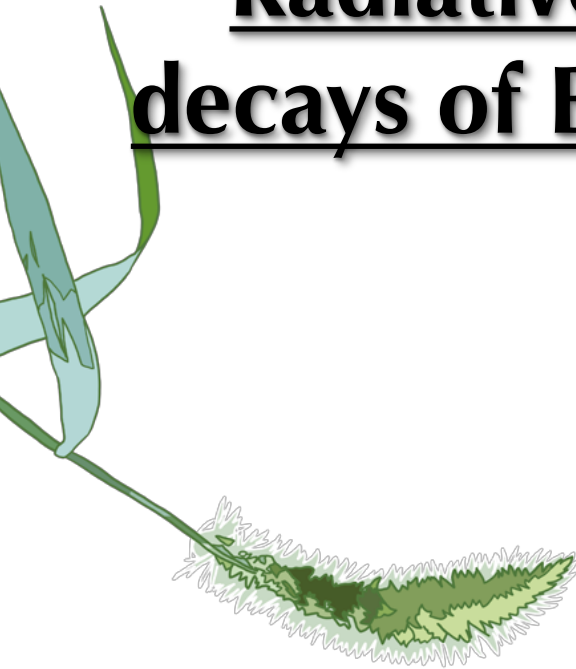# Radiative and Electroweak Penguin decays of B mesons at Belle and Belle II
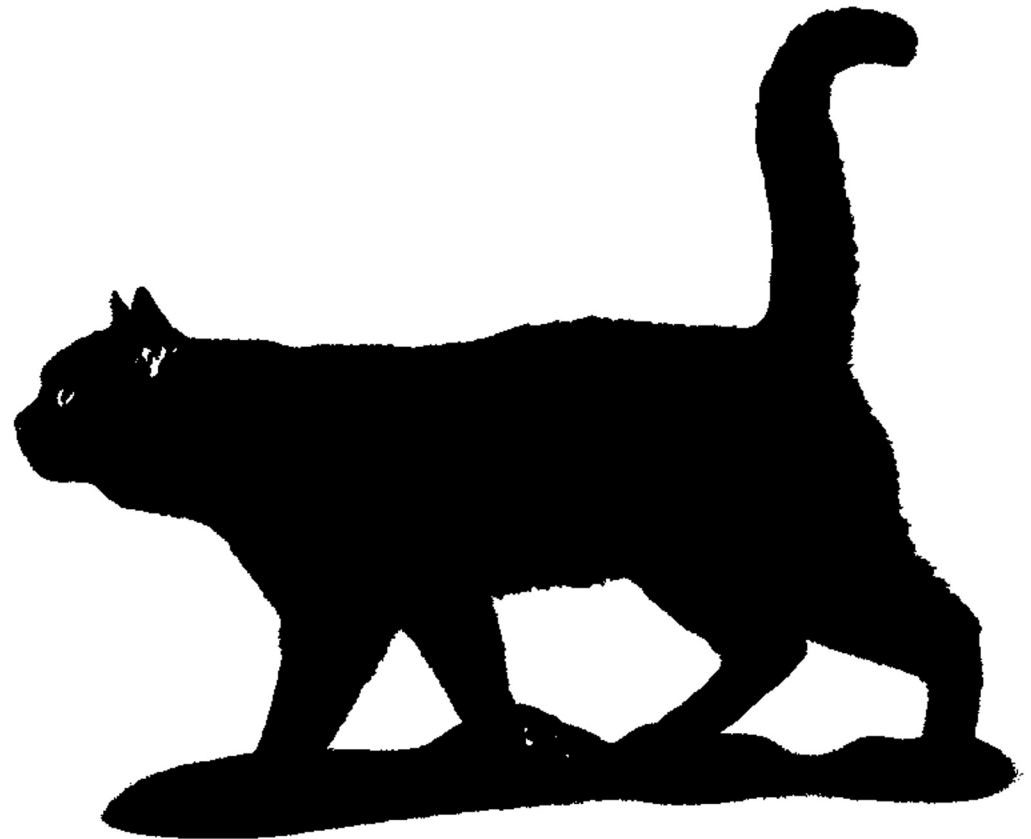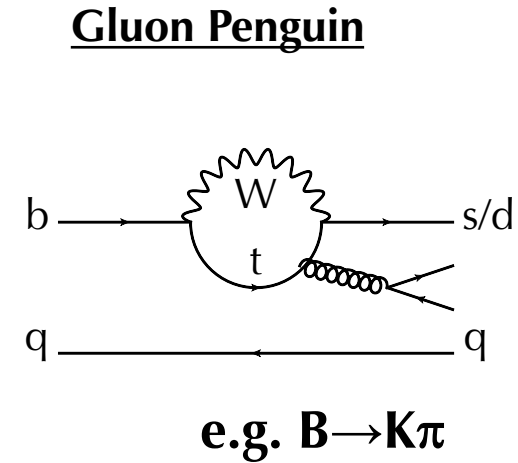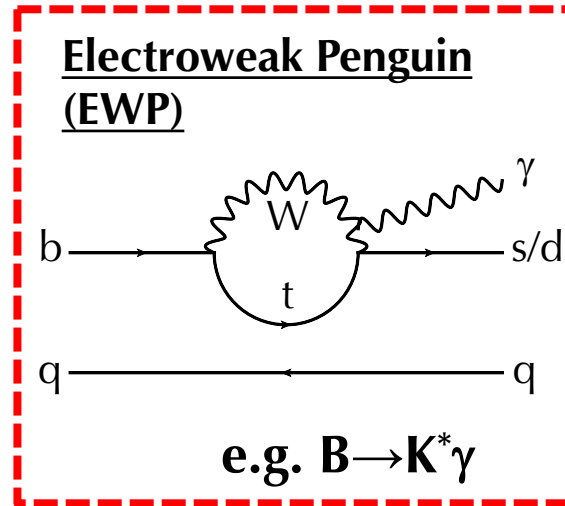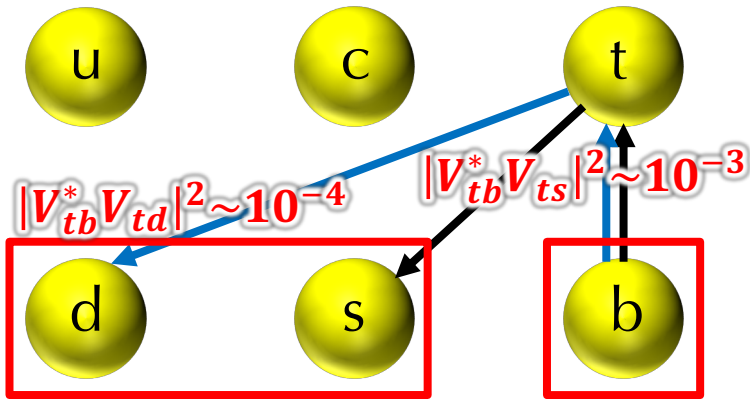
S. Watanuki
University of Cincinnati

