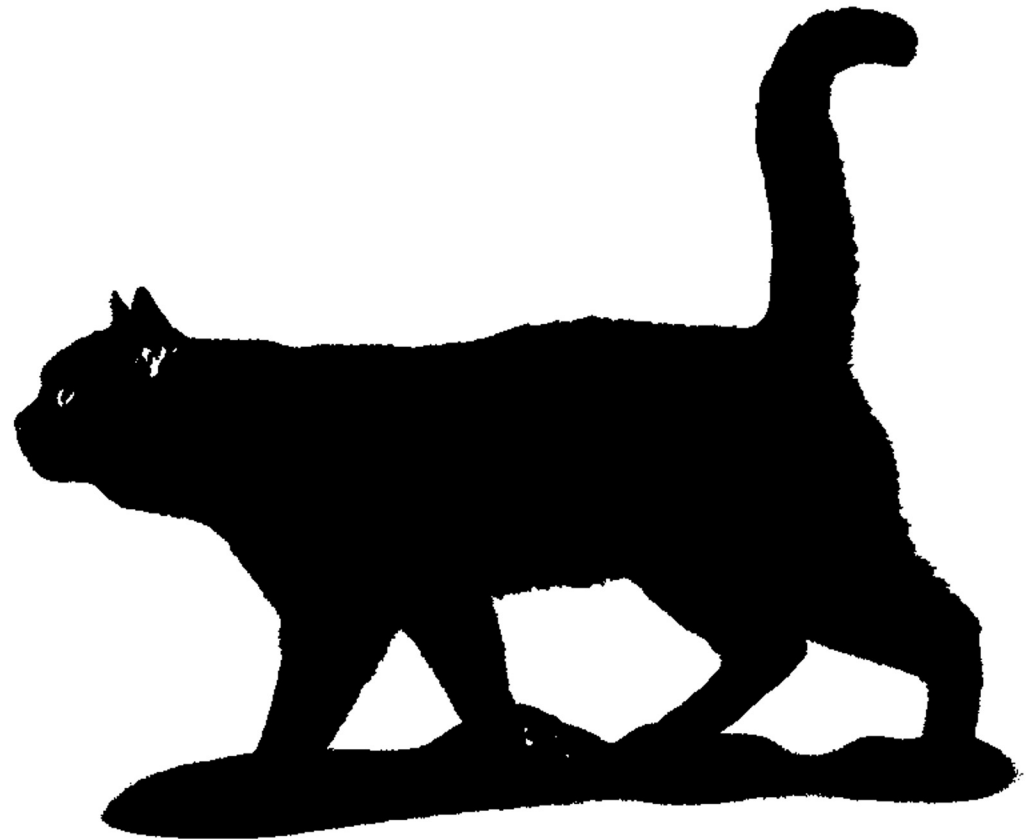
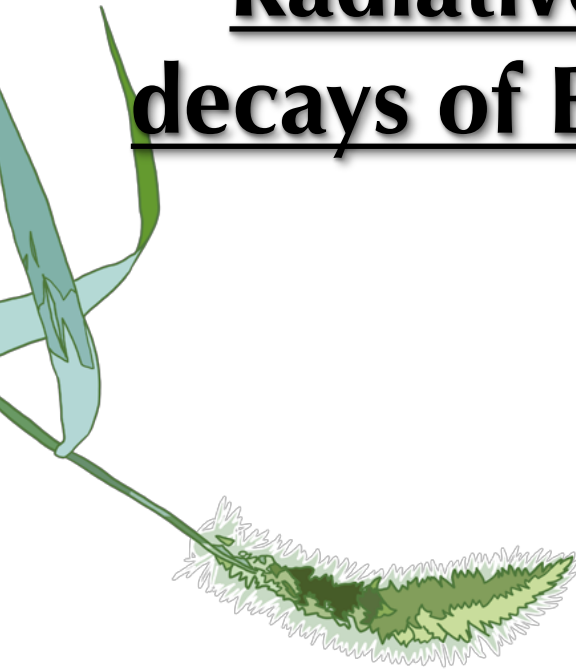
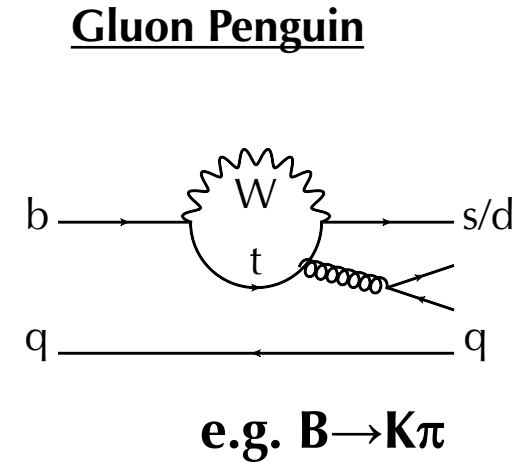
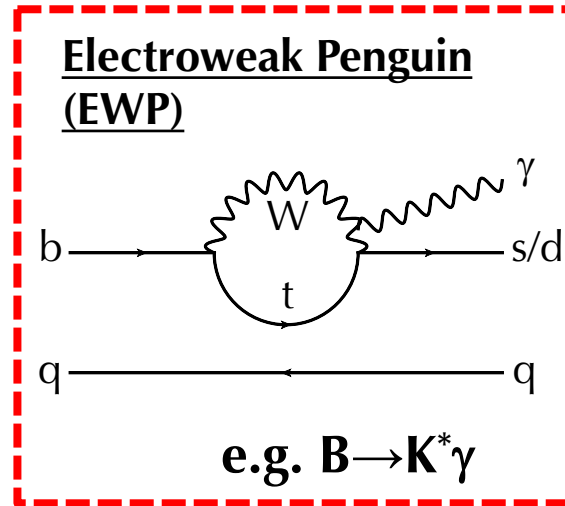
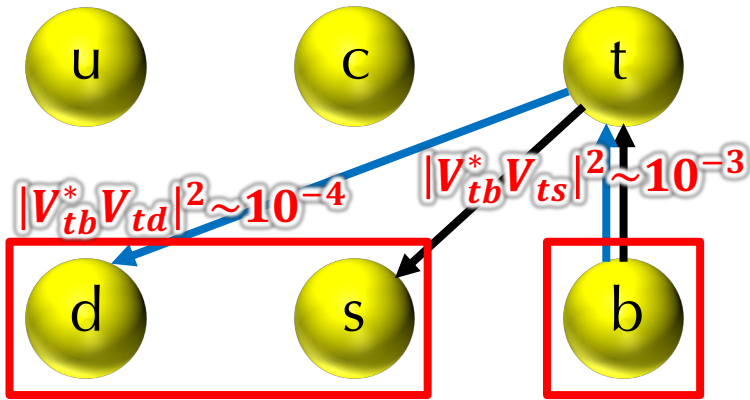


