Electroweak and radiative penguin *B* meson decays at Belle and Belle II

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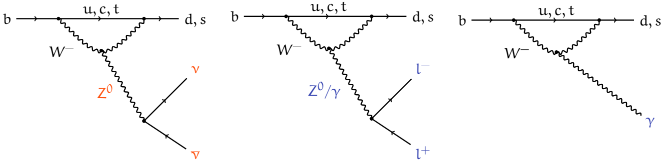
Moriond QCD 2024

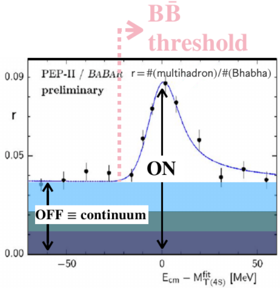
Electroweak and radiative penguin B decays

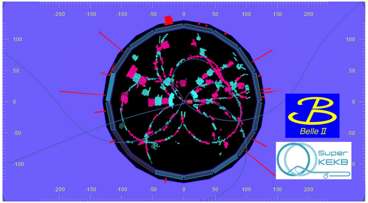
- Flavour changing neutral currents present only at loop level in the Standard Model
- Formidable place to look for New Physics that could interfere with radiative and electroweak penguin loops

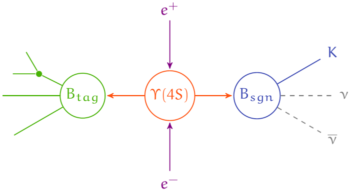


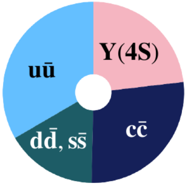
Advantages of an $e^+ e^-$ flavour factory

- Known initial kinematics and good hermeticity
  - possible to fully reconstruct events with invisible particles
- Clean environment (average 11 tracks per event)
  - efficient detection of neutrals ($\gamma, \pi^0, \eta, \ldots$)
- Run at the $\Upsilon(4S)$ mass just above $B\bar{B}$ threshold
  - Relatively low background
  - Data off-resonance provide control sample without $B\bar{B}$







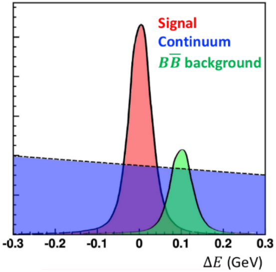


Hadronic cross-section @ $\sqrt{s} = 10.58$ GeV

Tools at an $e^+ e^-$ flavour factory

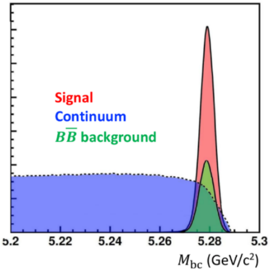
- Optimised variables to exploit information on initial kinematics
- Exploit different event shape to separate $B\bar{B}$ from continuum background

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

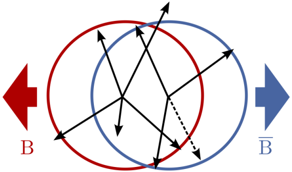


Expected $\Delta E \simeq 0$

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

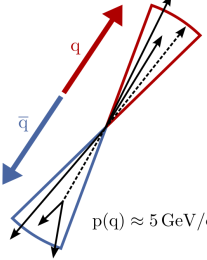


Expected $M_{bc} \simeq m_B$



$p(B) \approx 0.3\,\mathrm{GeV}/c$

$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

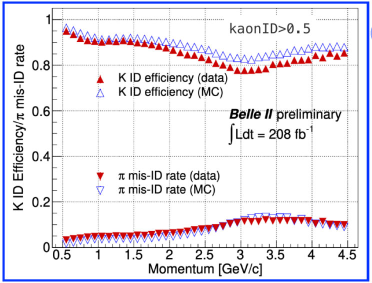


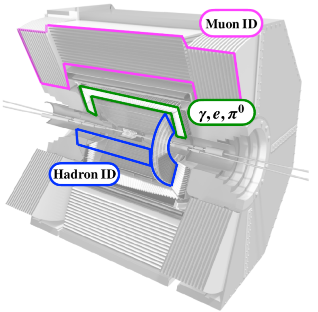
$p(q) \approx 5\,\mathrm{GeV}/c$

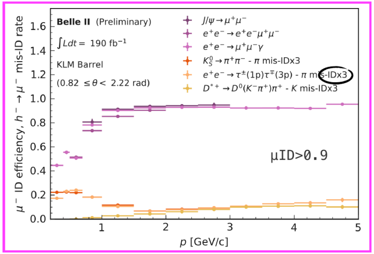
$e^+e^- \to q\bar{q} \quad (q \in \{u, d, s, c\})$

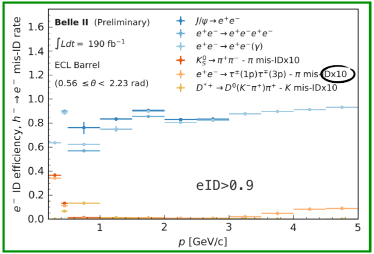
Key Belle II performance

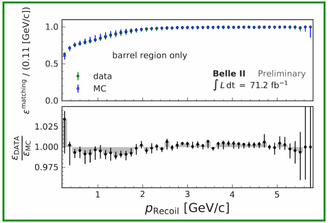
- Good kaon identification in full momentum range
  - $\varepsilon(K) \sim 90\%, \pi \to K \sim 6\%$
- High photon efficiency
  - $\varepsilon(\gamma) \sim 90\%$ ($p > 1.5$ GeV)
- Good lepton ID performance
  - $\varepsilon(\mu) \sim 90\%, \pi \to \mu \sim 7\%$
  - $\varepsilon(e) \sim 86\%, \pi \to e \sim 0.4\%$