Introduction of EWP

$|V_{tb}^* V_{td}|^2 \sim 10^{-4}$

$|V_{tb}^* V_{ts}|^2 \sim 10^{-3}$

Electroweak Penguin (EWP)

e.g. B→K*γ

Gluon Penguin

e.g. B→Kπ

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$_{tb}$~1**
   → Highly sensitive to the NP
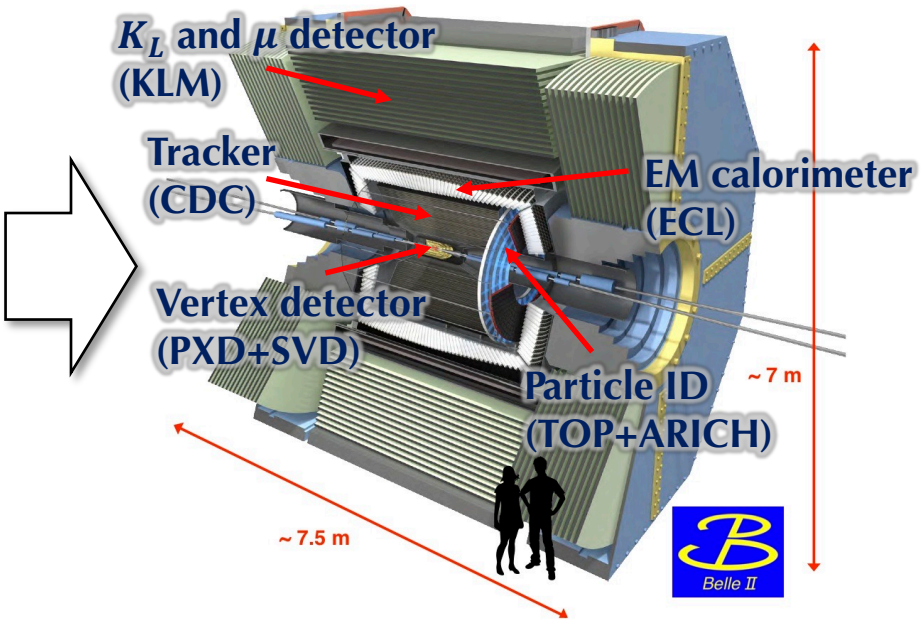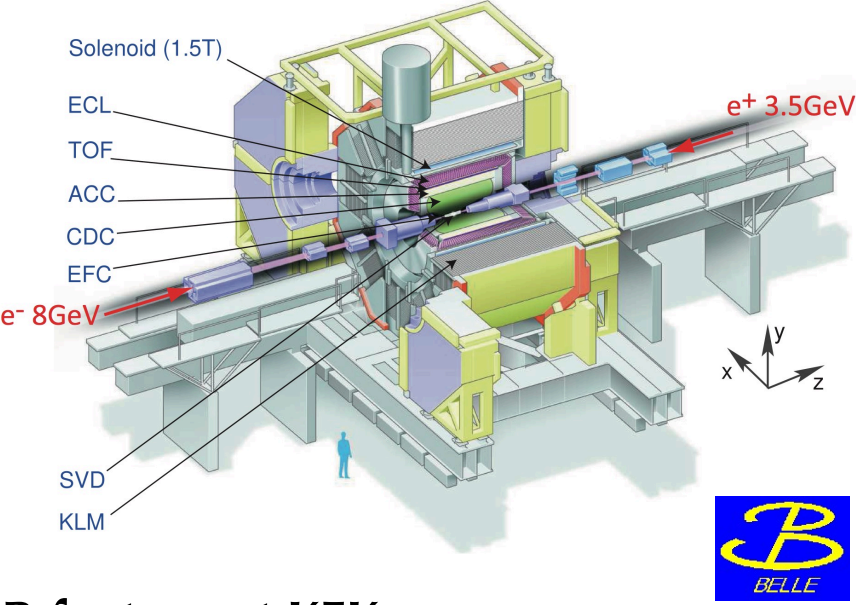➢ One of the main targets of B factory experiments

Introduction of Belle/Belle II
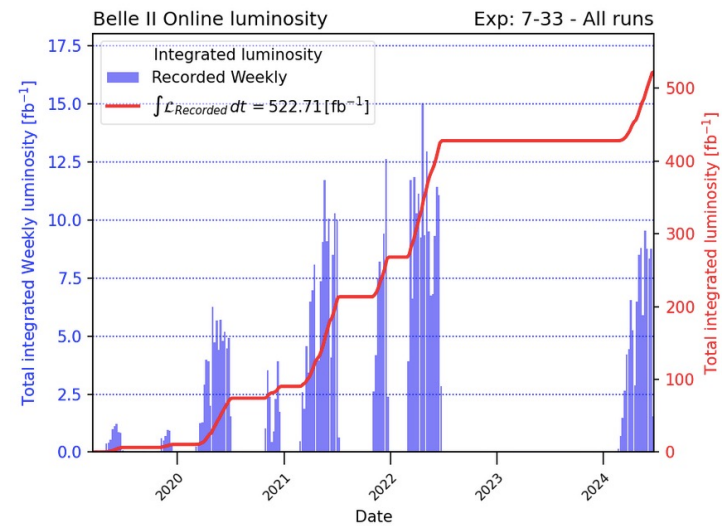
Belle — **711/fb on Υ(4S) resonance**

Belle II — **362/fb + α on Υ(4S) resonance**

Solenoid (1.5T)
ECL
TOF
ACC
CDC
EFC
e⁻ 8GeV
SVD
KLM
e⁺ 3.5GeV

K_L and μ detector (KLM)

Tracker (CDC)

Vertex detector (PXD+SVD)

EM calorimeter (ECL)

Particle ID (TOP+ARICH)

~ 7 m

~ 7.5 m

B factory at KEK

➤ Quantum correlated $B\bar{B}$ pairs from Υ(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

Belle II Online luminosity — Exp: 7-33 - All runs

Integrated luminosity
Recorded Weekly
$\int \mathcal{L}_{Recorded}\, dt = 522.71\,[fb^{-1}]$

Total integrated Weekly luminosity [fb⁻¹]
Total integrated luminosity [fb⁻¹]
Date