Radiative and Electroweak Penguin decays of B mesons at Belle and Belle II



S. Watanuki
University of Cincinnati

Introduction of EWP



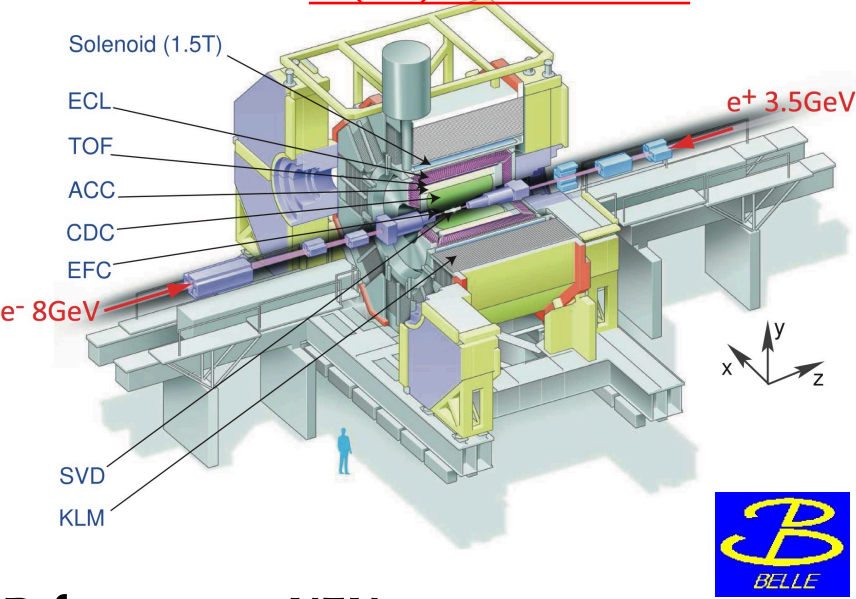
Today's topic!

- Flavor-changing-neutral-current (FCNC) occurs only by loop diagrams in the SM
 - New physics (NP) appearing in the loop can change the variables like branching ratio, CP asymmetry, and isospin asymmetry
 - Electroweak Penguin (EWP) is one of such loop diagrams
- FCNC of B meson is relatively large thanks to $V_{tb} \sim 1$
 - Highly sensitive to NP
- One of the main targets of B factory experiments

