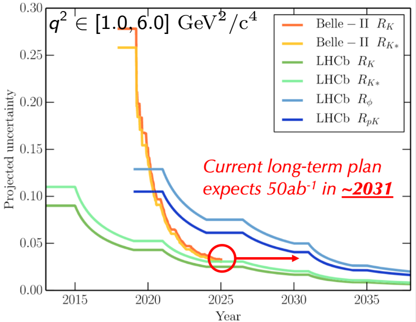


Belle II : stat. + syst.

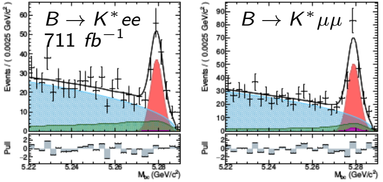
LHCb : stat.

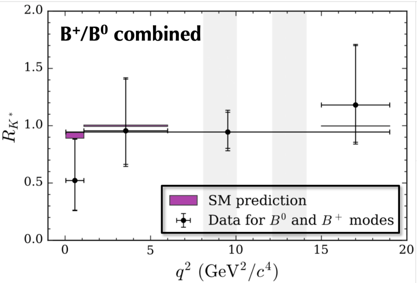
- R_{K^*} tests the lepton-flavor-universality in $B \to K^* \ell^+ \ell^-$.
- Reconstructed 4 decay modes;
  $B^+ \to K^{*+}(K^+\pi^0, K^0_S\pi^+)\ell^+\ell^-$
  $B^0 \to K^{*0}(K^+\pi^-, K^0_S\pi^0)\ell^+\ell^-$.
- Kinematic variables to distinguish signal from background;

$$M_{\rm bc} = \sqrt{E^2_{beam}/c^4 - |p_B|^2/c^4}$$
$$\Delta E = E_B - E_{beam}$$

- Background is suppressed using a Neural Network.
- $103^{+13.4}_{-12.7}$ and $139.9^{+16.0}_{-15.4}$ events for electron and muon modes.
- $R_{K^{*+}}$, $R_{K^{*0}}$ and R_{K^*} are measured for both low and high q^2 bins.
- Results consistent with the SM predictions.
- First result for $R_{K^{*+}}$ measurement.

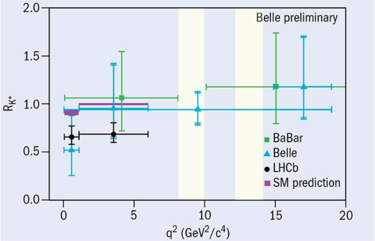
combinatorial, signal, charmonium, peaking, total



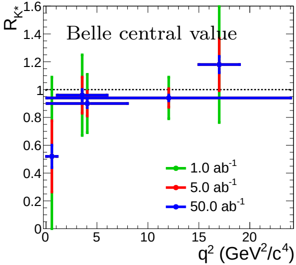


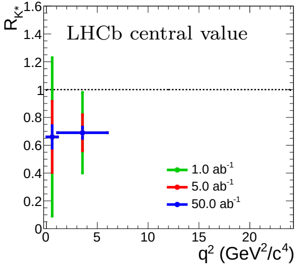
R_{K^*} Projections for Belle II

- Statistical uncertainty projections for 1 ab^{-1}, 5 ab^{-1} and 50.0 ab^{-1} data samples of Belle II.
- Belle and LHCb central values are used for plotting.
- Expected sensitivity with 1 ab^{-1}, 5 ab^{-1} and 50.0 ab^{-1} data samples are $\sim 15\%$, $\sim 6\%$ and $\sim 2\%$ for the whole q^2 region.



Belle II projections

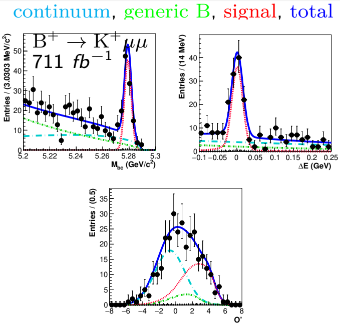


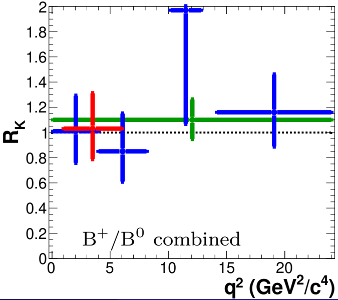


- With 50.0 ab^{-1} data sample of Belle II, the statistical uncertainty will be $\sim 2\%$ for whole q^2 region and within $3-4\%$ for different q^2 bins, except for $[0.045, 1.1]$ GeV$^2/c^4$ bin, which will have an uncertainty of $\sim 7\%$.

