B decays at e^+e^- colliders

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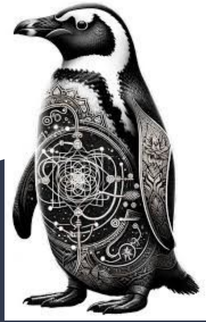
On behalf of the Belle & Belle II Collaborations



22nd Conference on Flavour physics and CP violation (FPCP 2024)

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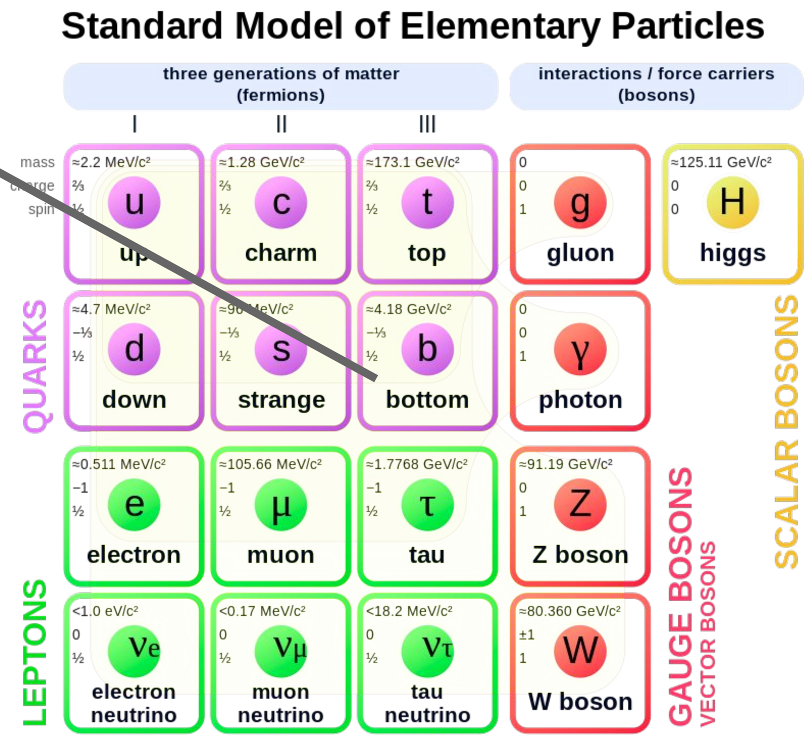
Outline

- Motivation
- Overview of B factories
- Probing $B \to K \nu \bar{\nu}$ at Belle II
- First measurement of $B \to K^*(892)\gamma$ at Belle II
- Results for exclusive $B \to \rho\gamma$ study using Belle + Belle II data
- Search for double radiative $B \to \gamma\gamma$ using Belle + Belle II data
- Summary

Motivation

The beautiful *b* quark

- Light enough to be produced abundantly
- Heavy enough to have many decays
- Myriad of final states and interactions to probe from
- Well known Standard Model predictions



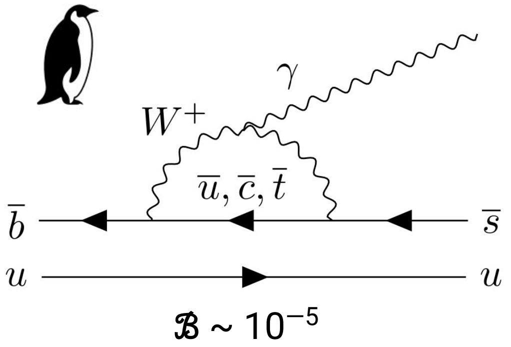
One of the main missions of B -factories is to perform searches for physics beyond SM in rare B decays

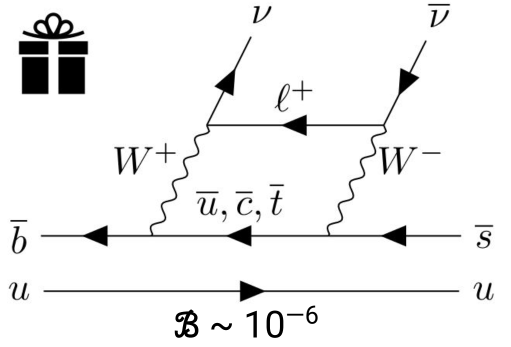
Rare B decay: branching fraction $\mathcal{B} < 5 \times 10^{-5}$
→ less than 5 in 100000 B-hadrons decay in this way

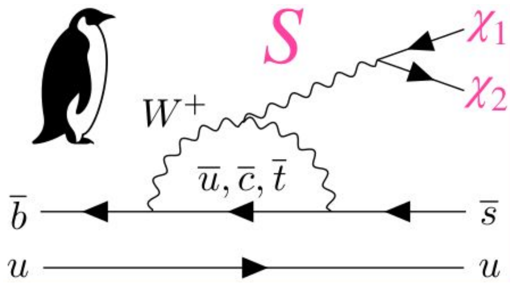
Rare decays!!!

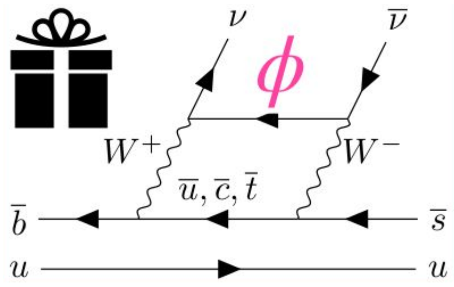
Flavour changing neutral currents (FCNC) decays of *B* mesons

- Forbidden at tree level, allowed at loop level [PRD 2 (1970) 1285]
- Standard Model (SM) contribution is small, sensitive to beyond SM
- BSM particles can contribute in the loop (eg. charged Higgs) or mediate the process at the tree level (eg leptoquarks).