New results since last Moriond QCD

- First evidence of $B^+ \to K^+ \nu\overline{\nu}$
- Search for rare $b \to ll$ decays
- $\mathcal{B}$, A_{CP} and Δ_{+0} of $B \to K^*\gamma$ (New for Moriond '24)
- $\mathcal{B}$, A_{CP} and A_{I} of $B \to \rho\gamma$
- Search for $B^0 \to \gamma\gamma$ (New for Moriond '24)

Datasets

	on-resonance	off-resonance
BELLE	$711\ \mathrm{fb}^{-1}$	$90\ \mathrm{fb}^{-1}$
Belle II	$362\ \mathrm{fb}^{-1}$	$42\ \mathrm{fb}^{-1}$

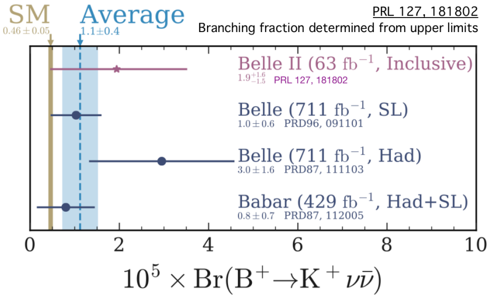
$$B^+ \to K^+ \nu \bar{\nu}$$

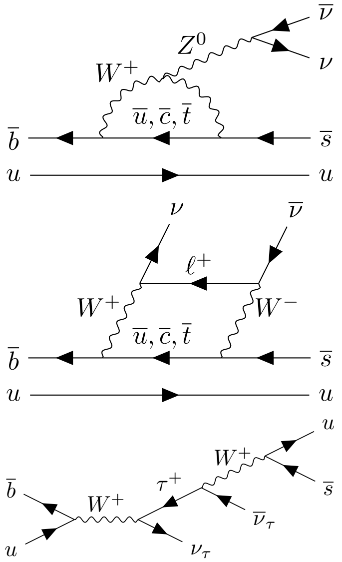
[arXiv:2311.14647 to appear in PRD]

Evidence for $B^+ \to K^+\nu\bar{\nu}$: motivations

[arXiv:2311.14647 to appear in PRD]

- $B^+ \to K^+\nu\bar{\nu}$ known with high accuracy in the SM
  - Clean SM computation (no charm loop contributions)
  - $\mathcal{B}_{SM} = (5.58 \pm 0.37) \times 10^{-6}$ [Parrott, Bouchard, Davies '23]
  - New physics could increase significantly the rate
  - Possible to recast to look for $B^+ \to K^+X_{dark}$
- Very challenging experimentally, not yet observed
  - Low $\mathcal{B}$, high background contributions
  - 3-body kinematics, no good variable to fit

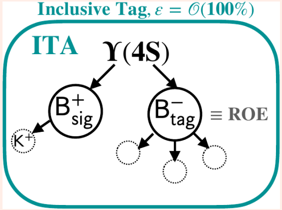




Evidence for $B^+ \to K^+\nu\bar{\nu}$: analysis strategy [arXiv:2311.14647 to appear in PRD]

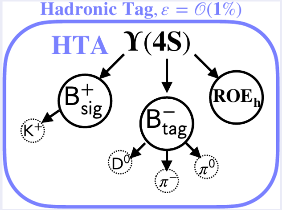
Inclusive tagged analysis (ITA): approach leading to the final sensitivity

- Select first signal kaon that minimises q^2_{rec} (computed as K^+ recoil)
- Two consecutive MVA classifiers
- Total efficiency $\sim$ 8%, purity $\sim$ 0.8%
- Binned fit to q^2_{rec} and output MVA classifier simultaneously for on and off resonance

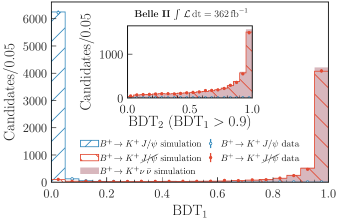


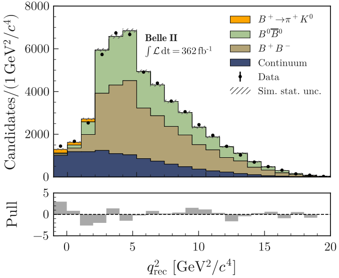
Hadronically tagged analysis (HTA): Less sensitive but well-established

- Select first tag B decaying hadronically
- One MVA classifier to reject background
- Total efficiency $\sim$ 0.4%, purity $\sim$ 3.5%
- Fit output MVA classifier