Introduction of Belle/Belle II

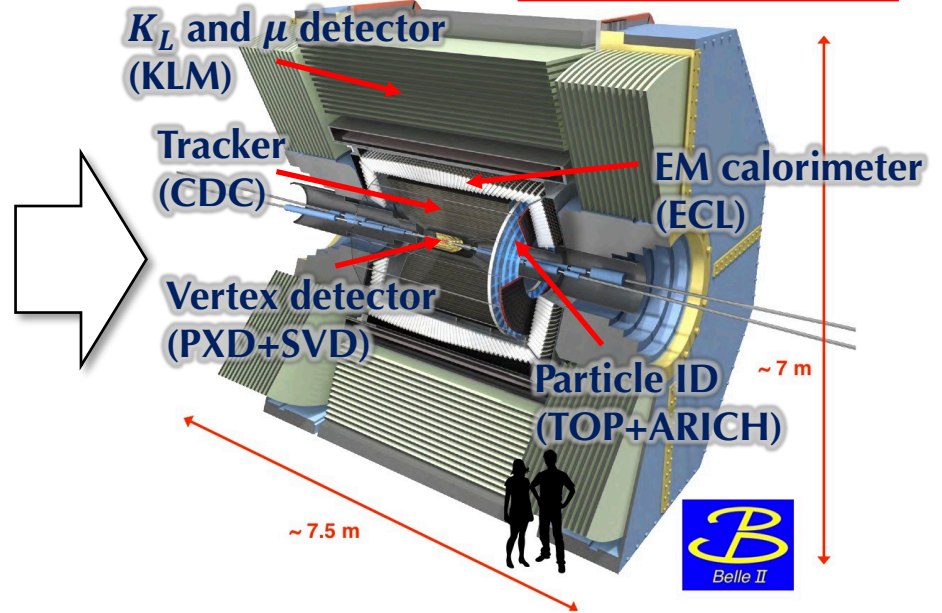
Belle

711/fb on Y(4S) resonance



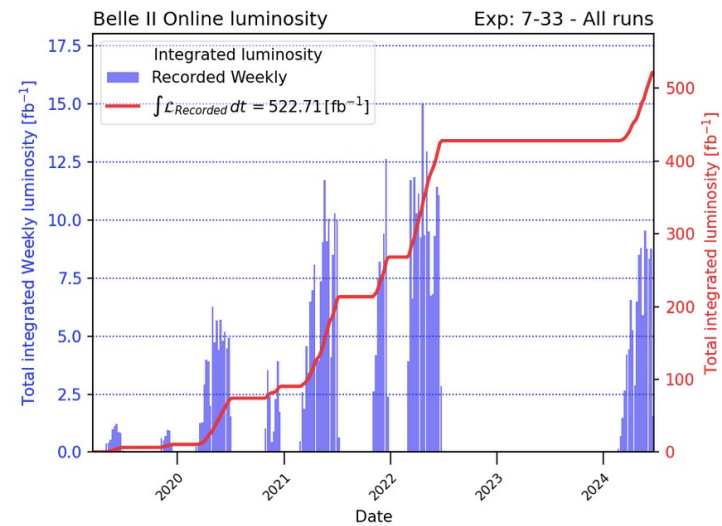
Belle II

Run1
362/fb + ~86/fb on Y(4S) resonance



B factory at KEK

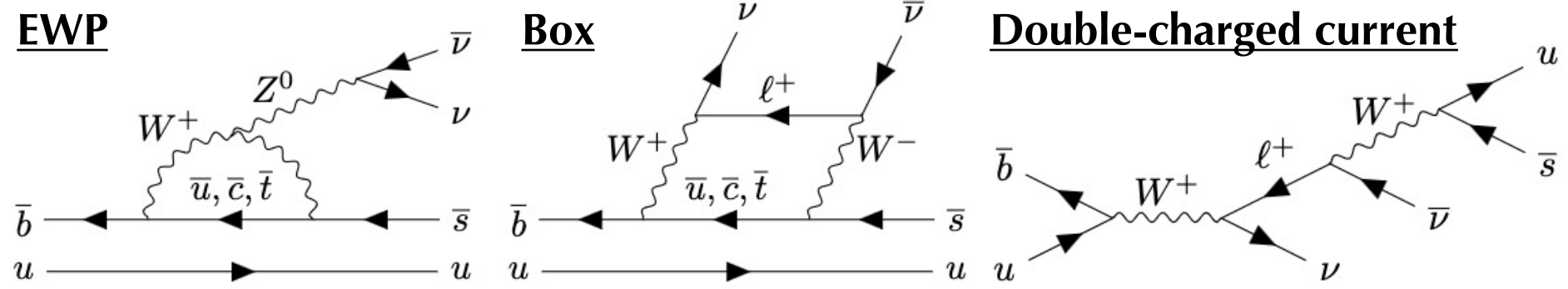
- Quantum correlated $B\bar{B}$ pairs from Y(4S) decay
- World record luminosity
 - Belle II updated the peak record of Belle ($L_{inst.} = 4.7 \times 10^{34} / cm^2 / sec.$)
- Clean environment with small background
- Belle II is smoothly operating with many upgrades from Belle



Topics

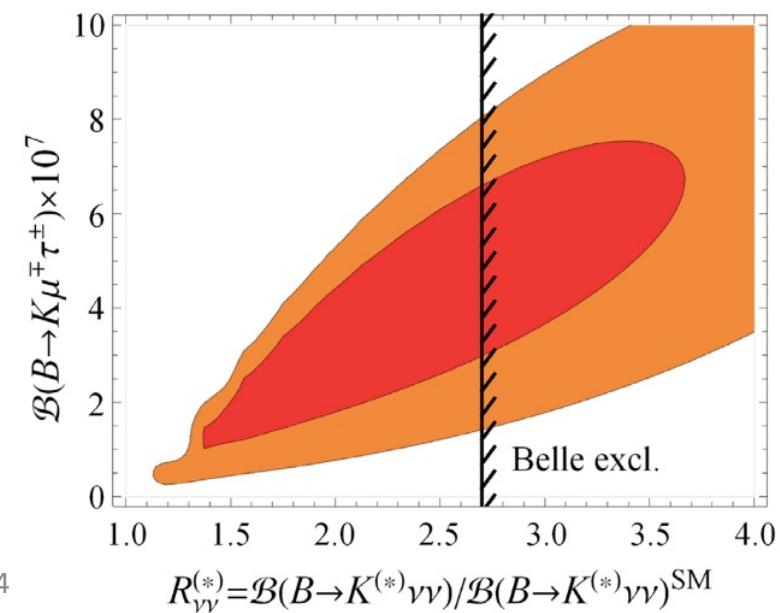
1. EWP process $B^+ \rightarrow K^+ \nu \bar{\nu}$ (**Belle II**)
2. Radiative $B \rightarrow K^*(892)\gamma$ (**Belle II**) **NEW!**
3. Radiative $B \rightarrow \rho\gamma$ (**Belle + Belle II**)
4. Double-radiative $B^0 \rightarrow \gamma\gamma$ (**Belle + Belle II**) **NEW!**
5. Time-dependent CPV of $B^0 \rightarrow K_S^0 \pi^0 \gamma$ (**Belle II**)
NEW!

EWP process $B^+ \rightarrow K^+ \nu \bar{\nu}$



- Dominated by the loop diagrams
 - New particles can appear in the loop
 - e.g., Leptoquark, invisible (ALP, dark sector, etc.)
- Unlike $b \rightarrow s \ell^+ \ell^-$, no photon exchange between the $\nu \bar{\nu}$
 - Theoretically clean
- 2 reconstruction methods with Belle II 362/fb:
 1. Inclusive-tag
 2. Hadronic-tag

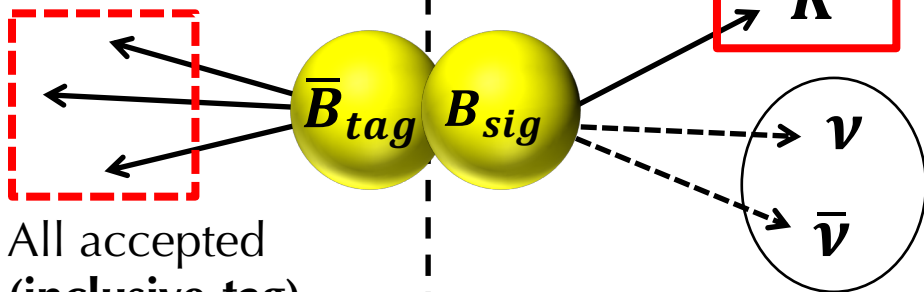
Enlarged $\mathcal{B}(B \rightarrow K \nu \bar{\nu})$ from SM indicates LFV $\mathcal{B}(B \rightarrow K \tau \mu)$
[PRD98,055003\(2018\)](https://arxiv.org/abs/1805.05503)