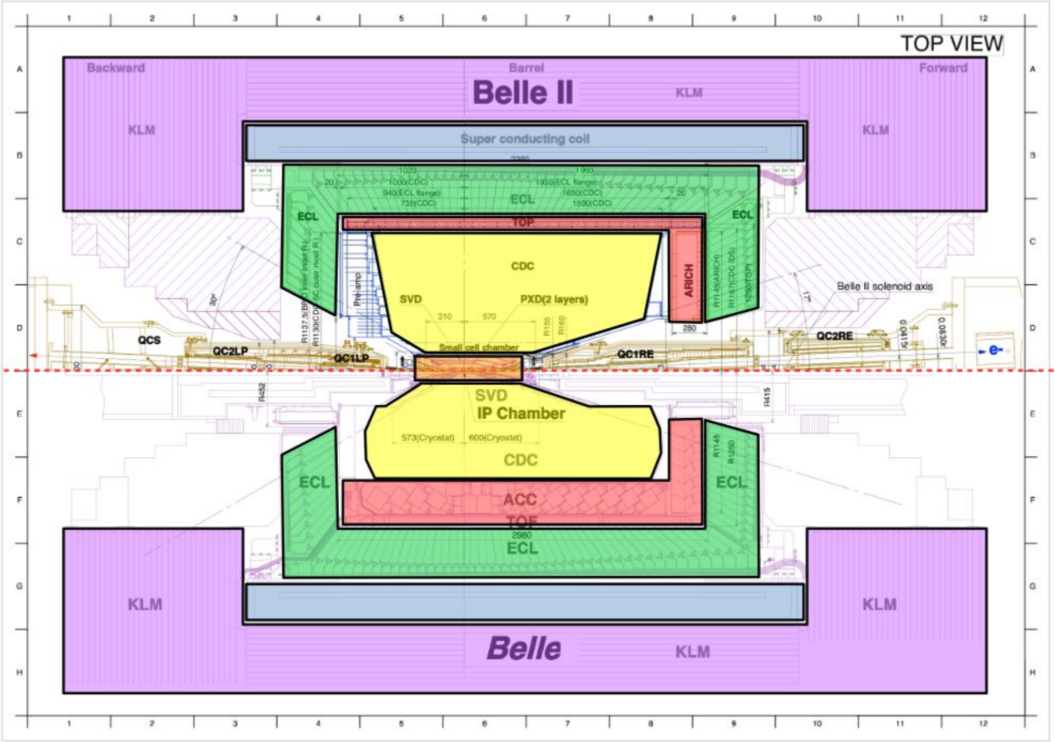




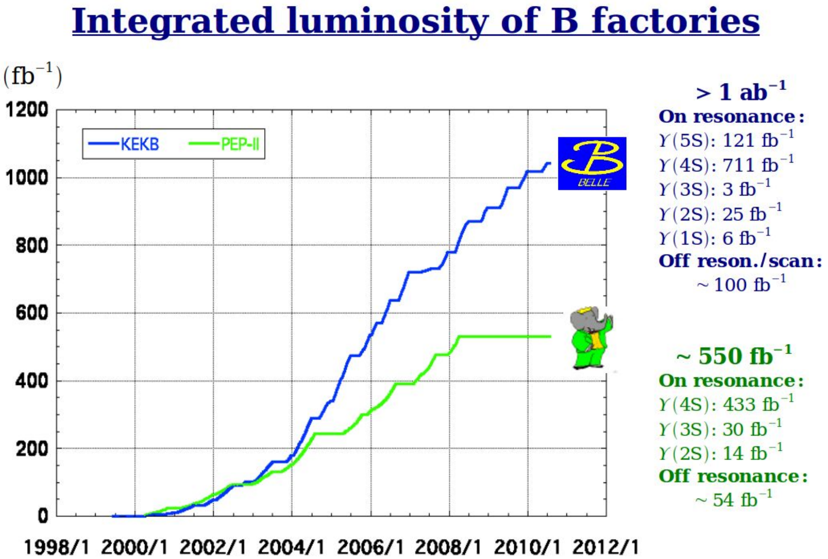
Belle & Belle II

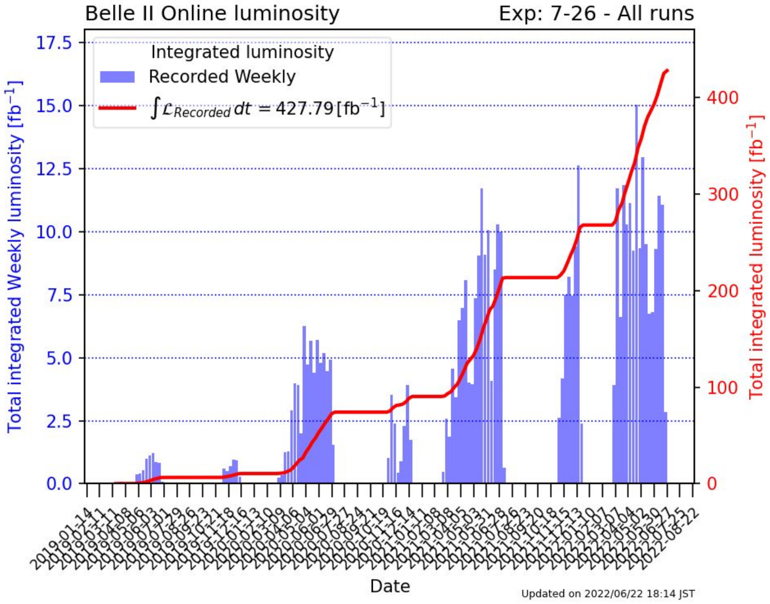
	Belle	Belle II
Vertexing	SVD	PXD + SVD
Tracking	CDC	CDC
K and π	ACC + TOF	ARICH + TOP
γ and e	ECL	ECL
μ and K^0_L	KLM	KLM

Belle TDR: NIM A **479** 117 (2002)
Belle II TDR: arXiv:1011.0352 (2010)