- Analysis relies on simulation for background suppression and background templates for the fit
  - Simulation is validated via several control channels on data
- Signal validation
  - Total efficiency with $B^+ \to J/\psi K^+$, removing J/ψ and correcting the kaon kinematics to match the signal
  - Kaon ID selection validated with $B^+ \to \overline{D}^0(\to K^+\pi^-)K^+$
- Background validation
  - Off-resonance data to correct for data/MC differences in normalisation and shape
  - Size of $B \to X_c(K_L^0 X)$ corrected using pion-enriched sideband
  - Modelling of K_L^0 detection efficiency in the calorimeter corrected using $e^+e^- \to \gamma\phi(\to K_S^0 K_L^0)$
  - Cross check $B^+ \to K^+K_S^0K_S^0$ to validate $B^+ \to K^+K_L^0K_L^0$
- Closure test measuring $\mathcal{B}(B^+ \to \pi^+K^0) = (2.5 \pm 0.5) \times 10^{-5}$
  - compatible with PDG $(2.38 \pm 0.08) \times 10^{-5}$



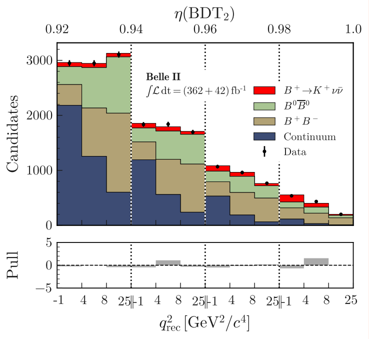


Evidence for $B^+ \to K^+\nu\bar{\nu}$: results

[arXiv:2311.14647 to appear in PRD]

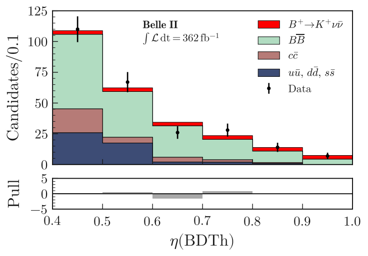
ITA

- $\mathcal{B} = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$
- 3.5σ significance
- 2.9σ deviation from SM



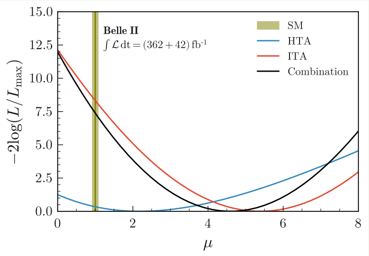
HTA

- $\mathcal{B} = (1.1^{+0.9+0.8}_{-0.8-0.5}) \times 10^{-5}$
- 1.1σ significance
- 0.6σ deviation from SM



Combination

- 1.2σ agreement between ITA and HTA, 2% common events
- $\mathcal{B} = (2.3 \pm 0.5^{+0.5}_{-0.5}) \times 10^{-5}$
- 3.5σ significance
- 2.7σ deviation from SM



Rare $b \longrightarrow dll$

Rare $b \to dll$: motivation

$b \to dll$ transitions

- FCNC sensitive to new physics complementary to $b \to sll$
- Extra CKM suppression $|V_{td}/V_{ts}|^2 \sim 0.04$ wrt $b \to sll$
- Typical $\mathcal{B} = \mathcal{O}(10^{-8})$ or smaller
- Probe lepton flavour universality

Goal

Look for all the $B^{\pm,0} \to (\eta, \omega, \pi^{\pm,0}, \rho^{\pm,0})ll$ decays (except $B^+ \to \pi^+\mu\mu$ and $B^+ \to \rho^0\mu\mu$ already seen by LHCb)

Channel	UL or BR	Collaboration
$B^0 \to \eta ee$	$< 10.8 \times 10^{-8}$	BaBar
$B^0 \to \eta\mu\mu$	$< 11.2 \times 10^{-8}$	BaBar
$B^0 \to \pi^0 ee$	$< 8.4 \times 10^{-8}$	BaBar
$B^0 \to \pi^0\mu\mu$	$< 6.9 \times 10^{-8}$	BaBar
$B^+ \to \pi^+ ee$	$< 8.0 \times 10^{-8}$	Belle
$B^+ \to \pi^+\mu\mu$	$(1.78 \pm 0.22 \pm 0.03) \times 10^{-8}$	LHCb
$B^0 \to \rho^0\mu\mu$	$(1.98 \pm 0.53) \times 10^{-8}$	LHCb

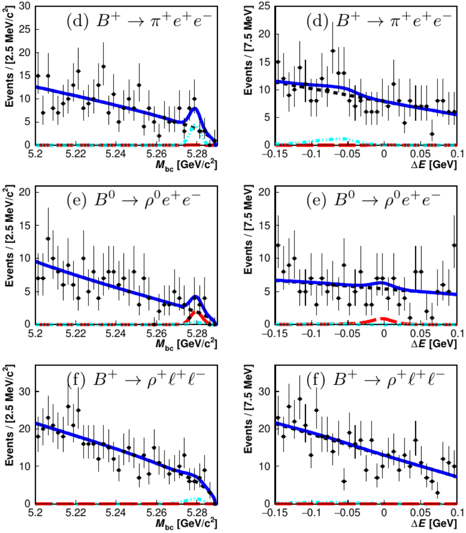
BaBar: [Phys.Rev.D 88 (2013) 3, 032012]
Belle: [Phys.Rev.D 78 (2008) 011101]
LHCb: [JHEP 10 (2015) 034, Phys.Lett.B 743 (2015) 46]