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Topics

1. EWP process $B^+ \to K^+ \nu \bar{\nu}$ (**Belle II**)

2. Radiative $B \to K^*(892)\gamma$ (**Belle II**) NEW!

3. Radiative $B \to \rho\gamma$ (**Belle + Belle II**)

4. Double-radiative $B^0 \to \gamma\gamma$ (**Belle + Belle II**) NEW!

5. Time-dependent CPV of $B^0 \to K_S^0 \pi^0 \gamma$ (**Belle II**) NEW!

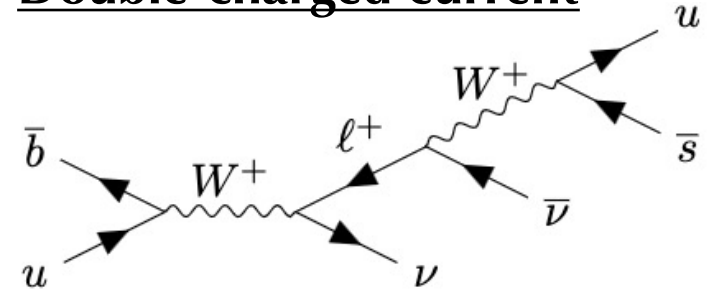# EWP process $B^+ \to K^+ \nu\bar{\nu}$
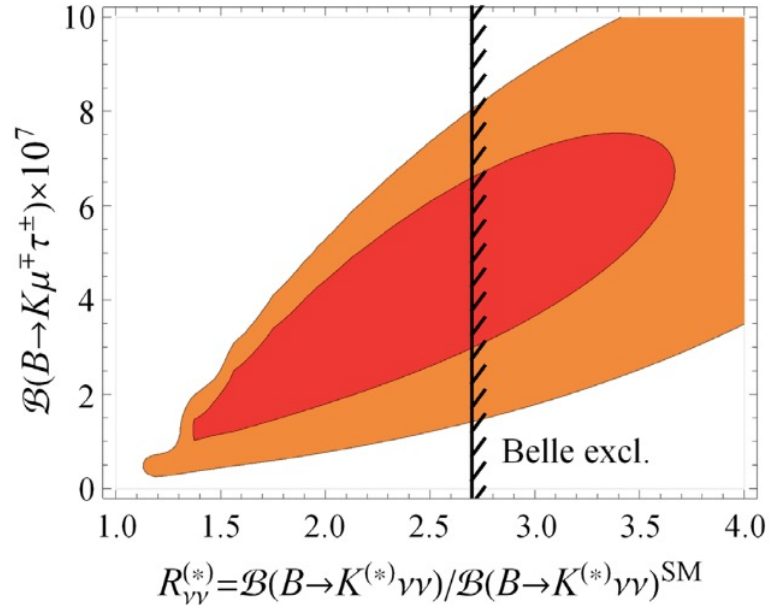
EWP
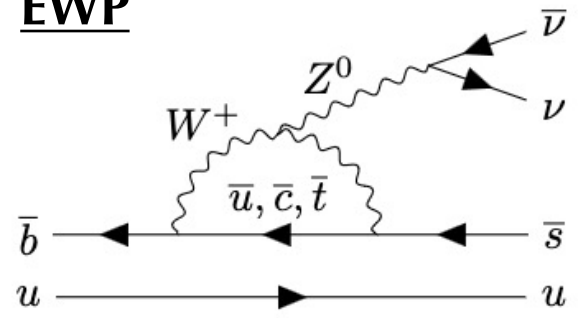
Box
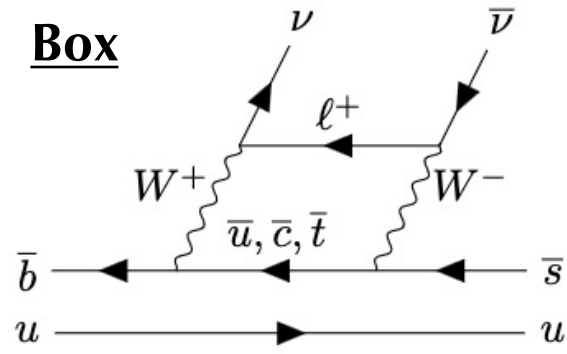
Double-charged current

➤ Dominated by the loop diagrams
  – New particles can appear in the loop
  – e.g., Leptoquark,
        invisible (ALP, dark sector, etc.)

➤ Unlike $b \to s\ell^+\ell^-$, no photon exchange between the $\nu\bar{\nu}$
  – Theoretically clean

➤ Two Belle II results with 362/fb:
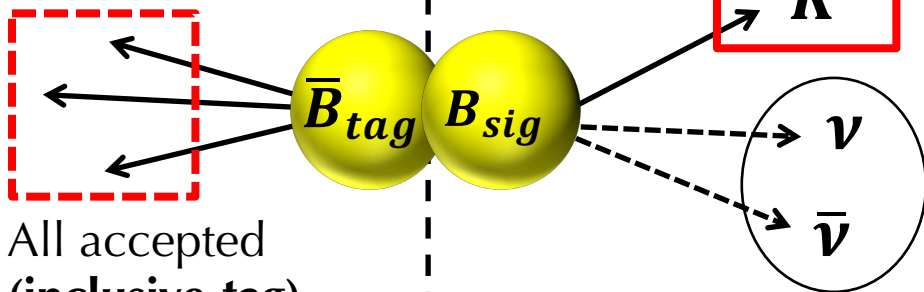 1. **Inclusive-tag**
  2. **Hadronic-tag**

Enlarged $\mathcal{B}(B \to K\nu\bar{\nu})$ from SM indicates LFV $\mathcal{B}(B \to K\tau\mu)$
PRD98,055003(2018)

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Analysis and results

Tag side B | **Signal B**

K^+

$\overline{B}_{tag}$ B_{sig}

ν

$\overline{\nu}$

$q^2 \equiv p^2_{\nu\overline{\nu}}$

- All accepted **(inclusive-tag)**
- Hadronic decays are reconstructed **(hadronic-tag)**
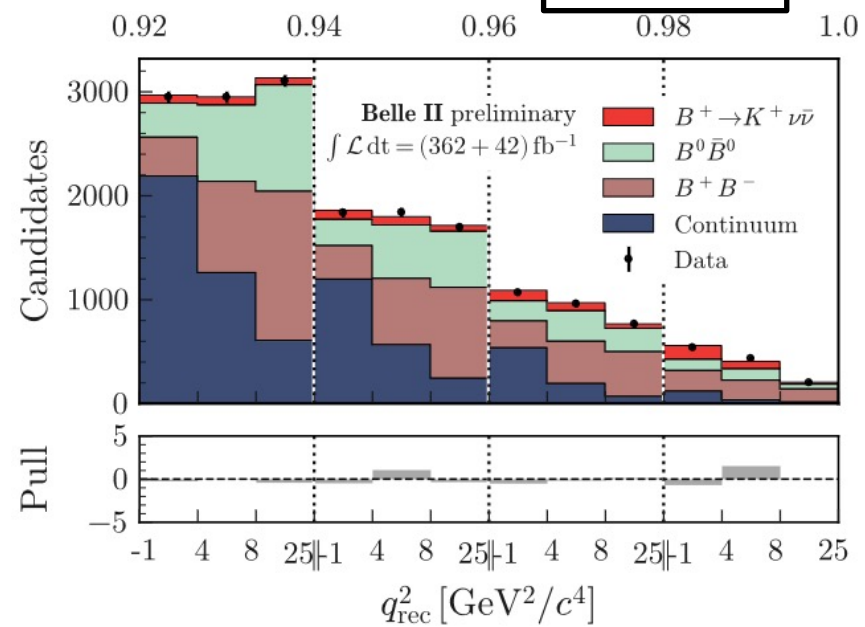
Tagging method	BR ($\times 10^5$)
Inclusive	$2.8 \pm 0.5 \pm 0.5$
Hadronic	$1.1^{+0.9\pm0.8}_{-0.8-0.5}$
Combined	$\mathbf{2.4 \pm 0.5^{+0.5}_{-0.4}}$

- Study with Belle II 362/fb
- First evidence of the decay (**3.5σ**)
- **2.8σ away from SM prediction**
- Need to cross check with Belle, and further study in Belle II
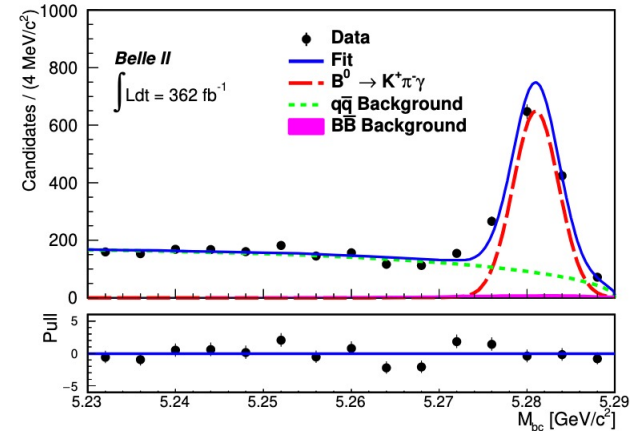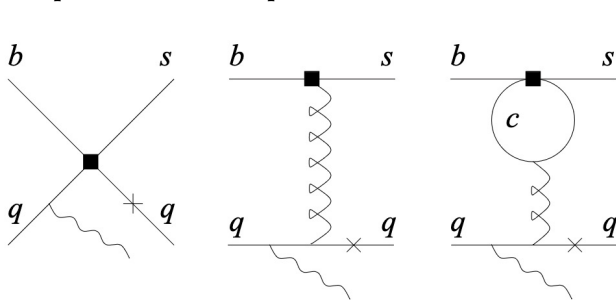- Inclusive method established