- R_K tests the lepton-flavor-universality in $B \to K\ell\ell$.
- Decay modes reconstructed, $B^+ \to K^+\ell\ell$ and $B^0 \to K^0_S\ell\ell$.
- Background from continuum and generic B are suppressed using Neural Network.
- Performed 3D fit in $M_{\rm bc}$, ΔE, and modified NN output (O') to extract the signal yield.
- 137 ± 14, 138 ± 15, $27.3^{+6.6}_{-5.8}$, and $21.8^{+7.0}_{-6.1}$ signal events for $B^+ \to K^+\mu\mu$, $B^+ \to K^+ee$, $B^0 \to K^0_S\mu\mu$, and $B^0 \to K^0_S ee$.
- R_{K^+}, R_{K^0}, R_K are measured for both low and high q^2 bins.

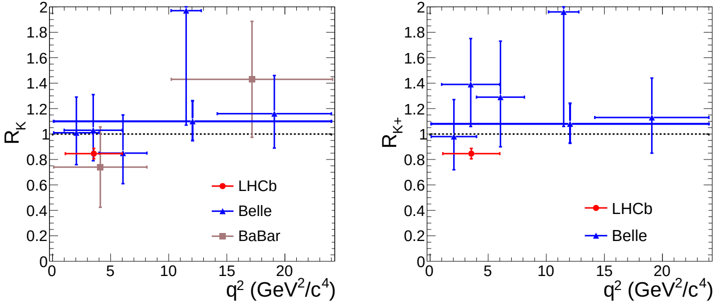
  $q^2 \in$ [0.1 , 4.0], [4.0 , 8.12], [1.0 , 6.0], [10.2, 12.8], $>$ 14.18, and $>$ 0.1 GeV$^2/c^4$
- R_K values for various q^2 bins agree with the SM prediction.





State-of-the-art of R_K

- LHCb shows result for only $B^+ \to K^+\ell\ell$.
- Belle and BaBar have results for both $B^+ \to K^+\ell\ell$ and $B^0 \to K^0\ell\ell$.

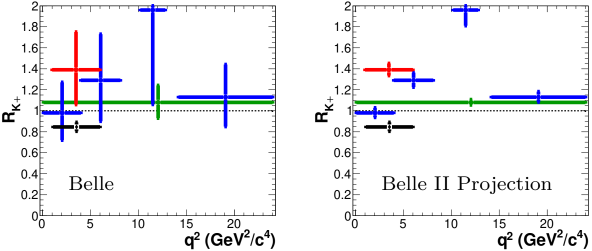


- For R_{K^+}, LHCb result shows negative deviation, while Belle result is above unity (though statistically limited).
- Belle [JHEP 03 (2021) 105] result of R_{K^+} for bin of interest $[1.0, 6.0]$ GeV$^2/c^4$ agrees with LHCb [arXiv:2103.11769] by 1.6σ.

R_{K^+} Projection for Belle II

- Belle result of R_{K^+} is projected to Belle II.

$q^2 \in$ **[0.1 , 4.0]**, **[4.0 , 8.12]**, **[1.0 , 6.0]**, **[10.2, 12.8]**, $>$ **14.18**, and $>$ **0.1** GeV^2/c^4 from Belle.
$q^2 \in$**[1.1 , 6.0]** GeV^2/c^4 from LHCb (9 fb^{-1})