Rare $b \to dll$: analysis strategy

- Reconstruct 12 decay chains

$$B \to \{\pi, \rho, \eta, \omega\}\ell\ell \quad \begin{cases} \rho^{+,0} \to \pi^+\pi^{0,-} \\ \eta \to \gamma\gamma, \pi^+\pi^-\pi^0 \\ \omega \to \pi^+\pi^-\pi^0 \end{cases}$$

- MVA classifier against continuum background
- Suppress specific peaking backgrounds
  - Veto around J/ψ and $\psi(2S)$ masses
  - Veto 2-misID $D^0 \to K^+\pi^-$ in $B^+ \to \rho^+ ll$
  - $p_{\pi^0} > 1$ GeV and $p_{\pi^+} > 1$ GeV in $B^+ \to \pi^+ ll$ against 2-photon backgrounds
  - $q^2_{ee} > 0.045$ GeV^2 against photon conversions and π^0 Dalitz decays
- 2D fit on M_{bc} and ΔE to extract signal yields
  - Model remaining peaking background (charmless, $B^+ \to K^+e^+e^-$)



Rare $b \to dll$: results

No signal observed, set 90% CL upper limits

channel	$N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	ε (%)	$\mathcal{B}^{\rm UL}$ (10^{-8})	$\mathcal{B}$ (10^{-8})
$B^0 \to \eta e^+e^-$	$0.0^{+1.4}_{-1.0}$	3.1	3.9	< 10.5	$0.0^{+4.9}_{-3.4} \pm 0.1$
$B^0 \to \eta\mu^+\mu^-$	$0.8^{+1.5}_{-1.1}$	4.2	5.9	< 9.4	$1.9^{+3.4}_{-2.5} \pm 0.2$
$B^0 \to \eta\ell^+\ell^-$	$0.5^{+1.0}_{-0.8}$	1.8	4.9	< 4.8	$1.3^{+2.8}_{-2.2} \pm 0.1$
$B^0 \to \omega e^+e^-$	$-0.3^{+3.2}_{-2.5}$	3.7	1.6	< 30.7	$-2.1^{+26.5}_{-20.8} \pm 0.2$
$B^0 \to \omega\mu^+\mu^-$	$1.7^{+2.3}_{-1.6}$	5.5	2.9	< 24.9	$7.7^{+10.8}_{-7.5} \pm 0.6$
$B^0 \to \omega\ell^+\ell^-$	$1.0^{+1.8}_{-1.3}$	3.6	2.2	< 22.0	$6.4^{+10.7}_{-7.8} \pm 0.5$
$B^0 \to \pi^0 e^+e^-$	$-2.9^{+1.8}_{-1.4}$	4.0	6.7	< 7.9	$-5.8^{+3.6}_{-2.8} \pm 0.5$
$B^0 \to \pi^0\mu^+\mu^-$	$-0.5^{+3.6}_{-2.7}$	6.1	13.7	< 5.9	$-0.4^{+3.5}_{-2.6} \pm 0.1$
$B^0 \to \pi^0\ell^+\ell^-$	$-1.8^{+1.6}_{-1.1}$	2.9	10.2	< 3.8	$-2.3^{+2.1}_{-1.5} \pm 0.2$
$B^+ \to \pi^+e^+e^-$	$0.1^{+2.5}_{-1.6}$	5.0	11.5	< 5.4	$0.1^{+2.7}_{-1.8} \pm 0.1$
$B^0 \to \rho^0 e^+e^-$	$5.6^{+3.5}_{-2.7}$	10.8	3.2	< 45.5	$23.6^{+14.6}_{-11.2} \pm 1.1$
$B^+ \to \rho^+ e^+e^-$	$-4.4^{+2.3}_{-2.0}$	5.3	1.4	< 46.7	$-38.2^{+24.5}_{-17.2} \pm 3.4$
$B^+ \to \rho^+\mu^+\mu^-$	$3.0^{+4.0}_{-3.0}$	8.7	2.9	< 38.1	$13.0^{+17.5}_{-13.3} \pm 1.1$
$B^+ \to \rho^+\ell^+\ell^-$	$0.4^{+2.3}_{-1.8}$	3.0	2.0	< 18.9	$2.5^{+14.6}_{-11.8} \pm 0.2$

- Obtained upper limits in the range $(3.8 - 47) \times 10^{-8}$
- Best upper limit for all serched decay modes
- $B^0 \to \omega ll$, and $B^{\pm,0} \to \rho^{\pm,0} ll$ searched for the first time

$$B \to K^*\gamma$$

New for Moriond '24

$B \to K^*\gamma$: motivation

New for Moriond '24

- 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
- Latest Belle measurement found evidence of isospin asymmetry at 3.1σ [Phys. Rev. Lett. 119, 191802 (2017)]