Belle II preliminary
$\int \mathcal{L}\,dt = (362 + 42)\,\text{fb}^{-1}$

$B^+ \to K^+ \nu\bar{\nu}$
$B^0\bar{B}^0$
$B^+ B^-$
Continuum
Data

Candidates

Pull

$q^2_{rec}\,[\text{GeV}^2/c^4]$

SM
0.497 ± 0.037
Average
1.4 ± 0.4

Home-cooked comparison

Belle II (362 fb^{-1}, Combined)
2.4 ± 0.7 This analysis, preliminary

Belle II (362 fb^{-1}, Hadronic)
1.1 ± 1.1 This analysis, preliminary

Belle II (362 fb^{-1}, Inclusive)
2.8 ± 0.7 This analysis, preliminary

This study

Belle II (63 fb^{-1}, Inclusive)
1.9 ± 1.5 PRL127, 181802

Belle (711 fb^{-1}, Semileptonic)*
1.0 ± 0.6 PRD96, 091101

Belle (711 fb^{-1}, Hadronic)*
3.0 ± 1.6 PRD87, 111103

Babar (418 fb^{-1}, Combined)
0.8 ± 0.6 PRD87, 112005

Babar (418 fb^{-1}, Semileptonic)
0.2 ± 0.8 PRD87, 112005

Babar (429 fb^{-1}, Hadronic)
1.5 ± 1.3 PRD87, 112005

*Belle reports only upper limits. We calculate BF ourselves

$10^5 \times \text{Br}(B^+ \to K^+ \nu\bar{\nu})$

S. Wata

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

Electroweak penguin
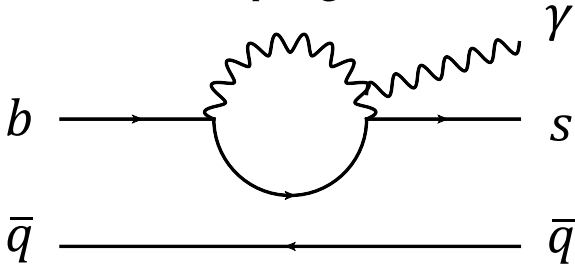
Spectator-dependent (minor)

➢ **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

Preliminary results

- $\mathcal{B}(K^*\gamma) = (4.12 \pm 0.08 \pm 0.11) \times 10^{-5}$
- $A_{CP}(K^*\gamma) = (-2.3 \pm 1.9 \pm 0.3)\%$
- $\Delta A_{CP} \equiv A_{CP}^{K^{*0}\gamma} - A_{CP}^{K^{*+}\gamma}$
  $= (2.2 \pm 3.8 \pm 0.7)\%$
- $\Delta_{0+} \equiv (\Gamma_{K^{*0}\gamma} - \Gamma_{K^{*+}\gamma})/(\Gamma_{K^{*0}\gamma} + \Gamma_{K^{*+}\gamma})$
  $= (5.1 \pm 2.0 \pm 1.5)\%$

Good agreement with the evidence in Belle

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

Radiative $B \to \rho\gamma$

- ➢ Rediscovery decay $B \to \rho\gamma$ is another FCNC $b \to d\gamma$ **process**
  - − BR is one order of magnitude less than $K^*\gamma$
  - − Independent NP search from $B \to K^*\gamma$
- ➢ 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 $B \to K^*\gamma$
  - − ~2σ tension for $A_I^{W.A.} = (30^{+16}_{-13})\%$ to date

$A_I(\rho\gamma)$

$\phi_2\ (\alpha)$

Belle II $B^0 \to \rho^0\gamma$

$\int Ldt = 362\ fb^{-1}$

Preliminary results

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

Conclusion

- ➢ Consistent with world average and SM prediction
  - − Especially, the A_I is close to $B \to K^*\gamma$
- ➢ World best precision is achieved

Double-radiative $B^0 \to \gamma\gamma$
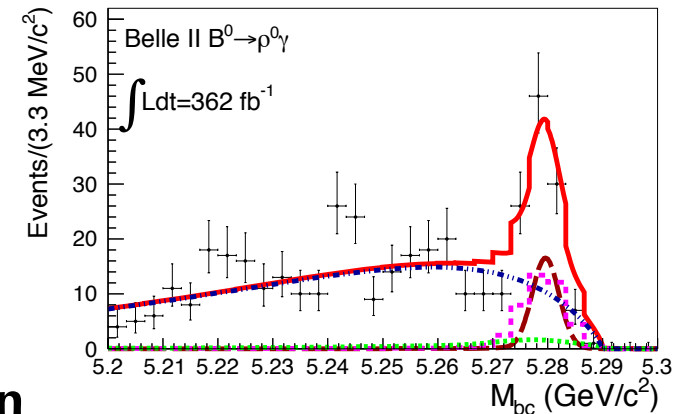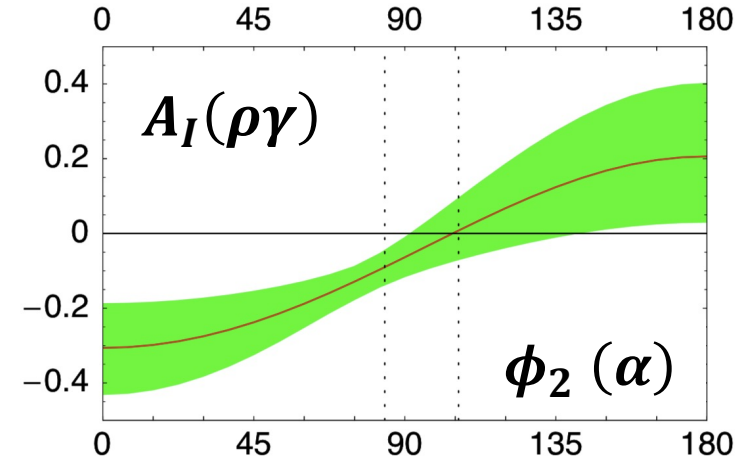
Box diagram **Penguin diagram** *expected small, but can lead A_{CP}*
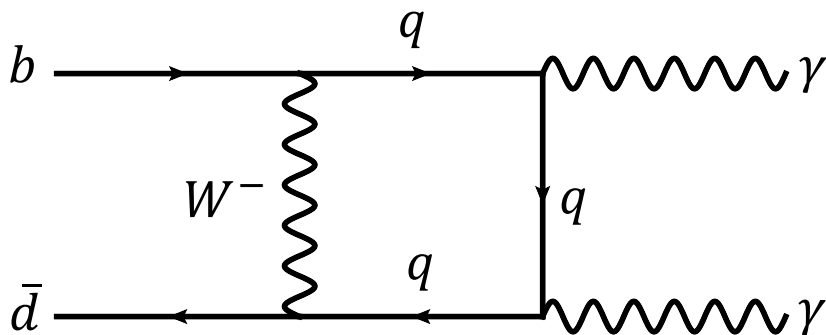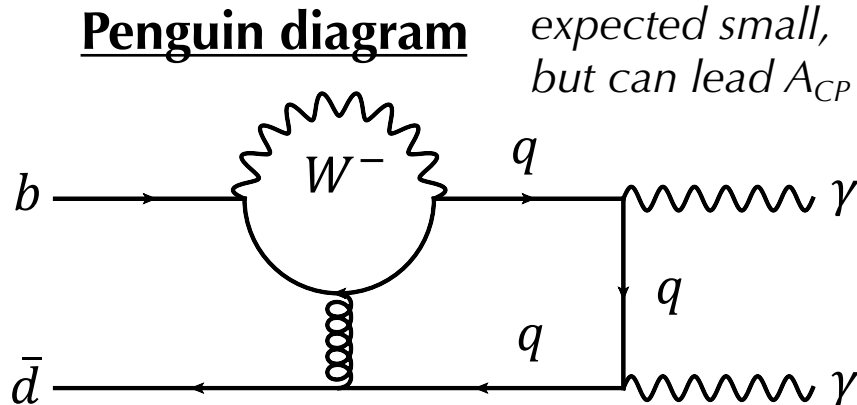
- In the SM, the decay is allowed only with loop diagrams;

