# B decays at $e^+e^-$ colliders

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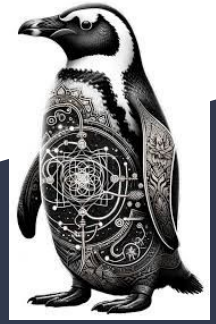
On behalf of the Belle & Belle II Collaboration

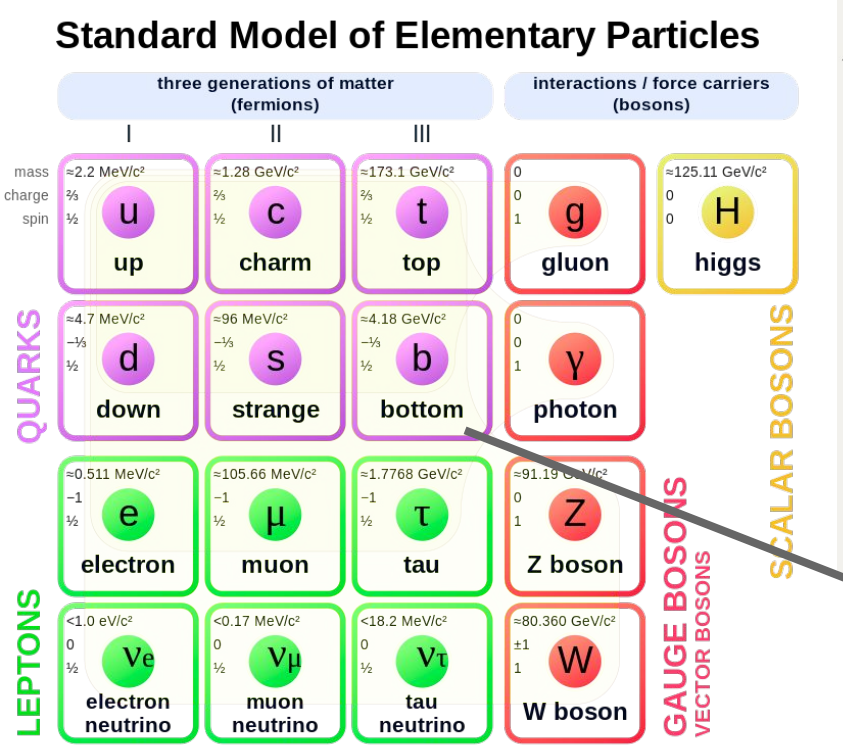


**22nd Conference on Flavour physics and CP violation (FPCP 2024)**
**May 27-31, 2024 Bangkok, Thailand**

# 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




$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}W_{\mu\nu}\cdot W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^{\alpha}_{\mu\nu}G^{\mu\nu}_{\alpha}}_{\text{kinetic energies and self-interactions of the gauge bosons}}$$

$$+ \underbrace{\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)L + \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g'YB_{\mu}\right)R}_{\text{kinetic energies and electroweak interactions of fermions}}$$

$$+ \underbrace{\frac{1}{2}\left|\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)\phi\right|^{2} - V(\phi)}_{W^{\pm},Z,\gamma \text{ and Higgs masses and couplings}}$$

$$+ \underbrace{g''\left(\bar{q}\gamma^{\mu}T_{a}q\right)G^{\alpha}_{\mu}}_{\text{interactions between quarks and gluons}} + \underbrace{\left(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.\right)}_{\text{fermion masses and couplings to Higgs}}$$

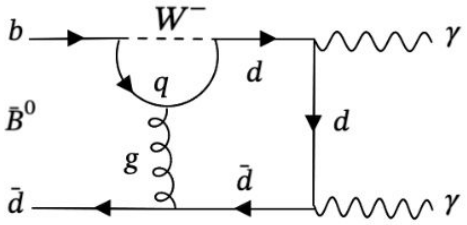
The elusive *b* quark

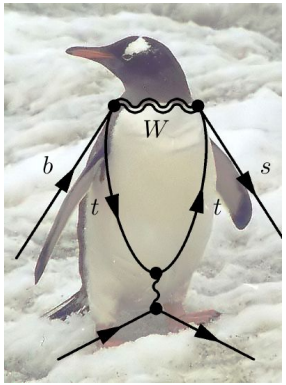
- Heaviest quark that can hadronize to a meson
- Myriad of final states and interactions to probe from

# Rare decays!!!

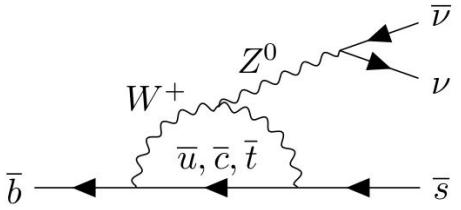
Flavour changing neutral currents (FCNC) decays of *B* mesons

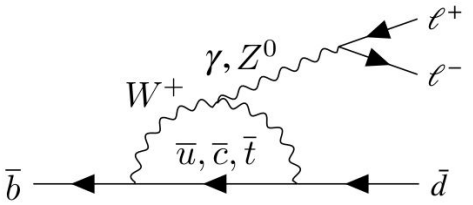
- Forbidden at tree level, allowed at loop level [PRD 2 (1970) 1285]
- Standard Model (SM) contribution is small, sensitive to beyond SM.
- BSM particles can contribute in the loop or mediate the process at the tree level.