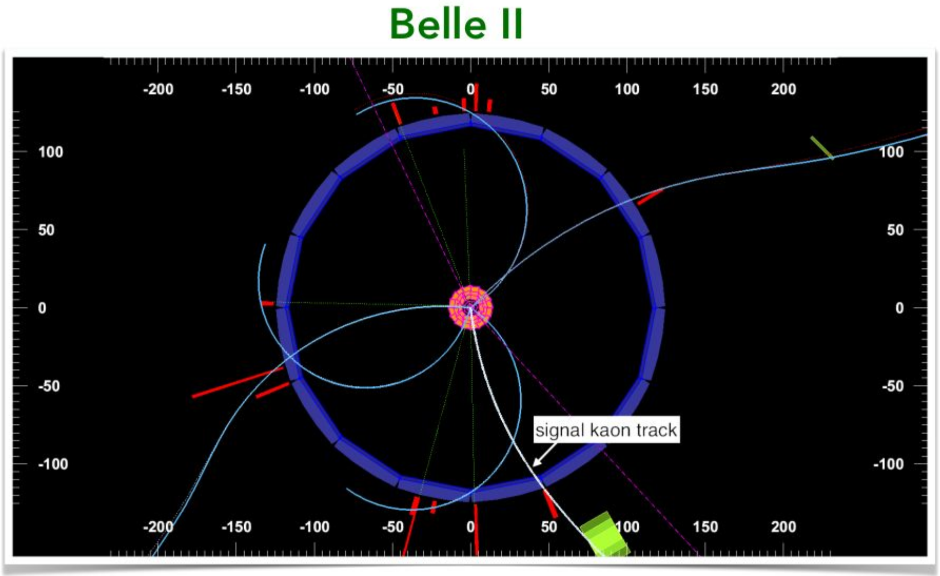
Belle/Belle II status





Belle II collected 362 fb-1 at $\Upsilon(4S)$ — equivalent to BaBar and ~1/2 of Belle sample
Belle II collected 42 fb-1 of off-resonance data [60 MeV below $\Upsilon(4S)$] compared to ~90 fb-1 from Belle

Events at B factories



$$B^+B^-(51.4 \pm 0.6)\%, \ B^0\overline{B}^0(48.6 \pm 0.6)\%$$

$$\sigma(e^+e^-) \to \Upsilon(4S) = 1.1\,nb$$

$$\sigma(e^+e^-) \to c\bar{c}(g) = 1.6\,nb$$

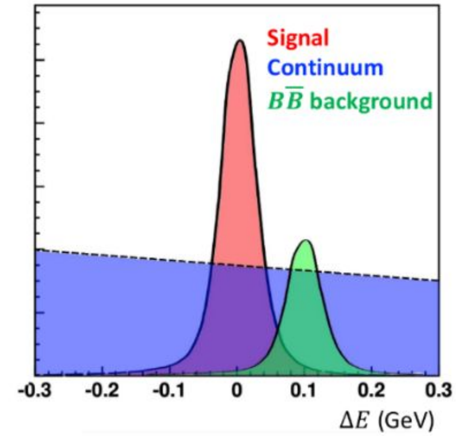
$$\sigma(e^+e^-) \to u\bar{u}(\gamma) = 1.3\,nb$$

- Principal background from light quark (continuum)
- Near 100% efficiency for B decays

- Clean environment with on average ~10-15 tracks, 3-4 π^0
- Known initial state kinematics

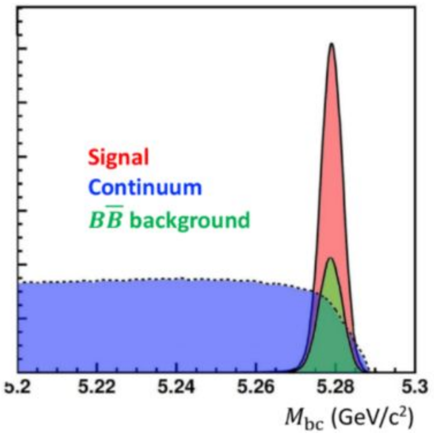
Event kinematics

$$\Delta E = E_B^* - \sqrt{s}/2$$

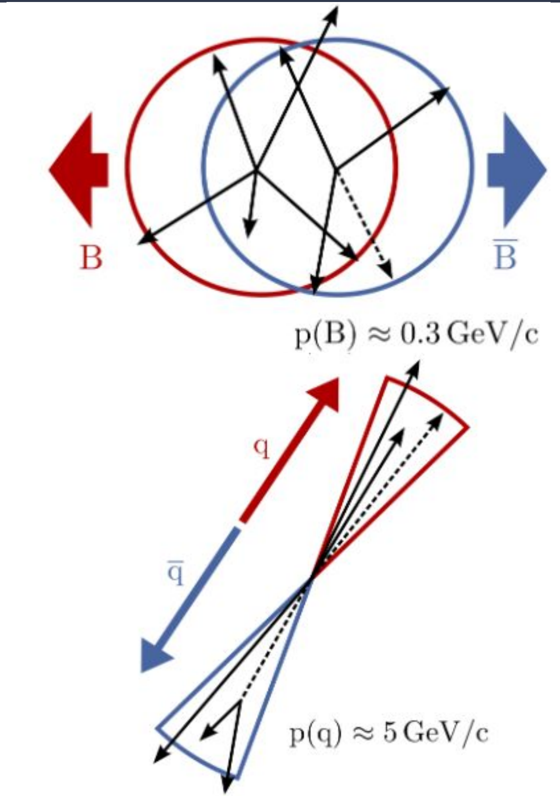


Expected $\Delta E \simeq 0$

$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - |\vec{p}_B^{\,*}|^2}$$



Expected $M_{bc} \simeq m_B$



B factory specific variables to exploit information on initial kinematics
Different event shape to separate BB from continuum background