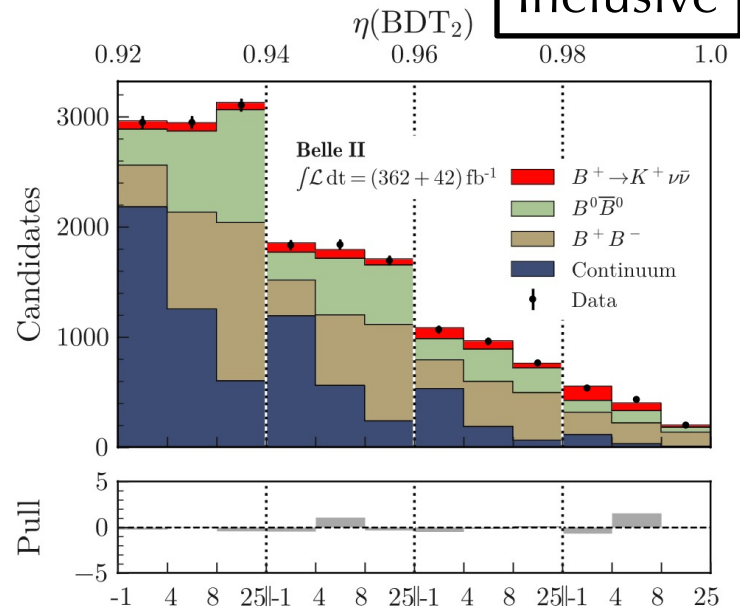
Analysis and results

Tag side B

Signal B



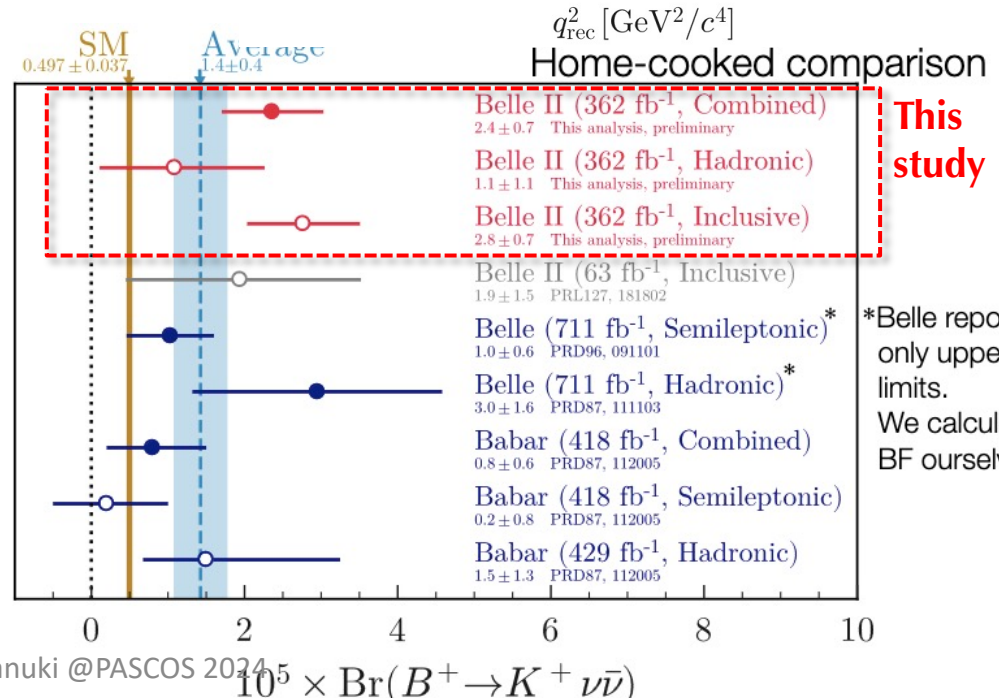
Inclusive



- All accepted (**inclusive-tag**)
- Hadronic decays are reconstructed (**hadronic-tag**)

$$q^2 \equiv p_{\nu\bar{\nu}}^2$$

Tagging method	BR ($\times 10^5$)
Inclusive	$2.7 \pm 0.5 \pm 0.5$
Hadronic	$1.1^{+0.9 \pm 0.8}_{-0.8 - 0.5}$
Combined	$2.3 \pm 0.5^{+0.5}_{-0.4}$

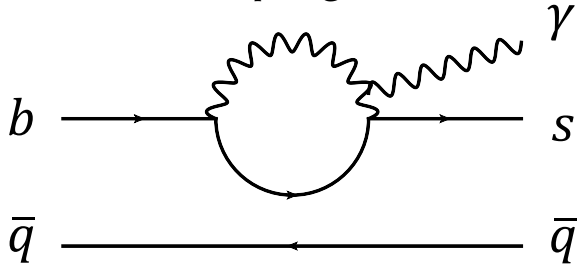


- [PRD 109, 112006](#) (2024)
- First evidence for the decay (3.5σ)
- 2.7σ away from SM prediction
- Need to cross check with Belle, and further study in Belle II
- Inclusive method established

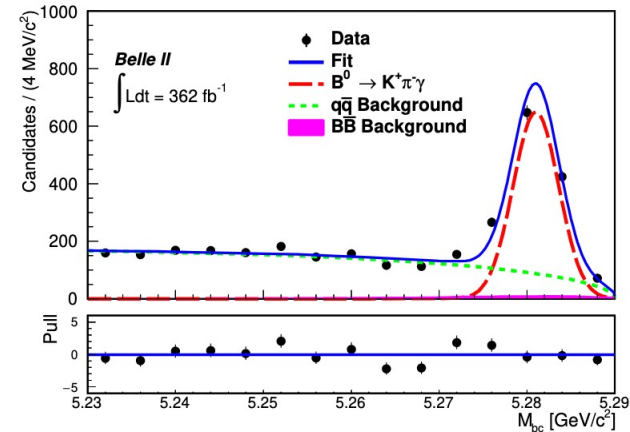
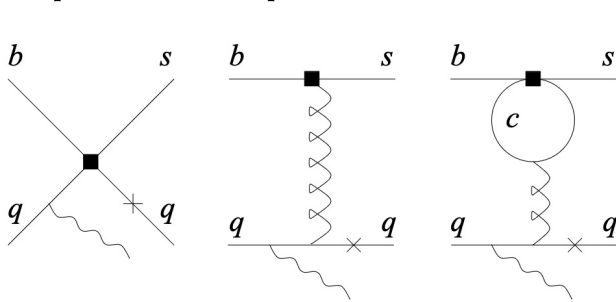
*Belle reports only upper limits. We calculate BF ourselves

Radiative $B \rightarrow K^*(892)\gamma$

Electroweak penguin



Spectator-dependent (minor)