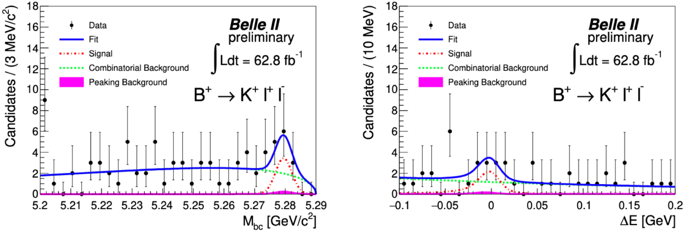


- Statistical sensitivity of Belle II will be $< 2\%$ for whole q^2 region and it will be $2.5 - 3.5\%$ for different q^2 bins.
- For $q^2 \in [1.0, 6.0]$ GeV^2/c^4 bin, considering same central value of Belle, the R_{K^+} of Belle II will deviate from LHCb [PRL 122, 191801 (2019)] by $> 10\sigma$.

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

- Preliminary measurement at Belle II on $b \to s\ell\ell$.
- $B^+ \to J/\psi(\ell\ell)K^+$ and $B^+ \to \psi(2S)(\ell\ell)K^+$ decays are rejected with di-lepton invariant mass vetoes.
- FastBDT (event shape, vertex quality, and kinematic variables) is used to suppress background from light quark and inclusive B decays.
- 2D fit in $M_{\rm bc}$ and ΔE to extract the signal yield.

$$M_{\rm bc} = \sqrt{E_{beam}^2/c^4 - |p_B|^2/c^4}$$
$$\Delta E = E_B - E_{beam}$$



- $8.6^{+4.3}_{-3.9} \pm 0.4$ signal events (2.7σ significance) with just 62.8 fb^{-1} of data sample (summer 2020).
- Available data was not enough to determine key observable like BR, R_K, A_I, etc..
- Updated $B \to K\ell\ell$ and $B \to K^*\ell\ell$ analyses are in progress.

$B \to X_s \ell\ell$ and R_{X_s} at Belle II

- Belle II can perform LFU test by measuring R_{X_s} in inclusive $B \to X_s \ell\ell$.
- $B \to X_s \ell\ell$ mode is the sum-of exclusive modes.
- Hadronic system X_s can be reconstructed from $Kn\pi$ final state, with $n \leqslant 4$, allowing for at most one neutral pion. Three-kaon modes can also be included.
- Belle [PRD 93 (2016) 032008] measurements are based on $M_{X_s} < 2.0$ GeV to reduce combinatorial background.
- M_{X_s} constraint can be loosen to better understand the X_s spectrum.
- Belle II detector has certainly a good resolution to the e^+e^- mode and the R_{X_s} measurement is promising.

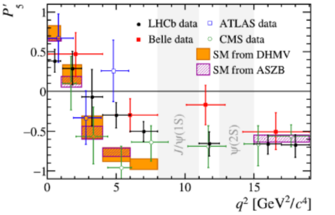
[PTEP 12, 123C01 (2019)]

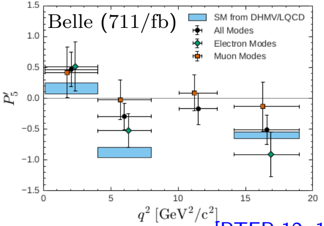
Observables	Belle (0.71 ab^{-1})	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
R_{X_s} ([1.0, 6.0] GeV$^2/c^4$)	32%	12%	4.0%
R_{X_s} ([$>$ 14.4] GeV$^2/c^4$)	28%	11%	3.4%

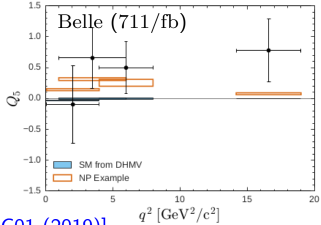
- R_{X_s} performance will be similar to R_{K^*} measurement.
- Reduction in systematic due to large data sample is crucial for precise measurement.