$B \to K \nu \bar{\nu}$: Motivation

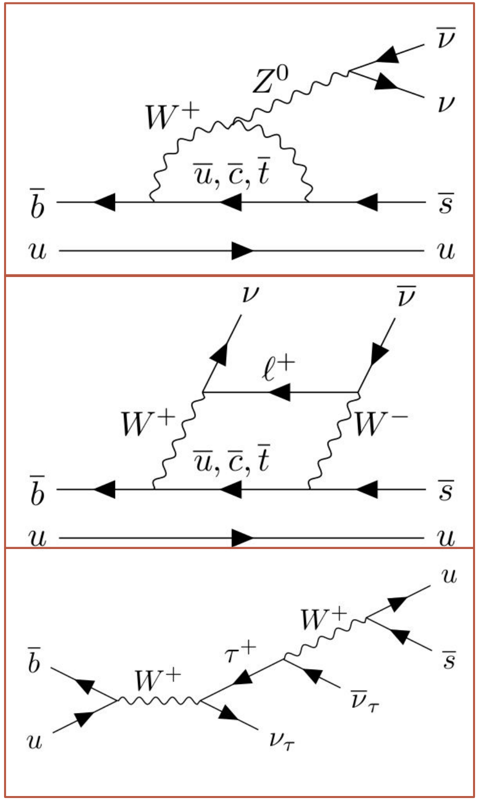
- $B^+ \to K^+ \nu\bar{\nu}$ is a challenging due to a single charged track in the final stat
- $\mathcal{B}$(SM) = (5.58 ± 0.37) x 10^{-5} [PRD 107, 014511]
- New physics could alter the rate (also angular observables for $B \to K^* \nu$

Advantages at Belle II:

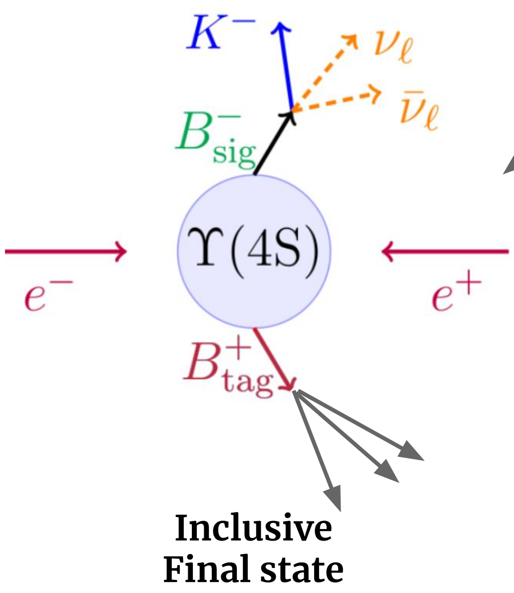
- Constraints from well-known initial state kinematics;
- Lower average multiplicity at the Y(4S) compared to hadronic collisior

NP scenarios:

- **Light** : axions [PRD 102, 015023 (2020)],
- dark scalars [PRD 101, 095006 (2020)],
- axion-like particles [JHEP 04 (2023) 131]
- **Heavy** : Z' [PL B 821 (2021) 136607],
- leptoquarks [PRD 98, 055003 (2018)]



$B \to K\nu\bar{\nu}$: Reconstruction

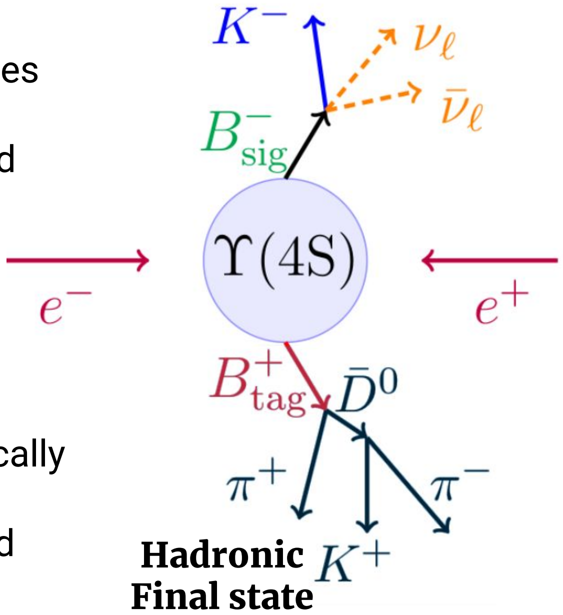


Inclusive tag analysis (ITA)

- Select first signal kaon that minimizes q^2_{rec} (computed as K^+ recoil)
- Nested BDT to suppress background
- Fit q^2_{rec} and BDT output

Hadronic tag analysis (HTA)

- Select first tag B decaying hadronically [Comput Softw Big Sci 3, 6 (2019)]
- Single BDT to suppress background
- Fit BDT output