➤ Golden channel of EWP

- A_{CP} is sensitive to the $Im(C_7)$
- $\Delta A_{CP} \equiv A_{CP}^{K^{*0}\gamma} - A_{CP}^{K^{*+}\gamma}$ is expected to provide a null test for SM
- Δ_{0+} was found to be non-zero in [Belle](#) (3.1σ)

Study with Belle II 362/fb data

- All results are consistent with SM and the world averages
- BR precision is compatible with that in Belle, even though systematics dominated
- To be submitted to JHEP

Preliminary results

- $\mathcal{B}(K^*\gamma) = (4.12 \pm 0.08 \pm 0.11) \times 10^{-5}$
- $A_{CP}(K^*\gamma) \equiv (\Gamma_{\bar{K}^*\gamma} - \Gamma_{K^*\gamma}) / (\Gamma_{\bar{K}^*\gamma} + \Gamma_{K^*\gamma}) = (-2.3 \pm 1.9 \pm 0.3)\%$
- $\Delta A_{CP} \equiv A_{CP}^{K^{*0}\gamma} - A_{CP}^{K^{*+}\gamma} = (2.2 \pm 3.8 \pm 0.7)\%$
- $\Delta_{0+} \equiv (\Gamma_{K^{*0}\gamma} - \Gamma_{K^{*+}\gamma}) / (\Gamma_{K^{*0}\gamma} + \Gamma_{K^{*+}\gamma}) = (5.1 \pm 2.0 \pm 1.0 \pm 1.1)\%$

3rd error for Δ_{0+} is due to f^{+-}/f^{00}

Good agreement with the evidence in Belle

$$\Delta_{0+}^{\text{Belle}} = (6.2 \pm 1.5 \pm 1.3)\%$$

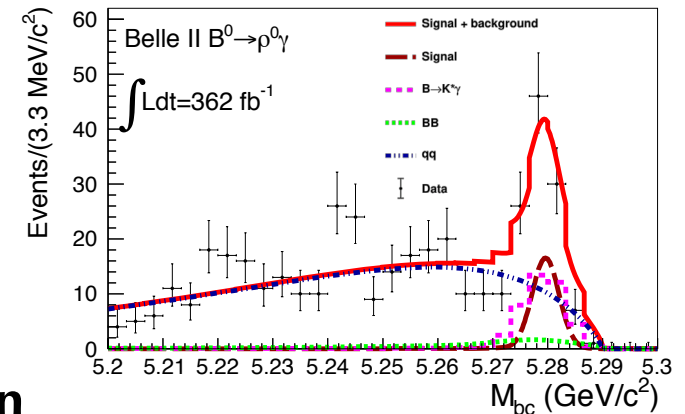
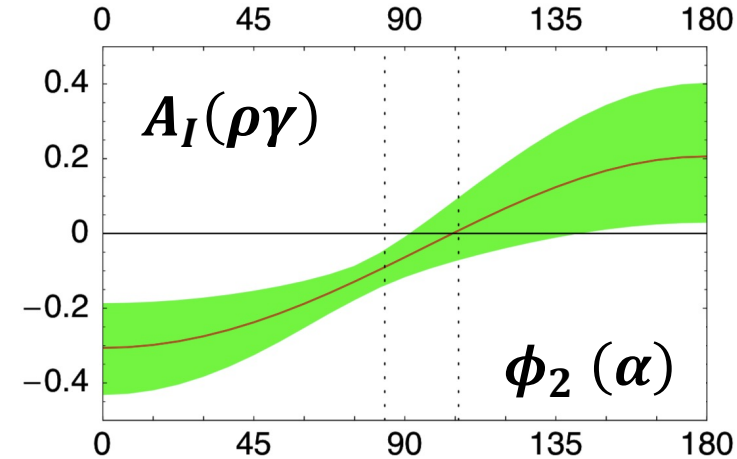
- The $B \rightarrow \rho\gamma$ decay occurs via another FCNC process, $b \rightarrow d\gamma$
 - BR is one order of magnitude less than $K^*\gamma$
 - Independent NP search from $B \rightarrow K^*\gamma$
- Possibility of hidden goldmine

Study with Belle (711/fb) + Belle II (362/fb)

- BR, A_{CP} , and isospin asymmetries ($A_I = (\Gamma_{\rho^0\gamma} - \Gamma_{\rho^+\gamma}) / (\Gamma_{\rho^0\gamma} + \Gamma_{\rho^+\gamma})$)
- In SM, A_I should be close to that of $B \rightarrow K^*\gamma$
 - $\sim 2\sigma$ tension for $A_I^{W.A.} = (30_{-13}^{+16})\%$ to date

Preliminary results

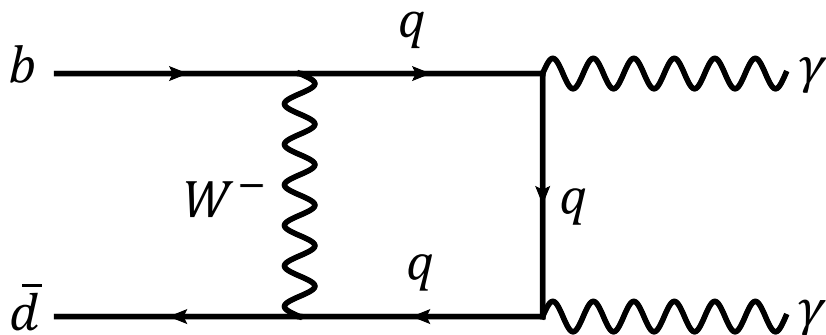
- $BR(\rho^+\gamma) = (13.1_{-1.9}^{+2.0} {}_{-1.2}^{+1.3}) \times 10^{-7}$
- $BR(\rho^0\gamma) = (7.5 \pm 1.3_{-0.8}^{+1.0}) \times 10^{-7}$
- $A_I = (10.9_{-11.7}^{+11.2} {}_{-6.2}^{+6.8} {}_{-3.9}^{+3.8})\%$
- $A_{CP} = (-8.2 \pm 15.2_{-1.2}^{+1.6})\%$