Angular analysis with $B^0 \to K^{*0}\ell^+\ell^-$ [PRL 118, 111801 (2017)]

- P_i' is free from form-factor uncertainty.
- Non-zero $Q_i = P_i^{\mu} - P_i^{e}$ [JHEP 05 (2013) 137] would suggest NP.
- Results on P_5'
  - LHCb P_5': $K^*\mu\mu$
    - 2.5σ in $q^2 \in (4.0, 6.0)$ GeV$^2/c^4$
    - 2.9σ in $q^2 \in (6.0, 8.0)$ GeV$^2/c^4$
  - Belle P_5': $K^*\ell\ell$
    - 2.6σ in $q^2 \in (4.0, 8.0)$ GeV$^2/c^4$, $\ell = \mu$







[PTEP 12, 123C01 (2019)]

Observables	Belle (0.71 ab^{-1})	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
P_5' ([1.0, 2.5] GeV$^2/c^4$)	0.47	0.17	0.054
P_5' ([2.5, 4.0] GeV$^2/c^4$)	0.42	0.15	0.049
P_5' ([4.0, 6.0] GeV$^2/c^4$)	0.34	0.12	0.040
P_5' (>14.2 GeV$^2/c^4$)	0.23	0.088	0.027

- Angular analysis for $B \to K^*ee$ mode in addition to $B \to K^*\mu\mu$ at Belle II.

Summary

- Flavor physics in e^+-e^- collisions offers an extremely rich physics program with many opportunities to probe New Physics.
- Access to charged and neutral B with equal efficiency.
- Equal sensitivity for muon and electron channels.
- Access to inclusive decay modes in addition to exclusive modes.
- LHCb will have much higher cross-section compared to Belle II *i.e.*, more $B\bar{B}$ pairs, and will lead the precision on the $R_{K^{(*)}}$ measurements. With the full dataset, Belle II will have comparable precision w.r.t LHCb final measurements.
- Long way to go.... a beginning has been made!

An exciting era of discoveries and precision measurements !!!

1808.10567

Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\overline{\nu})$ $[10^{-6}]$	***	20%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle II
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***	4	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb

Precision CKM Unitarity Triangle

CP Violation in b → s penguin decays

(Semi-)leptonic B decays

Radiative & EW Penguins

Charm

Lepton flavor violating τ decays
+ Dark sector & much more...

Systematics for R_K

- Systematic table for R_K at Belle.

Sources	Value (%)
Lepton identification	0.97
signal MC efficiency	0.25
Background suppression	0.4
PDF shape parameters	$0.1 - 0.3$

- Systematics like lepton identification, signal MC efficiency, and systematic due to cut on background suppression variable will decrease with the increase in data sample.
- PDF shape systematic depends upon the modeling.
- R_K or R_{K^*} systematic will be very small for Belle II and the results will be dominated by statistical uncertainty.

$B \to K^* \ell\ell$ angular analysis

The differential decay rate is given by:

$$\frac{1}{d\Gamma/dq^2}\ \frac{d^4\Gamma}{d\cos\theta_\ell\ d\cos\theta_K\ d\phi\ dq^2} =$$

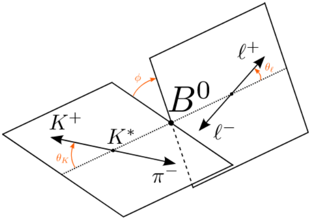
$$\frac{9}{32\pi}[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi +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

- In the lepton massless limit there are eight independent observables:

  F_L**:** Fraction of the longitudinal polarization of the K^*
  S_6**:** The forward-backward asymmetry of the dimuon system
  $S_{3,4,5,7,8,9}$: The remaining CP-averaged observables

- F_L and S_i are function of q^2.
- Observable P'_i and Q_i

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



- P'_i are free of form-factor uncertainties.
- Any deviation from zero for Q_i, would be a hint for NP.

Run Plan

- 2021 July 5. Total data collected $> 213\ \text{fb}^{-1}$
- 2021 summer shutdown
- 2021 Autumn run
  - $\Upsilon(4S)$: $\sim 400\ \text{fb}^{-1}$ (BaBar equivalent)
  - 10.75 GeV+scan for 10 fb^{-1} is planned.
- 2022 summer $\sim 700\ \text{fb}^{-1}$ (Belle equivalent)
- 2022 Long shutdown (LS1)
  - Full pixel in the 2^{nd} inner most layer.
  - TOP PMT replacement
- 2026: $\sim 15\ \text{ab}^{-1}$
- 2031: $\sim 50\ \text{ab}^{-1}$