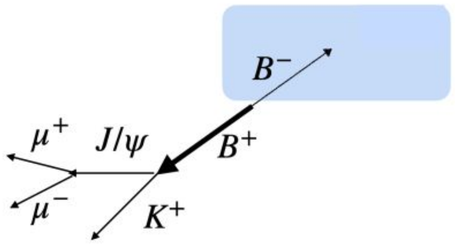


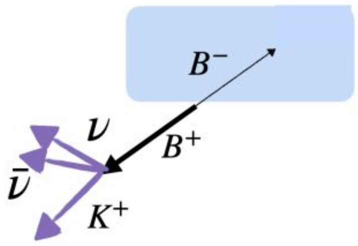
signal efficiency = 8%; purity = 0.9%

signal efficiency = 0.4%; purity = 3.5%

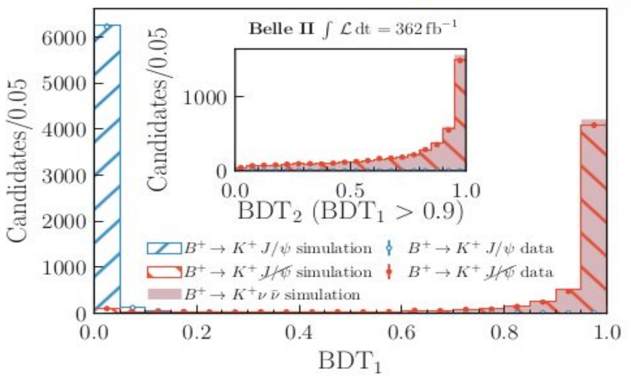
$B \to K\nu\bar{\nu}$: Validation

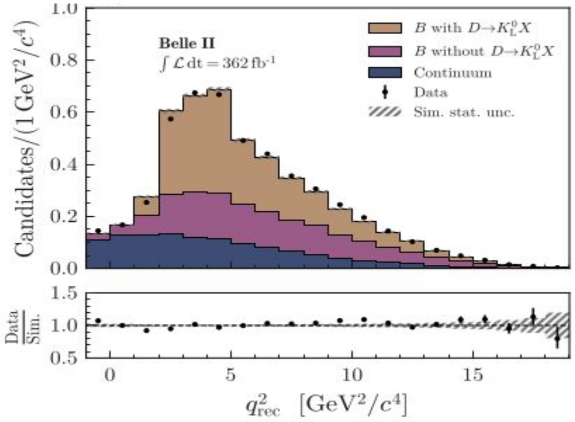
- Signal efficiency checked with signal embedded $B \to K\, J/\psi(\to \mu\, \mu\,)$
  Remove J/ψ and correct the kaon kinematics to match that of signal





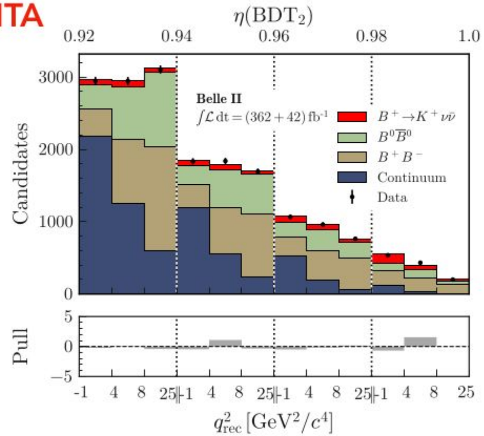
- Continuum validated with off-resonance
- $B \to X_c(\to K^0_L)$ validated from pion enriched sideband
- Signal like $B \to K^+ K^0_L K^0_L$ checked with $B \to K^+ K^0_S K^0_S$ [PRD 85 11201
- Similar treatment for $B \to K^+ K^0_S K^0_L$ and $B \to K^+ nn$





$B \to K\nu\bar{\nu}$: Results

ITA



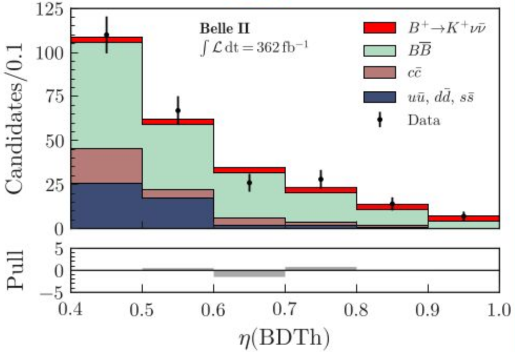
$\mu = 5.4 \pm 1.0(\text{stat}) \pm 1.1(\text{syst})$

corresponding to

$\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = 2.7 \pm 0.5(\text{stat}) \pm 0.5(\text{syst}) \times 10^{-5}$

- 3.5 σ compatibility wrt bkg only
- 2.9 σ compatibility wrt to the SM

HTA



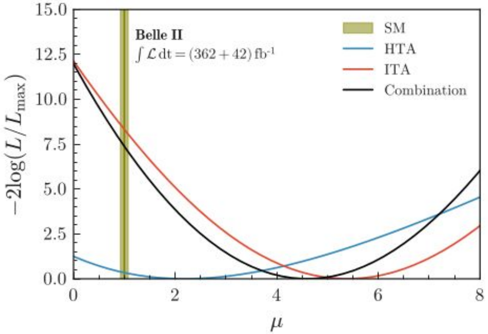
$\mu = 2.2^{+1.8}_{-1.7}(\text{stat})^{+1.6}_{-1.1}(\text{syst})$

corresponding to

$\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = [1.1^{+0.9}_{-0.8}(\text{stat})^{+0.8}_{-0.5}(\text{syst})] \times 10^{-5}$

- 1.1 σ compatibility wrt bkg only
- 0.6 σ compatibility wrt to the SM

Combination



$\mu = 4.6 \pm 1.0(\text{stat}) \pm 0.9(\text{syst})$

corresponding to

$\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = [2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \times 10^{-5}$

- Combination improves the ITA-only precision by 10%
- 3.5 σ significance wrt bkg
- 2.7 σ significance wrt SM

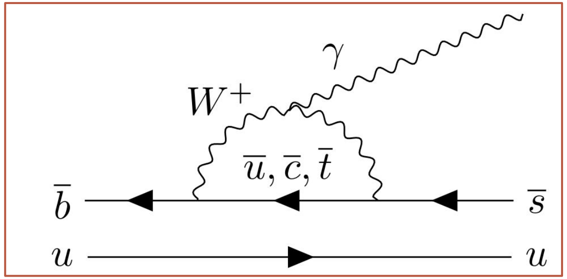
First measurement of B->K*(892)γ at Belle II

- Flavour changing neutral current decays sensitive to new physics
- CP (A_{CP}) and isospin (Δ_{+0}) asymmetries are theoretically clean thanks to form factor cancellations
- Asymmetries are ideal for BSM searches [PRD 88 (2013) 094004] [PRL 106 (2011) 141801]
- Belle measurement found evidence of isospin asymmetry at 3.1σ [PRL 119, 191802 (2017)]

$$A_{CP} = \frac{\Gamma(\bar{B} \to \overline{K^*}\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\bar{B} \to \overline{K^*}\gamma) + \Gamma(B \to K^*\gamma)}$$