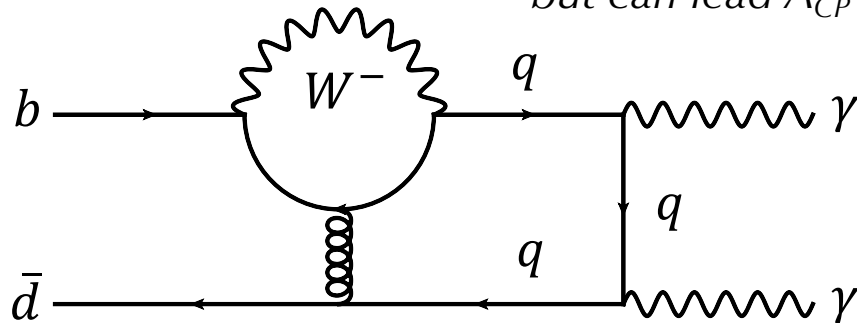
Conclusion

- Consistent with world average and SM prediction
 - Especially, the A_I is close to $B \rightarrow K^*\gamma$
- World best precision is achieved
- To be submitted to PRD

Box diagram



Penguin diagram



*expected small,
but can lead A_{CP}*

➤ In the SM, the decay is allowed only with loop diagrams;

$$- \mathcal{B}_{SM}(B^0 \rightarrow \gamma\gamma) = (1.4_{-0.8}^{+1.4}) \times 10^{-8}$$

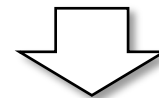
- Highly helicity suppressed in comparison to $B_s^0 \rightarrow \gamma\gamma$ (factor $|V_{td}|^2/|V_{ts}|^2 \sim 0.04$)

➤ NP effect in the loop can enhance the BF

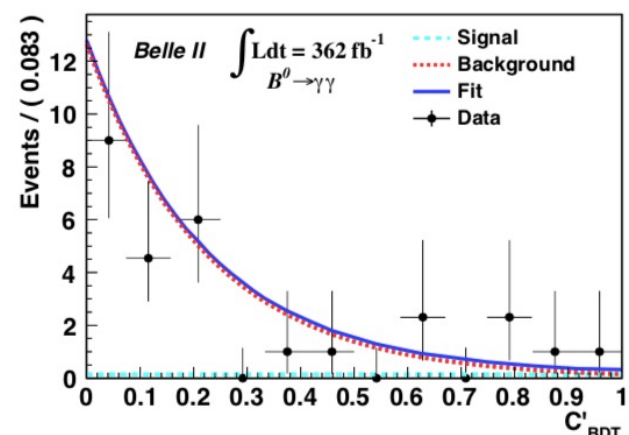
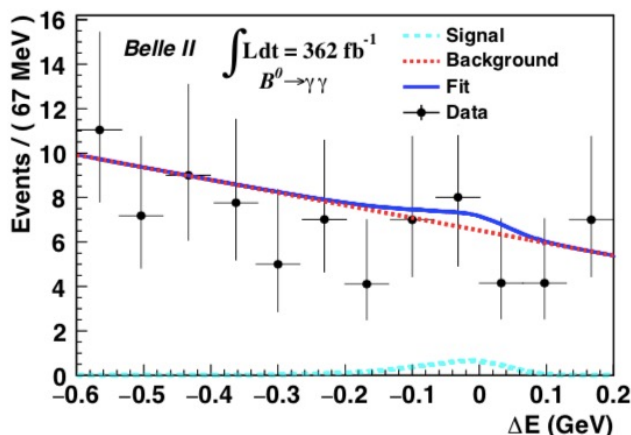
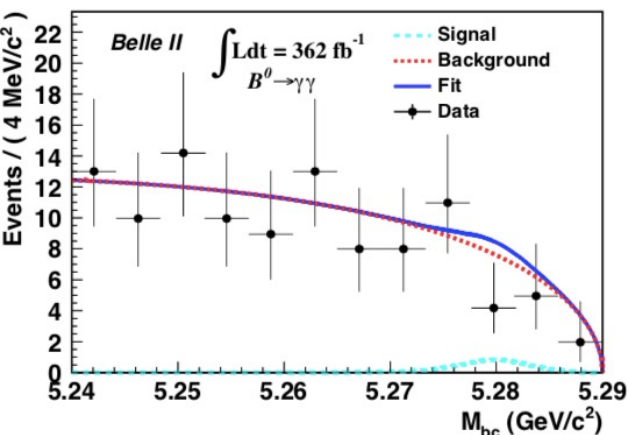
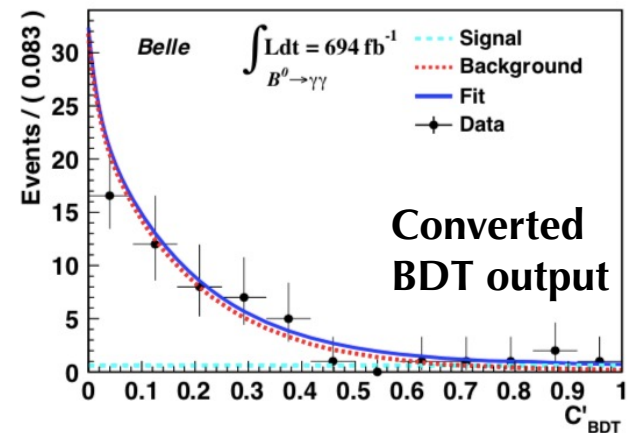
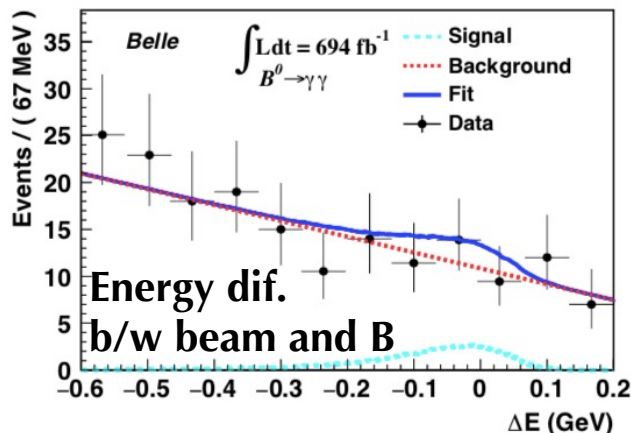
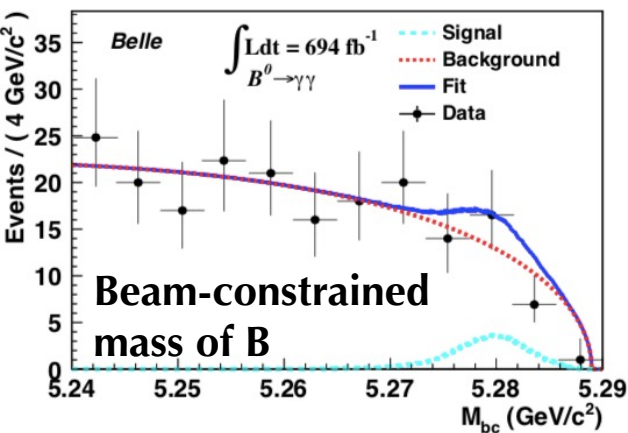
- Similar to $B \rightarrow X_{s/d}\gamma$ with Wilson coefficient C_7