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

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

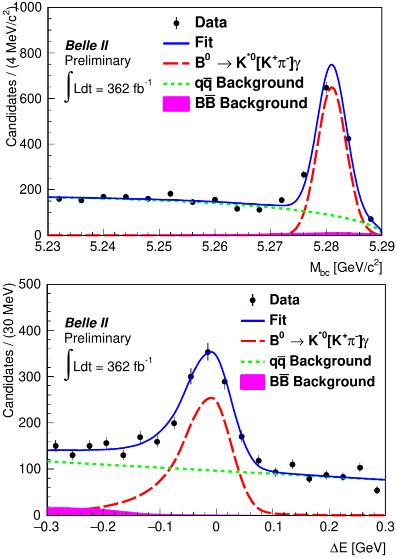
Goal

Using the 362 fb^{-1} Belle II run 1 dataset

- Measure $\mathcal{B}(B^{\pm,0} \to K^{*\pm,0}\gamma)$ with $K^* \to K^+\pi^-$, $K_S^0\pi^0$, $K^+\pi^0$ and $K_S^0\pi^+$
- Measure Δ_{+0} and A_{CP} for all modes except $B^0 \to K^{*0}(\to K_S^0\pi^0)\gamma$

$B \to K^*\gamma$: analysis strategy

New for Moriond '24



- Reconstruct 4 K^* modes: $K^+\pi^-$, $K_S^0\pi^0$, $K^+\pi^0$ and $K_S^0\pi^+$
- 2 MVA classifiers to reject
  - photons from asymmetric $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ decays
  - continuum events
- 2D M_{bc}-ΔE fit to extract
  - Simultaneously yields of B and anti-B for self-tagged modes for A_{CP} and $\mathcal{B}$
  - Yield of $B \to K^{*0}(\to K_S^0\pi^0)\gamma$ for $\mathcal{B}$

$B \to K^*\gamma$: results

New for Moriond '24

- Consistent with World average and SM
- Similar sensitivity as Belle despite smaller sample (thanks mainly to improved ΔE resolution, K_S^0 efficiency and continuum suppression)
- Asymmetries statistically limited

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

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

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

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

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

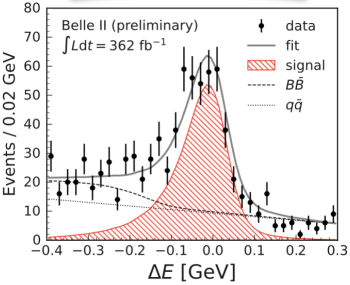
$$\Delta_{0+} = (5.1 \pm 2.0 \pm 1.5)\%,$$

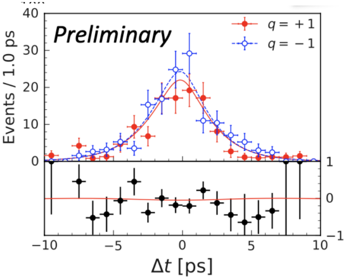
$B^0 \to K_S^0 \pi^0 \gamma$

- Goal: Measure time-dependent CPV in two regions
  - resonant: $K^*(892)\gamma$ $m_{K\pi} \in [0.8, 1]$ GeV
  - non resonant: $K_S^0\pi^0\gamma$ $m_{K\pi} \in [0.6, 0.8] \cup [1, 1.8]$ GeV
- Expect almost no CPV in SM as photons from B^0 ($\overline{B}^0$) are predominantly right-handed (left-handed) (Flipping photon polarisation suppressed by m_s/m_b)
- Strategy: fit to ΔE and M_{bc} followed by fit to Δt
- World best result thanks to better background suppression, vertexing and K_S^0 acceptance

resonant	non resonant
$S = 0.00^{+0.27+0.03}_{-0.26-0.04}$ $C = 0.10 \pm 0.13 \pm 0.03$	$S = 0.04^{+0.45}_{-0.44} \pm 0.10$ $C = -0.06 \pm 0.25 \pm 0.07$

HFLAV resonant: $S = -0.16 \pm 0.22$, $C = -0.07 \pm 0.12$





$$B \to \rho\gamma$$

$B \to \rho\gamma$: motivation

- SM $\mathcal{B}$ suppressed by $|V_{td}/V_{ts}| \simeq 0.04$ with respect to $B \to K^*\gamma$
- Previously observed at Belle [Phys.Rev.Lett.101:111801,2008] and BaBar [Phys.Rev.D78:112001,2008]
- Almost 2σ tension between current word average $A_{\mathrm{I}} = (30^{+16}_{-13}\%)$ and SM $(5.2 \pm 2.8)\%$ [Lyon, Zwicky '13]

$$A_{\mathrm{CP}}(B \to \rho\gamma) = \frac{\Gamma\left(\overline{B} \to \overline{\rho}\gamma\right) - \Gamma\left(B \to \rho\gamma\right)}{\Gamma\left(\overline{B} \to \overline{\rho}\gamma\right) + \Gamma\left(B \to \rho\gamma\right)}$$

$$A_{\mathrm{I}} = \frac{2\Gamma(\overset{(-)}{B^0} \to \rho^0\gamma) - \Gamma(B^\pm \to \rho^\pm\gamma)}{2\Gamma(\overset{(-)}{B^0} \to \rho^0\gamma) + \Gamma(B^\pm \to \rho^\pm\gamma)}$$