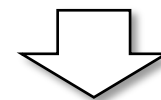$$- \; \mathcal{B}_{SM}(B^0 \to \gamma\gamma) = \left(1.4^{+1.4}_{-0.8}\right) \times 10^{-8}$$

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

- NP effect in the loop can enhance the BF

- Similar to $B \to X_{s/d}\gamma$ 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)	$< 3.2 \times 10^{-7}$

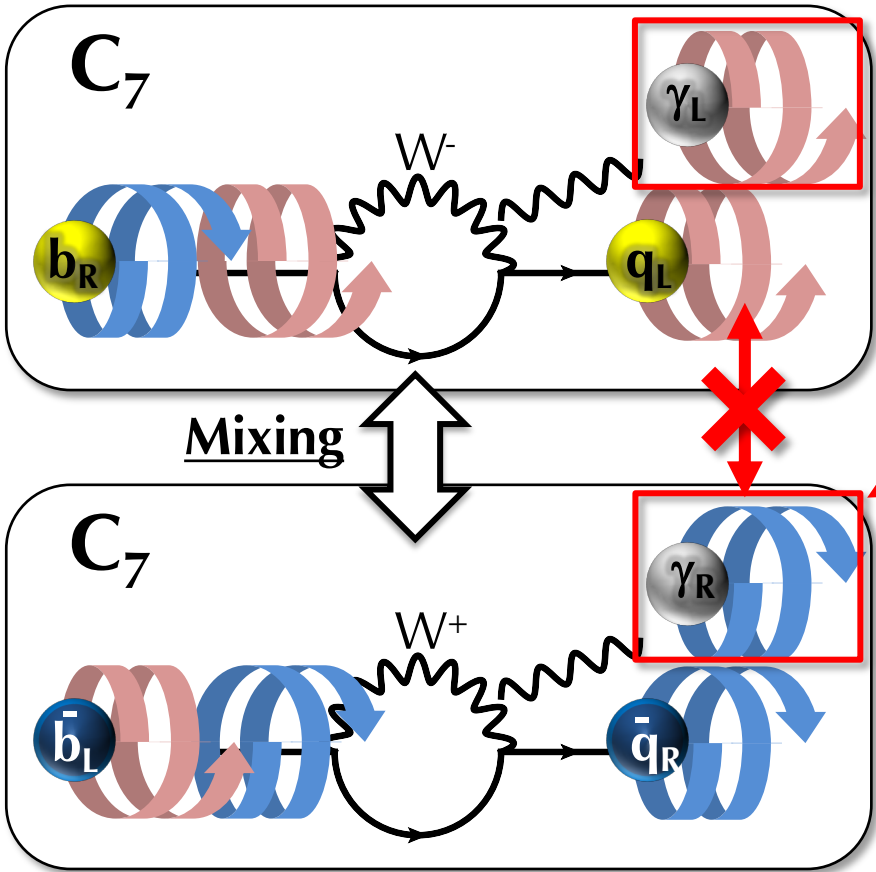To be updated by Belle + Belle II joint
→ **More than 1/ab**

- [2405.19734](2405.19734)

Results

Beam-constrained mass of B

Energy dif. b/w beam and B

Converted BDT output
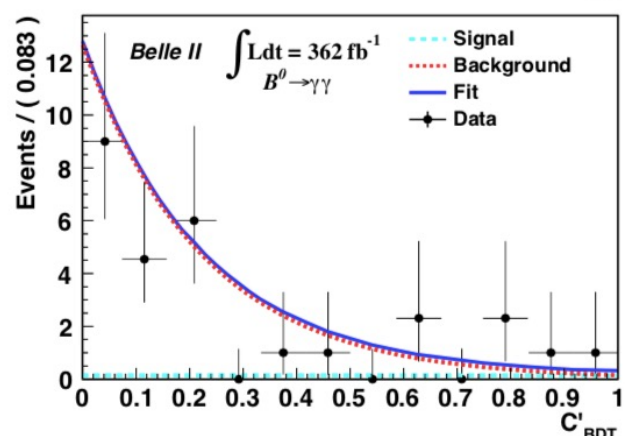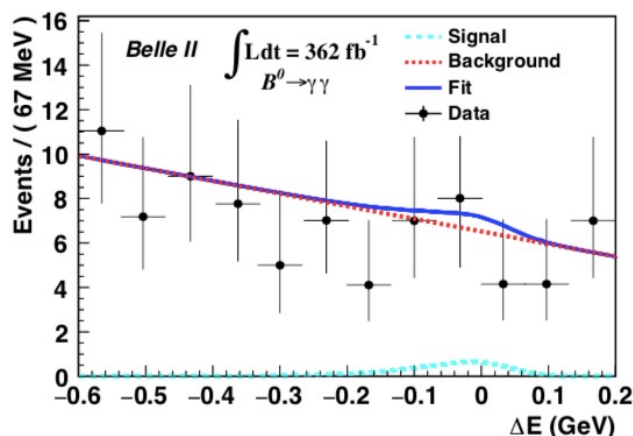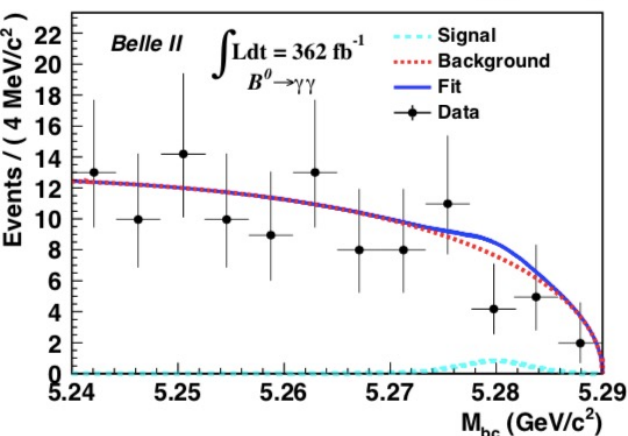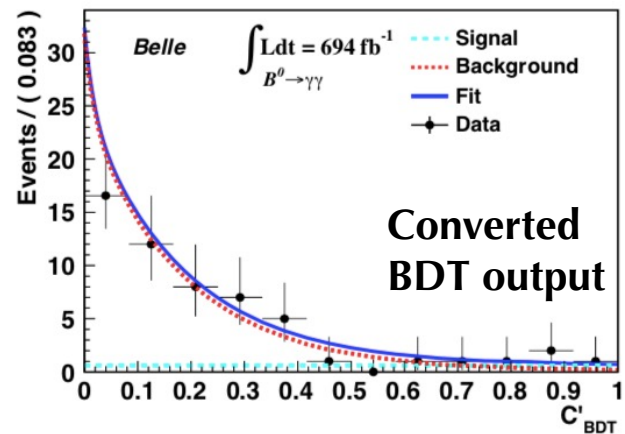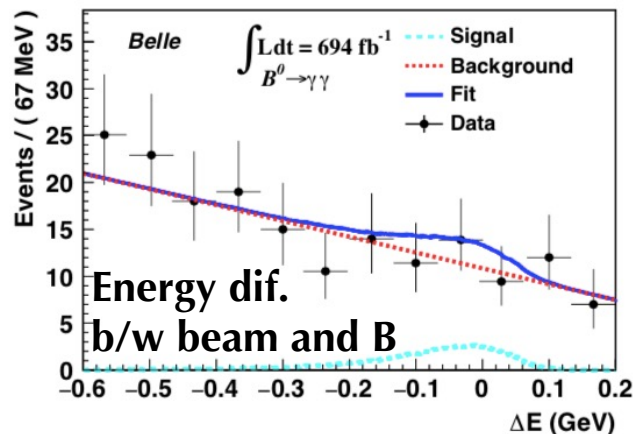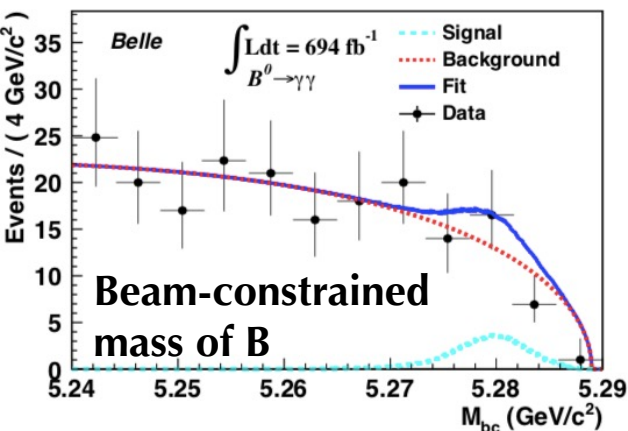
	$\mathcal{B}(B^0 \to \gamma\gamma)\times10^8$	U.L. (90% CL)
Belle	$5.4^{+3.3}_{-2.6} \pm 0.5$	$< 9.9\times10^{-8}$
Belle II	$1.7^{+3.7}_{-2.4} \pm 0.3$	$< 7.4\times10^{-8}$
Combined	$\mathbf{3.7^{+2.2}_{-1.8} \pm 0.7}$	$\mathbf{< 6.4\times10^{-8}}$