- Complementary test of C_7 for different contribution of 4-quark operators

Exp.	U.L.
Belle (104/fb)	$< 6.2 \times 10^{-7}$
BaBar (426/fb)	$< 3.2 \times 10^{-7}$



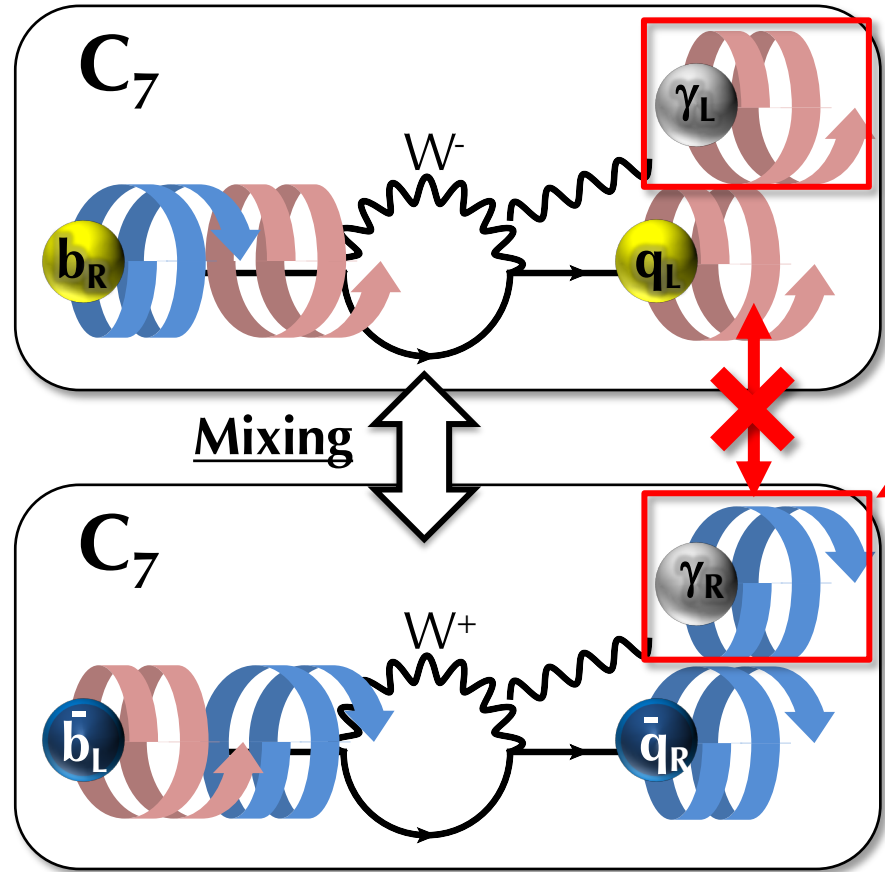
To be updated by
Belle + Belle II joint
→ **More than 1/ab**



Preliminary	$\mathcal{B}(B^0 \rightarrow \gamma\gamma) \times 10^8$	U.L. (90% CL)
Belle	$5.4^{+3.3}_{-2.6} \pm 0.5$	$< 9.9 \times 10^{-8}$
Belle II	$1.7^{+3.7}_{-2.4} \pm 0.3$	$< 7.4 \times 10^{-8}$
Combined	$3.7^{+2.2}_{-1.8} \pm 0.7$	$< 6.4 \times 10^{-8}$

- [arXiv:2405.19734](https://arxiv.org/abs/2405.19734)
- Observed signal significance is 2.5σ
- U.L. is order of 10^{-8} (same order of the SM prediction)
 - Expected U.L. from the simulation is $< 4.4 \times 10^{-8}$ at 90% CL

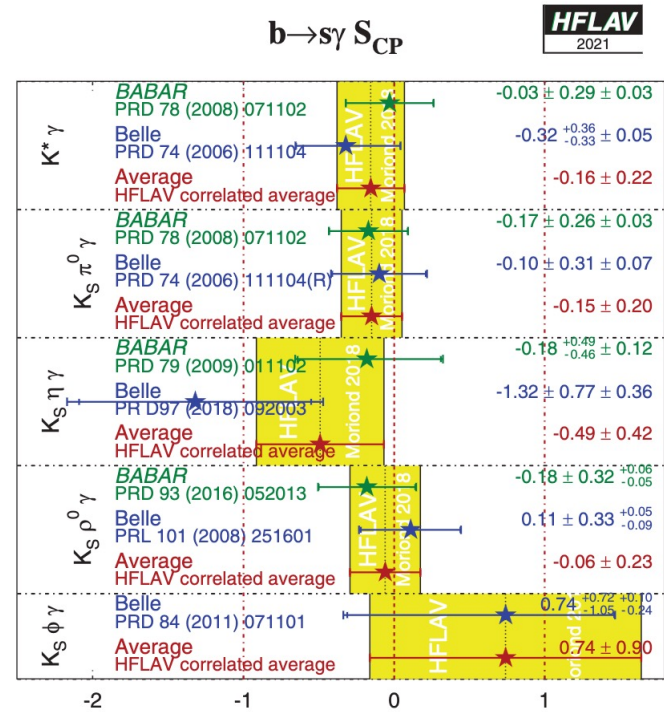
Time-dependent CPV of $B^0 \rightarrow K_S^0 \pi^0 \gamma$ ¹¹