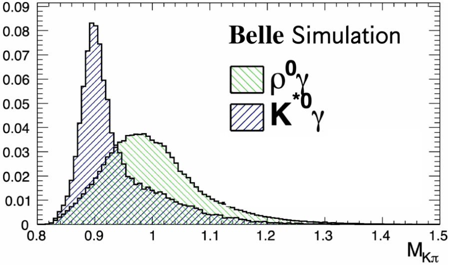
Goal

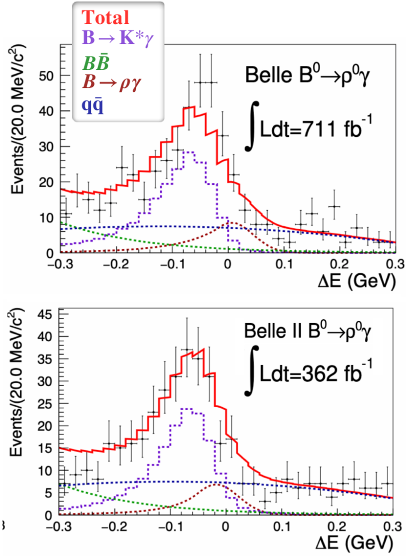
Using the 1.07 ab^{-1} Belle + Belle II dataset

- Measure $\mathcal{B}(B^{\pm,0} \to \rho^{\pm,0}\gamma)$ with $\rho^0 \to \pi^+\pi^-$, and $\rho^\pm \to \pi^\pm\pi^0$
- Measure $A_{\mathrm{CP}}(B^+ \to \rho^+\gamma)$ and $A_{\mathrm{I}}(B \to \rho\gamma)$

$B \to \rho\gamma$: analysis strategy

- 2 MVA classifiers against photons from π^0/η and continuum events
- Large background from $B \to K^*\gamma$ ($K \to \pi$ misID)
- Belle+Belle II simultaneous 3D fit of M_{bc}, ΔE and $M_{K\pi}$





$B \to \rho\gamma$: results

- Obtain most precise measurements to date
- Belle II performance similar to Belle despite smaller dataset
- A_{I} consistent with SM at 0.6σ

$$\begin{aligned}
\mathcal{B}\left(B^{+} \to \rho^{+}\gamma\right) &= \left(13.1^{+2.0+1.3}_{-1.9-1.2}\right) \times 10^{-7}, \\
\mathcal{B}\left(B^{0} \to \rho^{0}\gamma\right) &= \left(7.5 \pm 1.3^{+1.0}_{-0.8}\right) \times 10^{-7}, \\
A_{\mathrm{CP}}\left(B^{+} \to \rho^{+}\gamma\right) &= \left(-8.2 \pm 15.2^{+1.6}_{-1.2}\right) \%, \\
A_{\mathrm{I}}\left(B \to \rho\gamma\right) &= \left(10.9^{+11.2+6.8+3.8}_{-11.7-6.2-3.9}\right) \%,
\end{aligned}$$

Third uncertainty on A_{I} from f_{+-}/f_{00} and τ_{B^+}/τ_{B^0}

BELLE + Belle II

$$B^0 \to \gamma\gamma$$

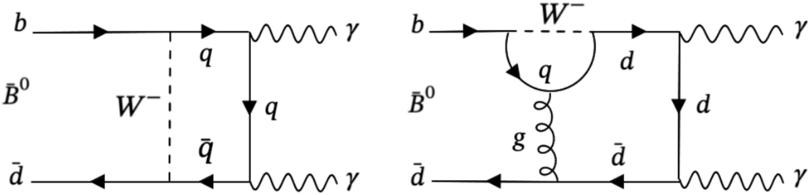
New for Moriond '24

$B^0 \to \gamma\gamma$: motivation

- Flavour changing neutral current decay sensitive to new physics
- Expected $\mathcal{B}(B^0 \to \gamma\gamma) = 1.4^{+1.4}_{-0.8} \times 10^{-8}$
  [Shen, Wang, Wei '20, Qin, Shen, Wang, Wang '23]
  - Significant long distance contribution
- Current best upper limit by BaBar
  $\mathcal{B}(B^0 \to \gamma\gamma) < 3.2 \times 10^{-7}$
  [Phys.Rev.D83:032006,2011]

Goal

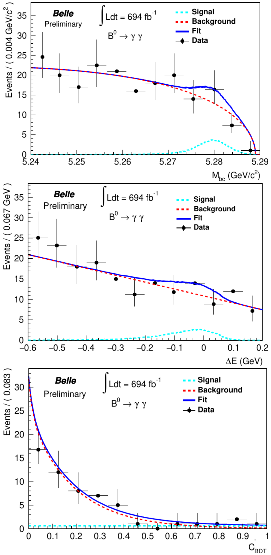
Search for the $B^0 \to \gamma\gamma$ decay using the 1.07 ab^{-1} Belle + Belle II dataset



$B^0 \to \gamma\gamma$: analysis strategy

New for Moriond '24

- Combine two high energy photons from the barrel
- 2 MVA classifiers against photons from π^0/η and continuum events
- Photon timing cuts to suppress peaking background in M_{bc} from combinations of back-to-back off-time photons
- Belle+Belle II simultaneous 3D fit on M_{bc}, ΔE and output MVA classifier
  - Use KDE to model $M_{bc} - \Delta E$ correlation for signal
- Use $B^0 \to K^{*0}(\to K^+\pi^-)\gamma$ as control channel to derive data/MC efficiency corrections