SM prediction is small (~1%)

$$\Delta A_{CP} = A_{CP}(B^0 \to K^{*0}\gamma) - A_{CP}(B^+ \to K^{*+}\gamma)$$

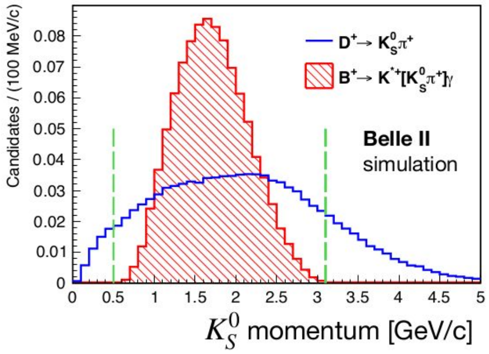


$$\Delta_{+0} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - (B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + (B^+ \to K^{*+}\gamma)}$$

SM prediction: 4.9 ± 2.6% [PRD 88 (2013) 094004]

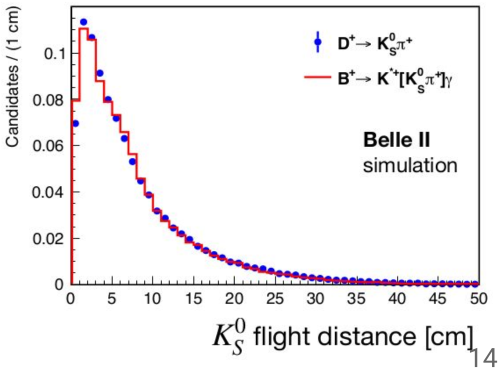
B->K*(892)γ: Analysis

- Analysis based on run 1 data (362 fb^{-1})
- Reconstruct $K^* \to K^+ \pi^-$, $K^0_S \pi^0$, $K^+ \pi^0$, $K^0_S \pi^-$
- Combine K* with a prompt photon to get B candidate
- Dedicated BDTs to suppress continuum, $\pi \to \gamma\gamma$, and $\eta \to \gamma\gamma$ decays



Fit strategy

- Perform 2D fit to ΔE and M_{bc} to extract signal yield



Control sample study

- Employed $B \to D^0 [D^0 \to K^- \pi^+] \pi^-$ to calibrate the BDTs (continuum, $\pi \to \gamma\gamma$, and $\eta \to \gamma\gamma$)
- Significant effort towards K^0_S systematics using $D^+ \to K^0_S \pi^+$

B->K*(892)γ : Results

- Consistent with World average and SM
- Asymmetries are statistically limited
- Similar sensitivity to Belle result despite half the data
  Δ_{0+} = 6.2 ± 1.5 (stat) ± 0.6 (sys) ± 1.2 (f_{+-}/f_{00}) [PRL 119, 191802 (2017)]
  (Thanks to improved K^0_S efficiency, continuum suppression, and addition of ΔE to fit model)

$$\mathcal{B}[B^0 \to K^{*0}\gamma] = (4.16 \pm 0.10 \pm 0.11) \times 10^{-5},$$

$$\mathcal{B}[B^+ \to K^{*+}\gamma] = (4.04 \pm 0.13 \pm 0.13) \times 10^{-5},$$

$$\mathcal{A}_{CP}[B^0 \to K^{*0}\gamma] = (-3.2 \pm 2.4 \pm 0.4)\%,$$

$$\mathcal{A}_{CP}[B^+ \to K^{*+}\gamma] = (-1.0 \pm 3.0 \pm 0.6)\%,$$

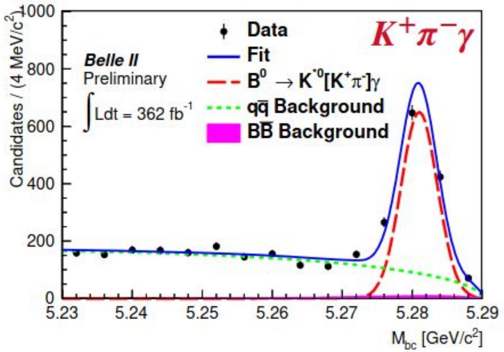
$$\Delta\mathcal{A}_{CP} = (2.2 \pm 3.8 \pm 0.7)\%,$$

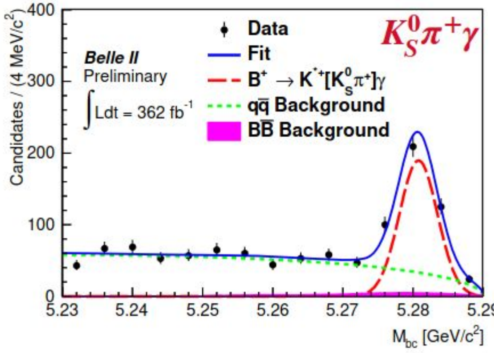
$$\Delta_{0+} = (5.1 \pm 2.0 \pm 1.0 \pm 1.1)\%$$

Uncertainty:
stat. + sys. + f_{+-}/f_{00} (for Δ_{0+})

⇒ Scope to improve results which are statistically limited

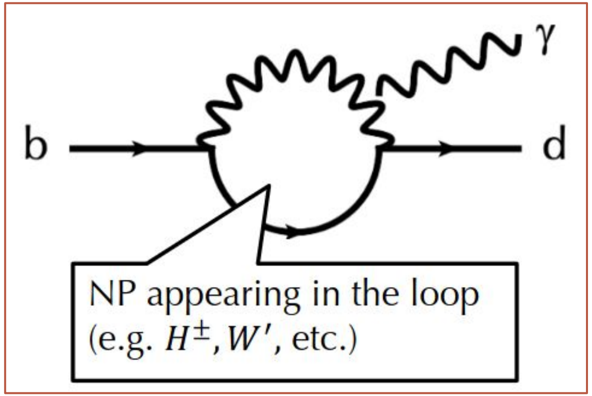
B^0, B^+





Exclusive measurement of B→ργ at Belle and Belle II

- Flavor changing neutral current with b → d transition
- Independent search for NP [PRD 88 (2013) 094004]
- SM branching fraction suppressed by |Vtd /Vts | ~ 0.04 with respect to B->K*(892)γ
- The first “charmless” study with Belle and Belle II joint data
- Earlier results from Belle [Phys. Rev. Lett. 101, 111801] and BaBar [Phys. Rev. D 78, 112001].