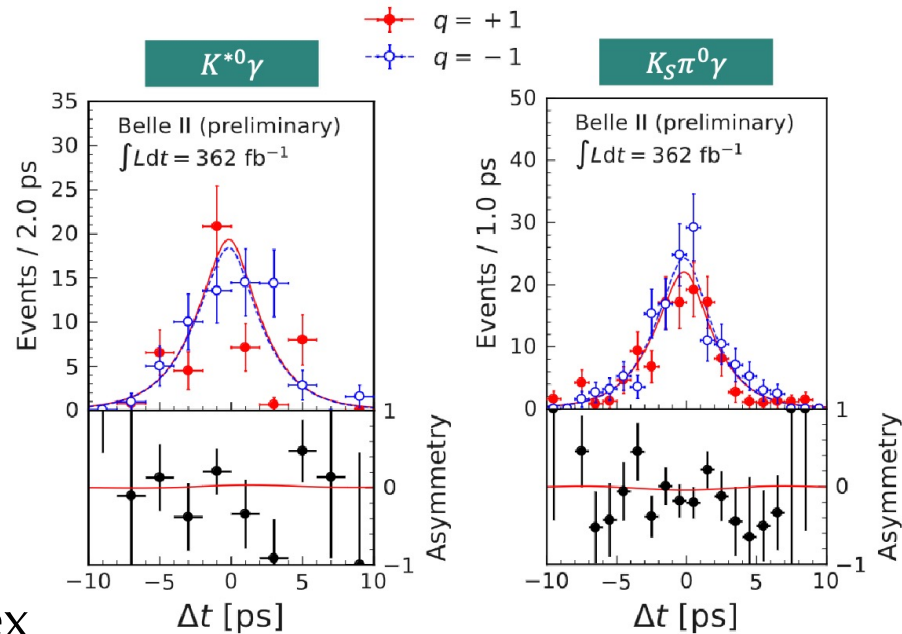
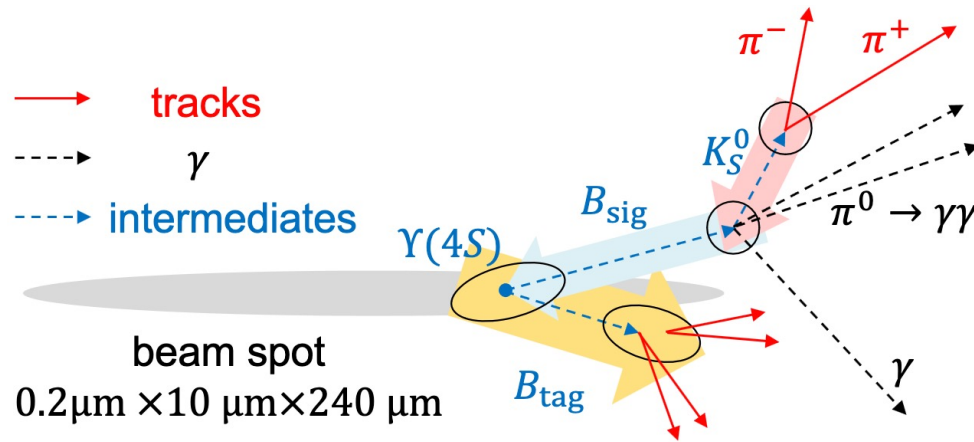
C'_7 (suppressed in SM)

Interference is suppressed in the SM
Non-zero TDCPV indicates NP

- New physics which enhances the right-handed photon process can allow a non-zero TDCPV for $B^0 \rightarrow V\gamma$
- The NP effect can be independent between $V = K^{*0}$ and $V = \rho^0$



$B^0 \rightarrow K_S^0 \pi^0 \gamma$ in Belle II



- 362/fb, preliminary result
- No charged track from the primary vertex

- Assuming beam spot to which the K_S^0 momentum is extrapolated

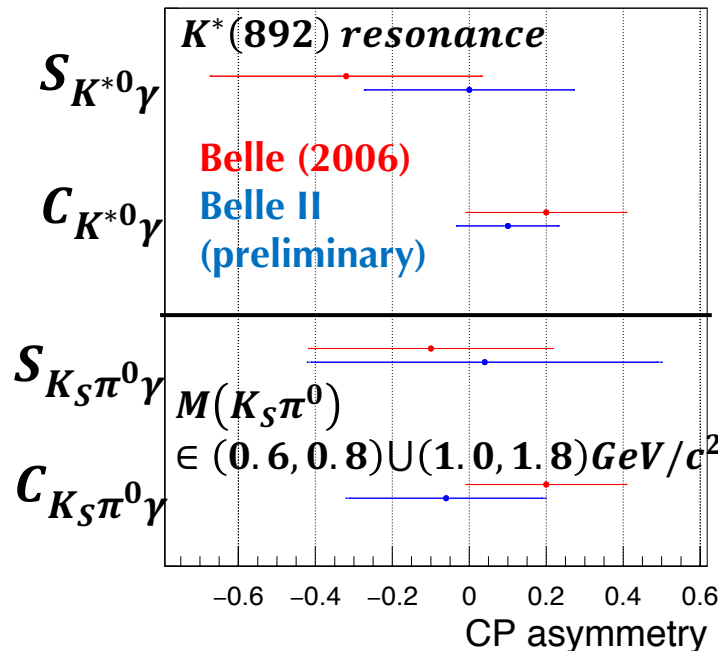
- Very challenging

- **Unique analysis for B factory**

- **Belle II result is better than Belle (2006)** for the $K^*(892)$ resonance

- Thanks to the improved flavor-tagging and vertex resolutions

- To be submitted to PRL



Summary

- Reported the EWP analyses in Belle and Belle II
 - Some studies use Belle + Belle II data to achieve the current best precision
 - No evidence for new physics so far
- Many world-leading results
 - 3.5σ evidence for $B^+ \rightarrow K^+ \nu \bar{\nu}$
 - World best precision for $B \rightarrow \rho\gamma, B \rightarrow \gamma\gamma$ by Belle + Belle II
 - Most of them are unique to Belle / Belle II for the final states with neutral particles or missing energy
- Thanks to many updates, some studies in Belle II showed comparable (or rather better) precision than Belle
- Please look forward the new results from Belle II run2!