$B^0 \to \gamma\gamma$: results

New for Moriond '24

- $9.1^{+5.6}_{-4.4}/615 \pm 25$ and $1.9^{+4.2}_{-2.8}/317 \pm 18$ signal/background events in Belle and Belle II datasets
- Belle II performance similar to Belle despite smaller dataset
- 2.5σ combined significance
- 90% CL upper limit improved by a factor 5 over BaBar, sensitivity close to SM expected value

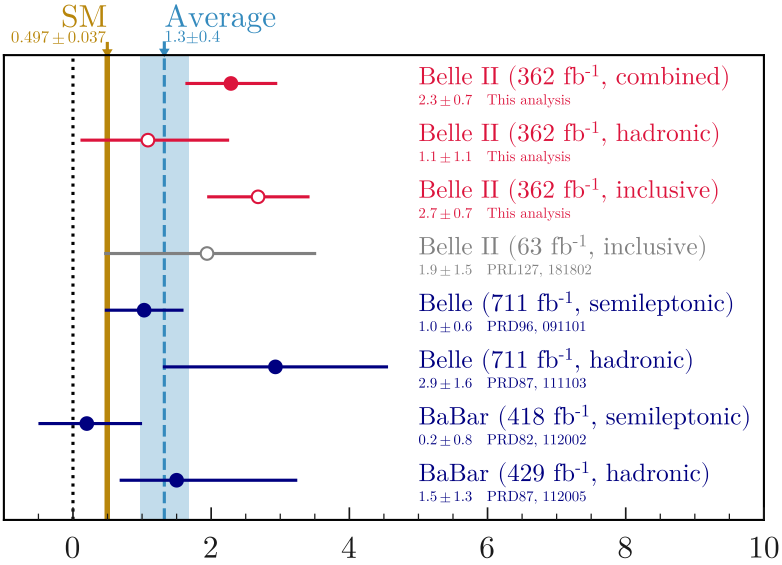
	$\mathcal{B}(B^0 \to \gamma\gamma)$	$\mathcal{B}(B^0 \to \gamma\gamma)$ (at 90% CL)
Belle	$(5.4^{+3.3}_{-2.6} \pm 0.5) \times 10^{-8}$	$< 9.9 \times 10^{-8}$
Belle II	$(1.7^{+3.7}_{-2.4} \pm 0.3) \times 10^{-8}$	$< 7.4 \times 10^{-8}$
Combined	$(3.7^{+2.2}_{-1.8} \pm 0.7) \times 10^{-8}$	$< 6.4 \times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

Conclusion

- Electroweak and radiative penguin B decays are promising place to look for New Physics
- Five Belle and Belle II new results since last Moriond
  - First evidence of $B^+ \to K^+\nu\bar{\nu}$ with Belle II
  - Best upper limits on rare $b \to ll$ decays with Belle
  - New measurements of $\mathcal{B}$, A_{CP} and Δ_{+0} of $B \to K^*\gamma$ with Belle II
  - Best measurements of $\mathcal{B}$, A_{CP} and A_{I} of $B \to \rho\gamma$ with Belle+Belle II
  - Best upper limit on $B^0 \to \gamma\gamma$ with Belle+Belle II
- Results statistically limited; Belle II Run 2 data taking just started, stay tuned for updates

BACKUP

$B^+ \to K^+\nu\bar{\nu}$



$B \to K^*\gamma$: systematics

Table 3. Systematic uncertainties (%) for branching fraction measurements.

Source	$K^{*0}[K^+\pi^-]\gamma$	$K^{*0}[K^0_S\pi^0]\gamma$	$K^{*+}[K^+\pi^0]\gamma$	$K^{*+}[K^0_S\pi^+]\gamma$
B counting	1.5	1.5	1.5	1.5
$f^{\pm}/f^{00}$	1.6	1.6	1.6	1.6
γ selection	0.9	0.9	0.9	0.9
π^0 veto	0.7	0.7	0.7	0.7
η veto	0.2	0.2	0.2	0.2
Tracking efficiency	0.5	0.5	0.2	0.7
π^+ selection	0.2	–	–	0.2
K^+ selection	0.4	–	0.4	–
K^0_S reconstruction	–	1.4	–	1.4
π^0 reconstruction	–	3.9	3.9	–
χ^2 requirement	0.2	1.0	0.2	1.0
CSBDT requirement	0.3	0.4	0.4	0.3
Best candidate selection	0.1	1.0	0.6	0.2
Fit bias	0.1	0.9	0.5	0.2
Signal PDF model	0.1	0.4	0.3	0.2
KDE PDF model	0.1	0.8	0.6	0.2
Simulation sample size	0.2	0.8	0.4	0.5
Self-crossfeed fraction	–	1.0	1.0	–
Total	2.6	5.4	4.9	3.2

Table 2. Systematic uncertainties (%) for $\mathcal{A}_{CP}$ measurements.

Source	$K^{*0}[K^+\pi^-]\gamma$	$K^{*+}[K^+\pi^0]\gamma$	$K^{*+}[K^0_S\pi^+]\gamma$
Fit bias	0.1	0.2	0.2
Signal PDF model	0.1	0.1	0.1
KDE PDF model	0.1	0.4	0.2
Best candidate selection	0.1	0.5	0.2
K^+ asymmetry	–	0.6	–
π^+ asymmetry	–	–	0.6
$K^+\pi^-$ asymmetry	0.3	–	–
Total	0.4	0.9	0.7

Table 4. Correlation matrix for systematic uncertainties in the branching fractions.