➢ Simultaneous 3D unbinned ML fit

➢ Observed signal significance is 2.5σ

➢ U.L. is order of 10⁻⁸

   – reached to the same order of the SM prediction!

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 $B^0 \to V\gamma$
- The NP effect can be independent between $V = K^{*0}$ and $V = \rho^0$
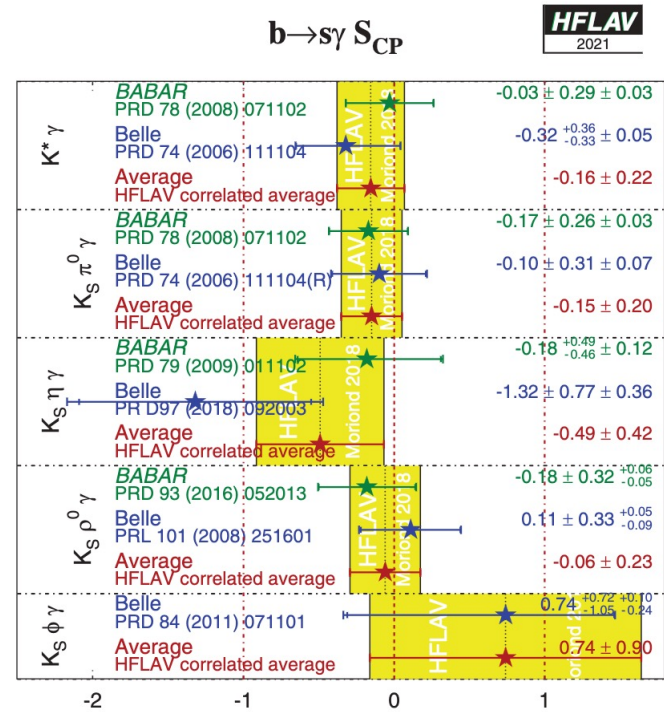
$B^0 \to K_S^0 \pi^0 \gamma$ in Belle II
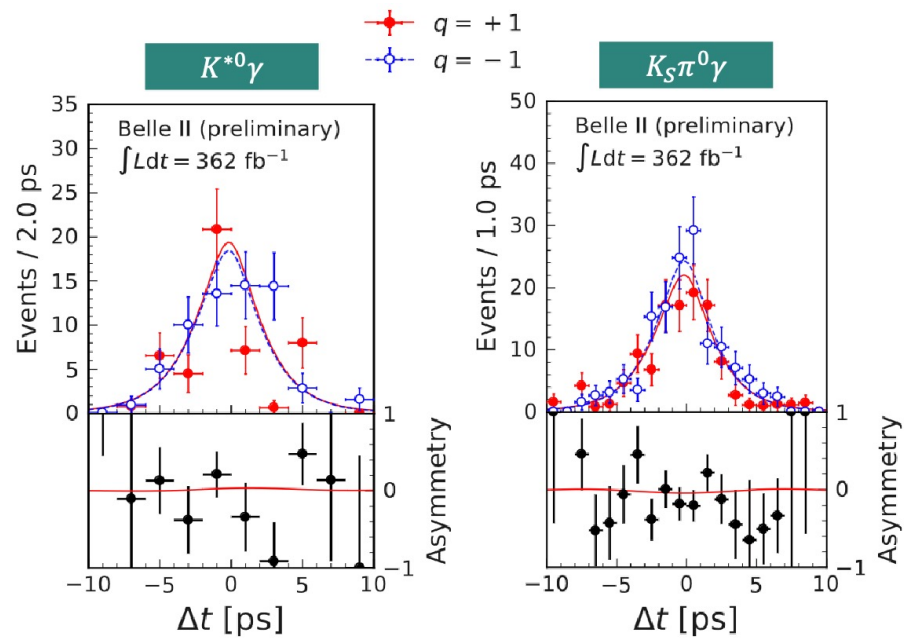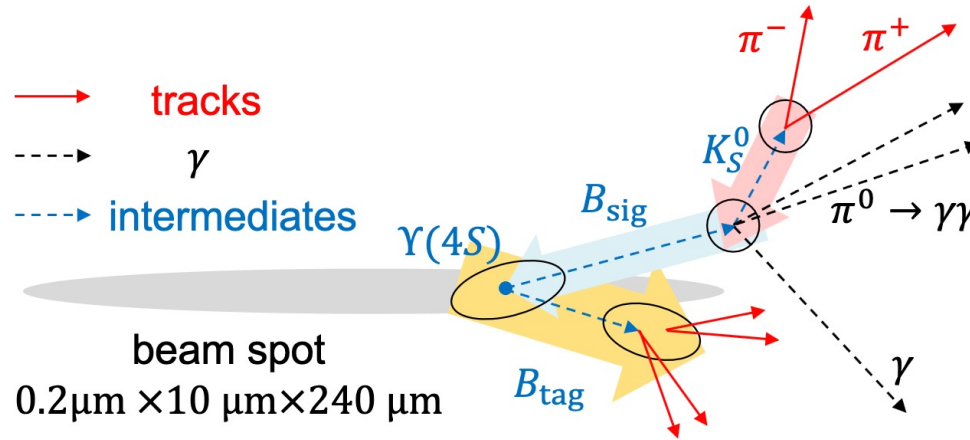
> 362/fb, preliminary result