$$\Delta_{0+} = \frac{2 \times \Gamma(B^0 \to \rho^0 \gamma) - \Gamma(B^+ \to \rho^+ \gamma)}{2 \times \Gamma(B^0 \to \rho^0 \gamma) + \Gamma(B^+ \to \rho^+ \gamma)}$$

$$\mathcal{A}_{CP} = \frac{\Gamma(B^0 \to \rho^0 \gamma) - \Gamma(B^+ \to \rho^+ \gamma)}{\Gamma(B^0 \to \rho^0 \gamma) + \Gamma(B^+ \to \rho^+ \gamma)}$$

SM prediction: 5.2 ± 2.8% [PRD 88 (2013) 094004]

Current world average deviates by 2σ from SM

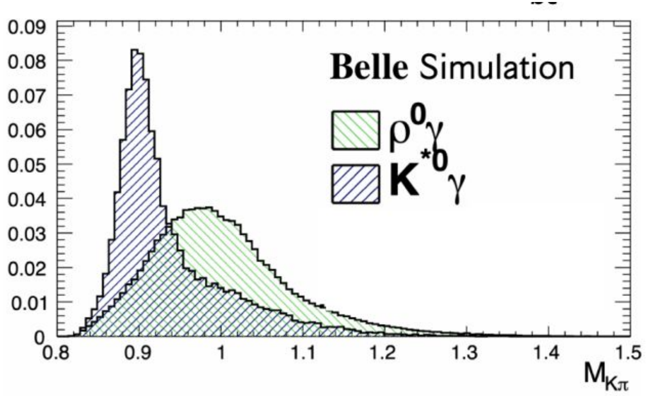
B→ργ : Analysis

- Analysis based on Belle (711 fb^{-1}) + Belle II (362 fb^{-1}) data
- Reconstruct $\rho^0 \to \pi^+\pi^-$ and $\rho^+ \to \pi^+\pi^0$, combine with prompt photon
- Define $M_{K\pi}$ as the invariant mass calculated assuming π^+ is K^+
- The $M_{K\pi}$ helps separate $K^*\gamma$ background better compared to $M_{\pi\pi}$
- Dedicated BDTs to suppress continuum, $\pi \to \gamma\gamma$, and $\eta \to \gamma\gamma$ decays

Fit Strategy

- Perform Belle+Belle II simultaneous 3D fit of M_{bc}, ΔE and $M_{K\pi}$

- **Control sample study**
- Employed $B \to K^{*0} [K^-\pi^+]\gamma$ to calibrate the BDTs (continuum, $\pi \to \gamma\gamma$, and $\eta \to \gamma\gamma$) and signal PDF modelling

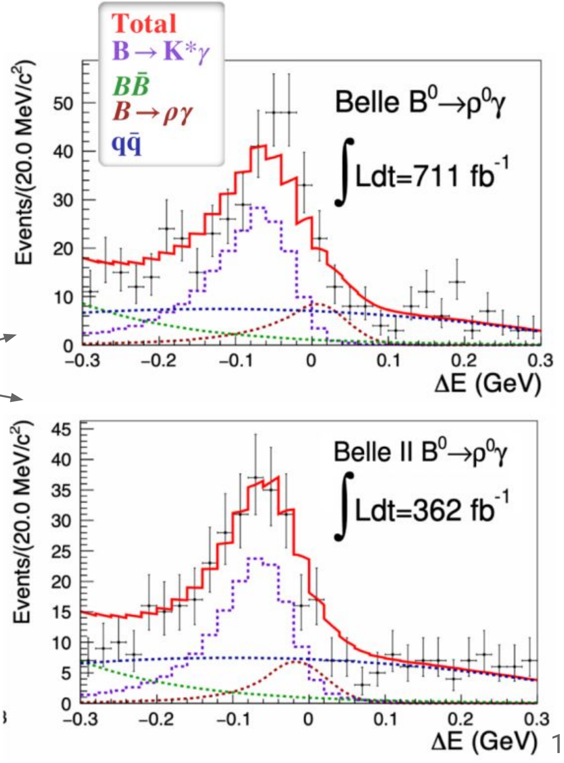


Impact of $M_{K\pi}$

B→ργ : Results

- Result for the isospin asymmetry consistent with the SM
- All measured observables are the most precise to date
- Results supersede previous Belle measurement [PRL 101 111801 (2008)]

Signal enriched projections
$M_{\rm bc} > 5.27$ GeV/c^2
$M_{K\pi} > 0.92$ GeV/c^2



$$\mathcal{B}\left(B^+ \to \rho^+\gamma\right) = \left(12.9^{+2.0+1.3}_{-1.9-1.2}\right) \times 10^{-7},$$
$$\mathcal{B}\left(B^0 \to \rho^0\gamma\right) = \left(7.5^{+1.3+1.0}_{-1.3-0.8}\right) \times 10^{-7},$$
$$A_{\rm CP}\left(B^+ \to \rho^+\gamma\right) = \left(-8.4^{+15.2+1.3}_{-15.3-1.4}\right)\%,$$
$$A_{\rm I}\left(B \to \rho\gamma\right) = \left(11.0^{+11.2+7.1+3.8}_{-11.7-6.3-3.9}\right)\%,$$

Uncertainty:
stat. + sys. + f_{+-}/f_{00} (for A_I)