	$B^0 \to K^+\pi^-\gamma$	$B^0 \to K^0_S\pi^0\gamma$	$B^+ \to K^+\pi^0\gamma$	$B^+ \to K^0_S\pi^+\gamma$
$B^0 \to K^+\pi^-\gamma$	1	0.4556	0.5047	0.7870
$B^0 \to K^0_S\pi^0\gamma$		1	0.8141	0.5519
$B^+ \to K^+\pi^0\gamma$			1	0.4034
$B^+ \to K^0_S\pi^+\gamma$				1

$B \to \rho\gamma$: systematics

Source	$\mathcal{B}_{\rho^+\gamma} \times 10^8$	$\mathcal{B}_{\rho^0\gamma} \times 10^8$	A_I	A_{CP}
Reconstruction	4.1	1.3	1.4%	0.5%
Selection	9.0	3.4	4.0%	0.5%
Fixed PDF	1.1	2.7	1.8%	0.2%
Signal shape	4.7	3.0	3.1%	0.5%
Histogram PDF	1.0	0.6	0.5%	0.1%
$K^*\gamma$ yield	3.4	5.4	3.1%	0.1%
$B\overline{B}$ peaking yield	2.2	0.8	0.9%	0.2%
$B\overline{B}$ peaking A_{CP}	0.1	0.0	0.1%	1.0%
Number of $B\overline{B}$'s	1.7	1.4	0.3%	0.1%
Other parameters	4.0	3.6	3.9%	0.0%
Total	12.5	8.6	7.5%	1.4%

$B^0 \to \gamma\gamma$: systematics

TABLE I. Summary of systematic uncertainties on the signal yield.

Source	Belle (events)	Belle II (events)
Fit bias	$+0.16$	$+0.12$
PDF parameterization	$^{+0.56}_{-0.48}$	$^{+0.30}_{-0.32}$
Shape Modeling	$+0.06$	$+0.04$
Total (sum in quadrature)	$^{+0.58}_{-0.48}$	$^{+0.30}_{-0.32}$

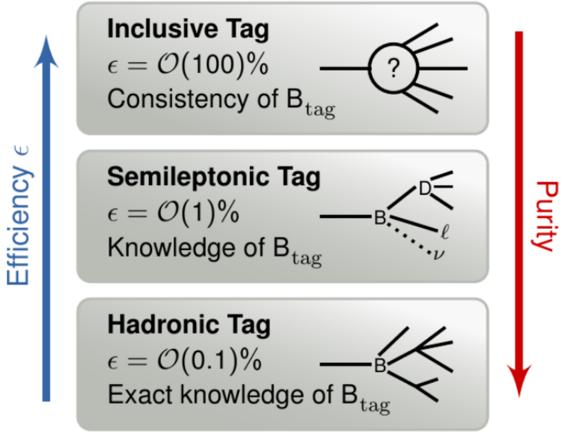
TABLE II. Summary of systematic uncertainties on signal efficiencies.

Source	Belle (%)	Belle II (%)
Photon Detection Efficiency	4.0	2.7
Reconstruction Efficiency (ϵ_{rec})	0.6	0.5
Number of $B\overline{B}$	1.3	1.5
f^{00}	2.5	2.5
C_{BDT} requirement	0.4	0.9
π^0/η veto	0.3	0.4
Timing requirement efficiency	2.8	–
Total (sum in quadrature)	5.7	4.1

Rare $b \to ll$: systematics

source	ηee	$\eta\mu\mu$	ωee	$\omega\mu\mu$	$\pi^0 ee$	$\pi^0\mu\mu$	$\pi^+ ee$	$\rho^0 ee$	$\rho^0\mu\mu$	$\rho^+ ee$	$\rho^+\mu\mu$
μ	—	0.6	—	0.6	—	0.6	—	—	0.6	—	0.6
e	0.8	—	0.8	—	0.8	—	0.8	0.8	—	0.8	—
π^+	1.0	1.0	1.0	1.0	—	—	0.5	1.0	1.0	0.5	0.5
π^0	2.3	2.3	2.3	2.3	2.3	2.3	—	—	—	2.3	2.3
γ	4.0	4.0	—	—	—	—	—	—	—	—	—
BDT	7.1	6.6	7.1	6.6	7.1	6.6	1.4	1.4	0.8	7.1	6.6
MC	0.48	0.37	0.73	0.53	0.34	0.24	0.24	0.53	0.34	0.80	0.54
track	0.7-1.4	0.7-1.4	1.4	1.4	0.7	0.7	1.05	1.4	1.4	1.05	1.05
PDF	0.04	0.04	0.43	0.07	0.10	0.09	0.50	0.20	0.06	0.34	0.32
$f^{+-/00}$	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45
$N_{B\bar{B}}$	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Total	9.27	8.87	8.25	7.78	8.06	7.60	3.50	3.72	3.47	8.15	7.68

Tagging strategies



Cross sections at the $\Upsilon(4S)$