> No charged track from the primary vertex
> - Assuming beam spot to which the K_S^0 momentum is extrapolated
> - Very challenging

> **Belle II result is better than Belle (2006)** for the $K^*(892)$ resonance
> - Thanks to the improved flavor-tagging and vertex resolutions
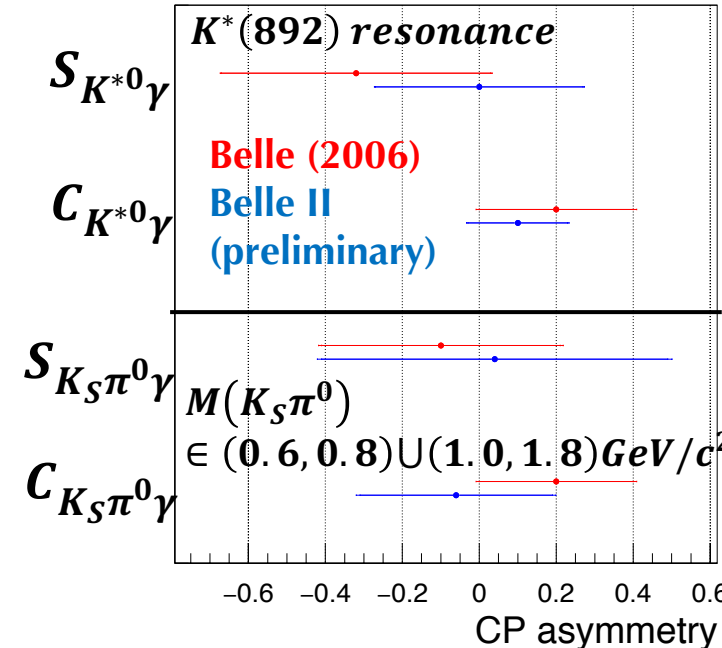
Summary

➢ 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 $B^+ \to K^+ \nu \bar{\nu}$
  - World best precision for $B \to \rho \gamma, B \to \gamma \gamma$ by Belle + Belle II

➢ 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!

Backup

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Kνν fitting

Signal discriminator

Inclusive
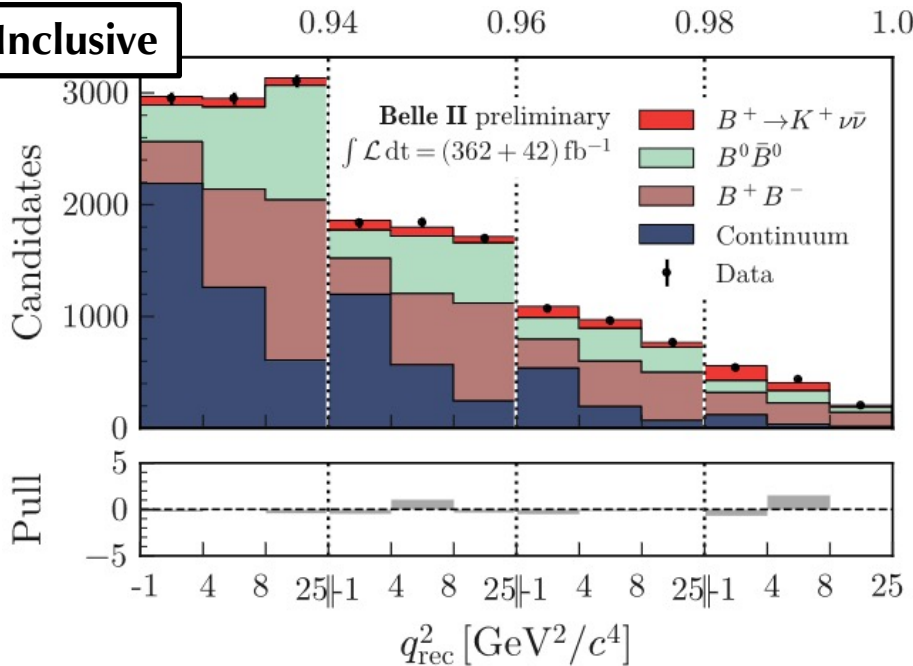
Hadronic
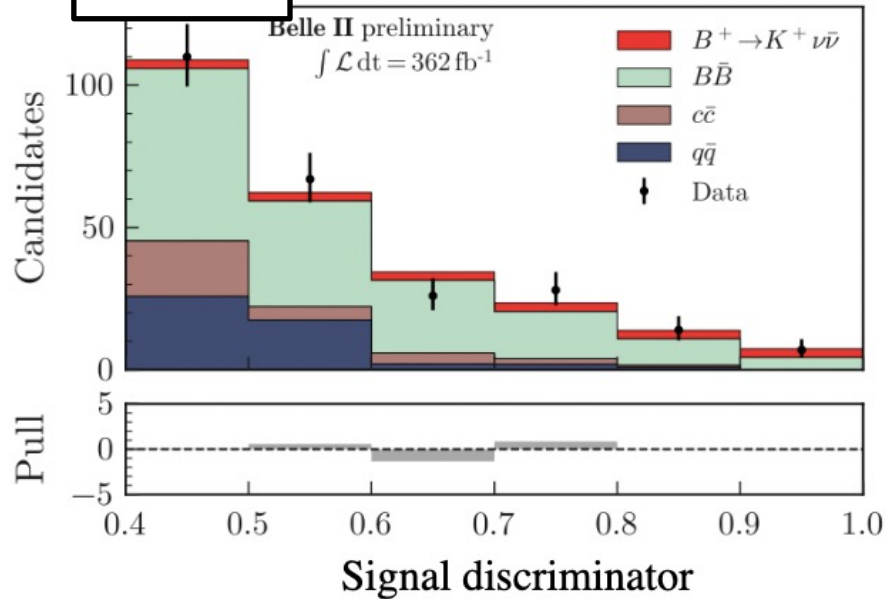
Results
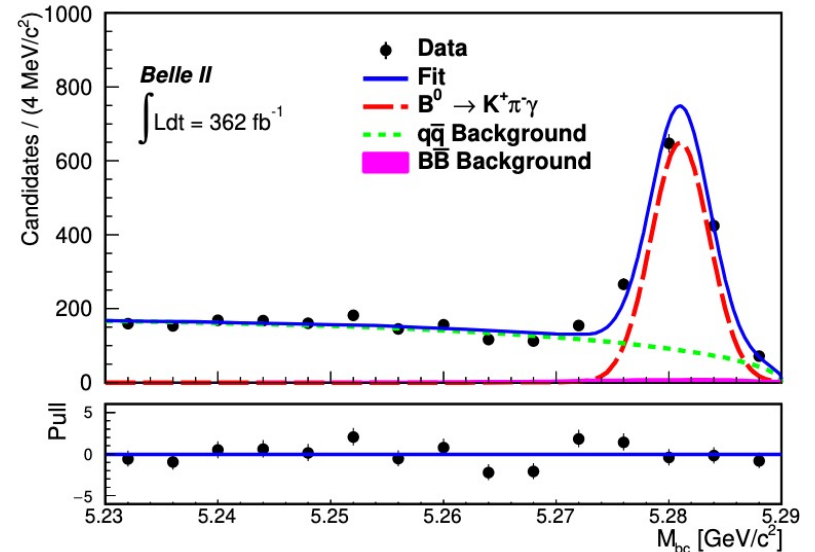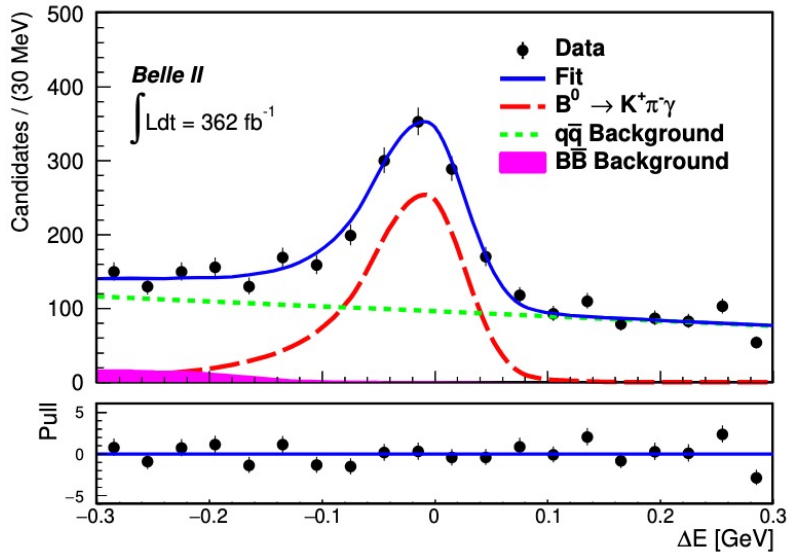
	A_{CP} (%)	$\mathcal{B} \times 10^5$
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	$-3.2 \pm 2.4 \pm 0.4$	$4.15 \pm 0.10 \pm 0.11$
$B^0 \to K^{*0}[K^0_S\pi^0]\gamma$	-	$4.24 \pm 0.37 \pm 0.23$
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	$1.5 \pm 4.2 \pm 0.9$	$3.91 \pm 0.18 \pm 0.19$
$B^+ \to K^{*+}[K^0_S\pi^+]\gamma$	$-3.5 \pm 4.3 \pm 0.7$	$4.13 \pm 0.19 \pm 0.13$
$B \to K^*\gamma$	$-2.3 \pm 1.9 \pm 0.3$	$4.12 \pm 0.08 \pm 0.11$
	ΔA_{CP} (%)	Δ_{0+} (%)
$B \to K^*\gamma$	$2.2 \pm 3.8 \pm 0.7$	$5.1 \pm 2.0 \pm 1.5$