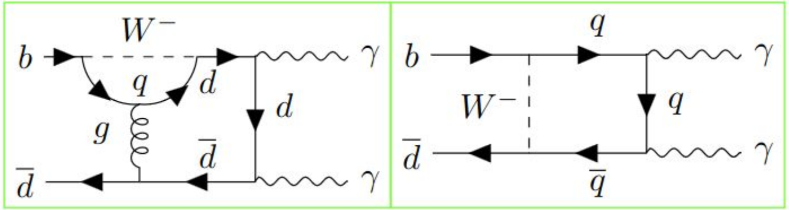
Double radiative $B^0 \to \gamma\gamma$ at Belle + Belle II

- Very rare decay with $\mathcal{B}(SM) = (1.4^{+1.4}_{-0.8}) \times 10^{-8}$ [JHEP 12, 169 (2020)]
- Highly CKM suppressed relative to $B_s \to \gamma\gamma$
- Challenging due to the presence of two photons in the final state; large backgrounds

Previous searches:

- PLB 363 (1995) 137-144
- PRD 73, 051107 (2006)
- PRD 83, 032006 (2011)

Experiment	Integrated Luminosity ($\int \mathcal{L}\, dt$)	Limit @ 90 C.L.
L3	73 pb^{-1}	3.9×10^{-5}
Belle	104 fb^{-1}	6.2×10^{-7}
Babar	426 fb^{-1}	3.2×10^{-7}



$B\to\gamma\gamma$: Analysis

- Analysis based on combined Belle (362 fb^{-1}) + Belle II (694 fb^{-1}) data
- Reconstruct signal from two prompt photons
- Peaking background in M_{bc} due to back-to-back off time photons
  => Suppressed using photon timing cuts
- Dedicated BDTs to suppress continuum, $\pi \to \gamma\gamma$, and $\eta \to \gamma\gamma$ decays

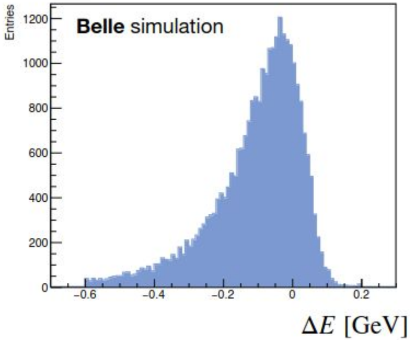
Fit strategy

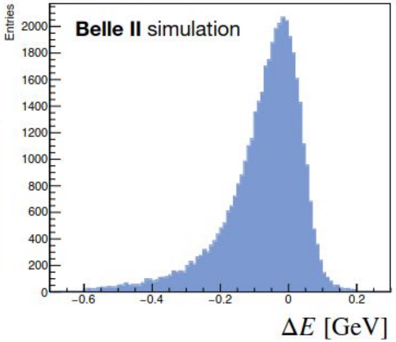
- 3D fit to ΔE, M_{bc} and transformed continuum BDT output (C'_{BDT})
- Use $B^0 \to K^*(892)[K^+\pi^-]\gamma$ as control sample

Belle vs **Belle II**

- Improved signal efficiency per fb^{-1} bkg
- Improved ΔE resolution

	Belle	Belle II
Sig efficiency	23%	31%
Exp. bkg/fb^{-1}	~ 0.8	





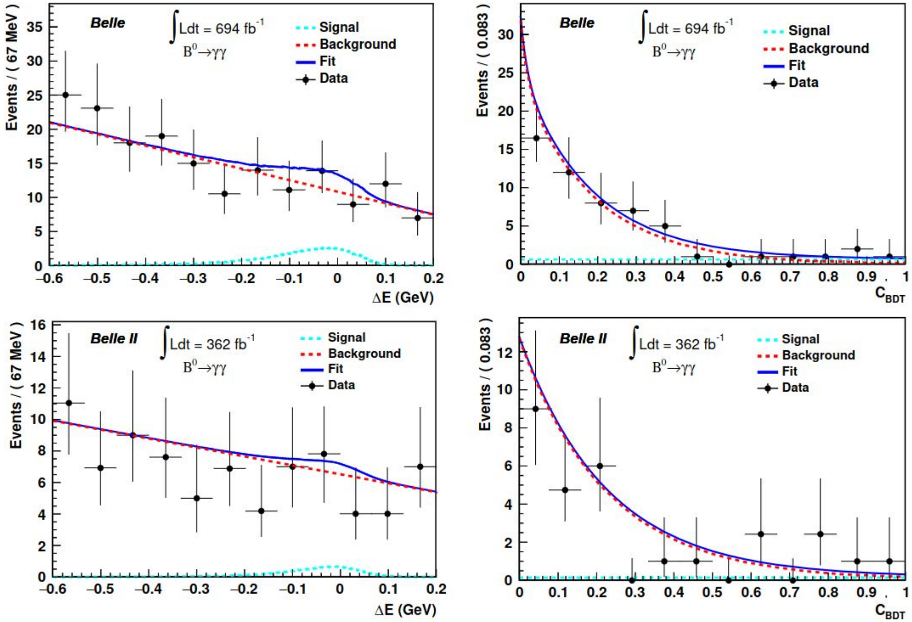
$B->\gamma\gamma$: Results

- Combined signal yield = $11.0^{+6.5}_{-5.5}$
- Since no significant signal ⇒ set 90% C.L. limits
- Sensitivity approaching SM prediction

→ **best upper limit with Belle II data**

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

Expected 90 C.L. 4.4×10^{-8}



ΔE

C'_{BDT}

- Uncertainties are comparable between Belle and Belle II, despite Belle II having a smaller dataset.
- 5x improvement over previous best UL by Babar [PRD 83 (2011) 032006]

Summary

- FCNC's are attractive to probe SM and physics beyond.
- First evidence for $B^+ \to K^+ \nu\bar{\nu}$ decay with 2.7σ compatibility with SM [arxiv: 2311.14647, to appear in PRD]
- World's most precise measurement of $B \to \rho\gamma$ decays using Belle + Belle II data.
- First measurement of $B \to K^*(892)\gamma$ at Belle II
- Best upper limit for $B \to \gamma\gamma$ the rarest decay measured with Belle + Belle II data so far