Results
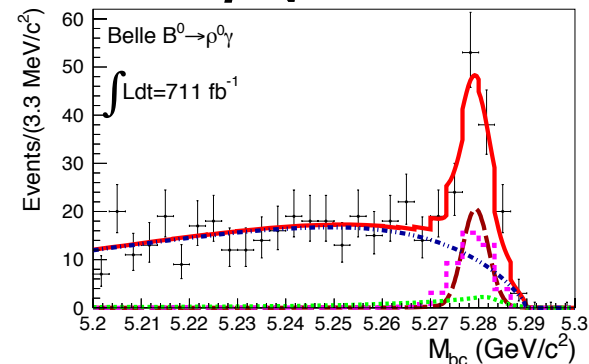
$B^+ \to \rho^+\gamma$ (Belle)
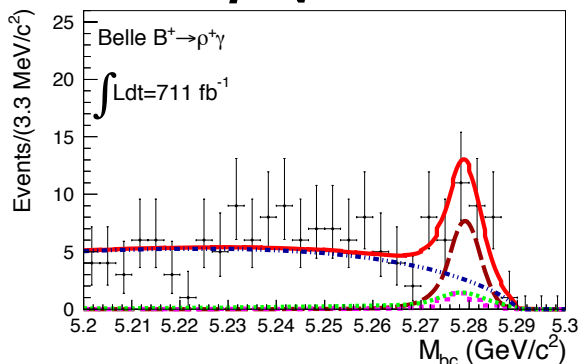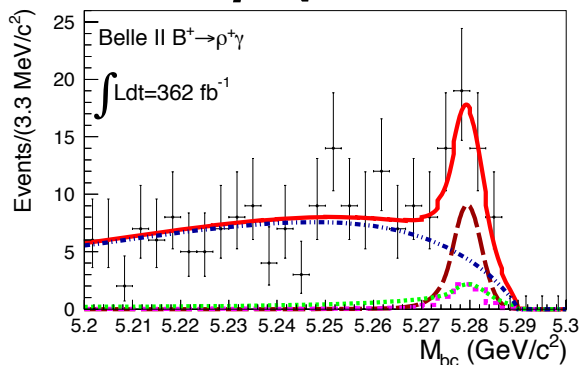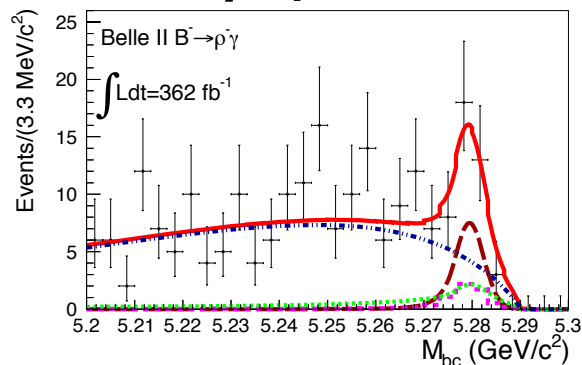

$B^- \to \rho^-\gamma$ (Belle)
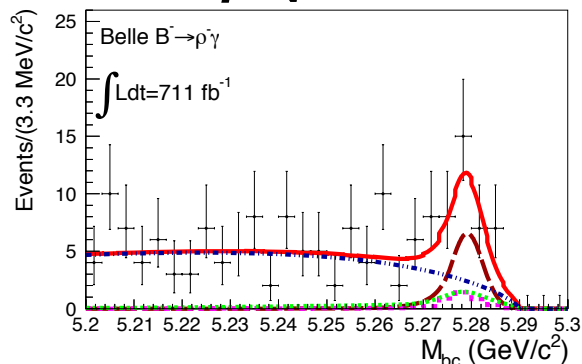
$B^0 \to \rho^0\gamma$ (Belle)

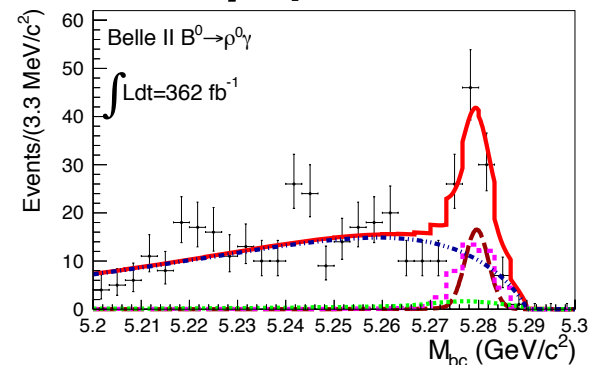

$B^+ \to \rho^+\gamma$ (Belle II)

$B^- \to \rho^-\gamma$ (Belle II)

$B^0 \to \rho^0\gamma$ (Belle II)

Preliminary result

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