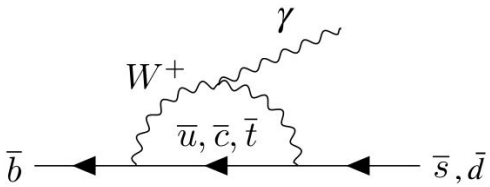



Electroweak penguins

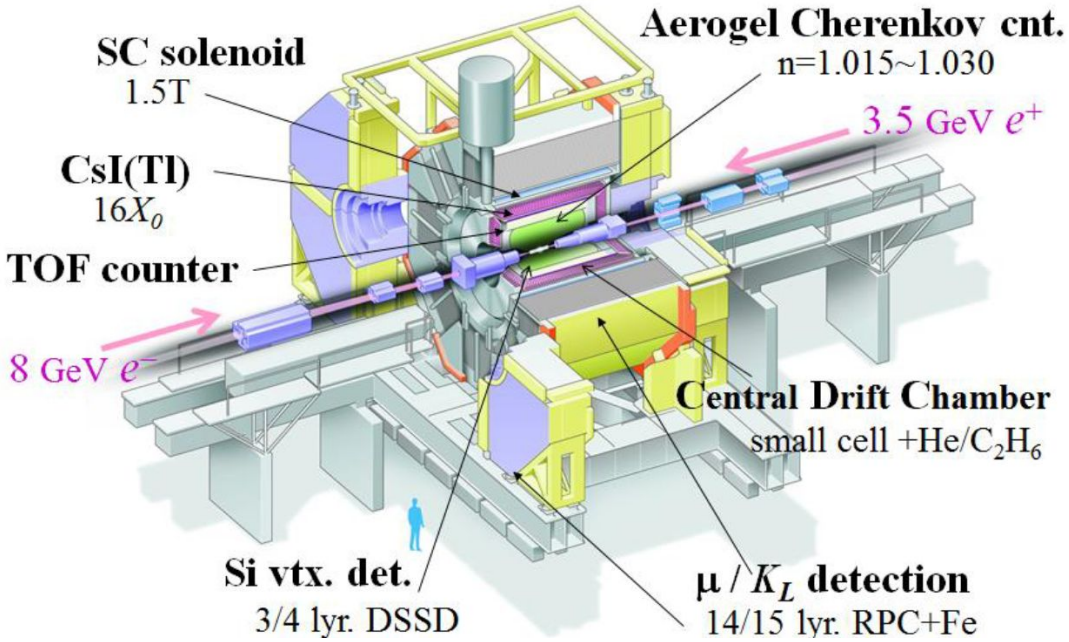


# Belle

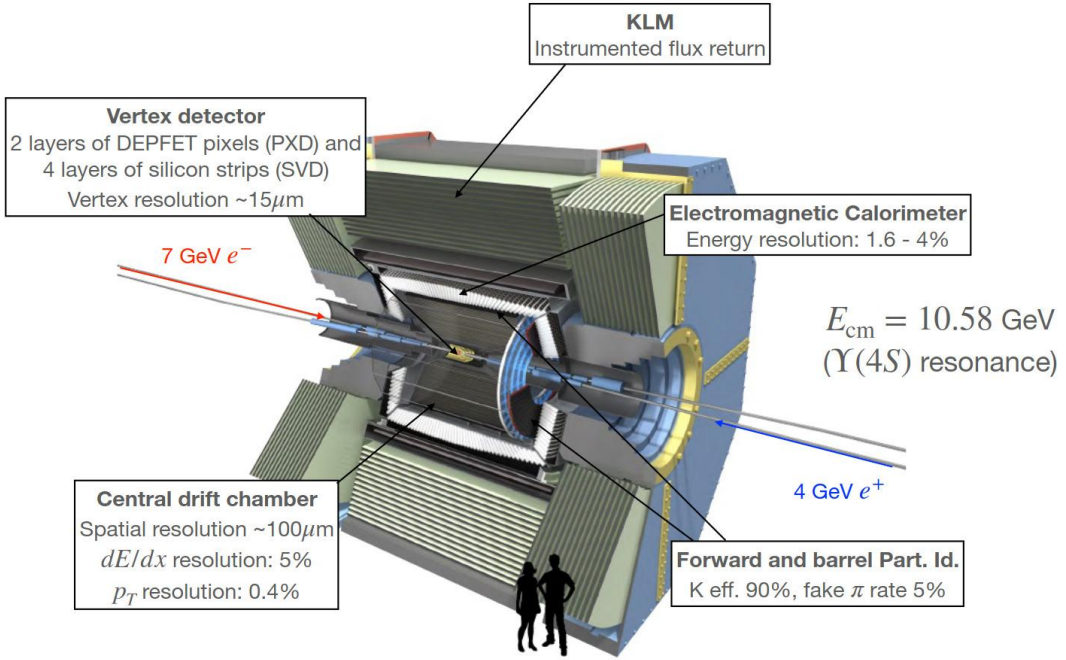
- SVD (3/4 layers) ⇒ Vertex Reco.
- ACC+TOF ⇒ Particle ID (K/π)
- ECL ⇒ $\gamma$ and e
- CDC ⇒ Tracking
- KLM ⇒ RPC




Belle TDR: A. Abashian et al., Nucl. Instrum. Meth. A479, 117 (2002)

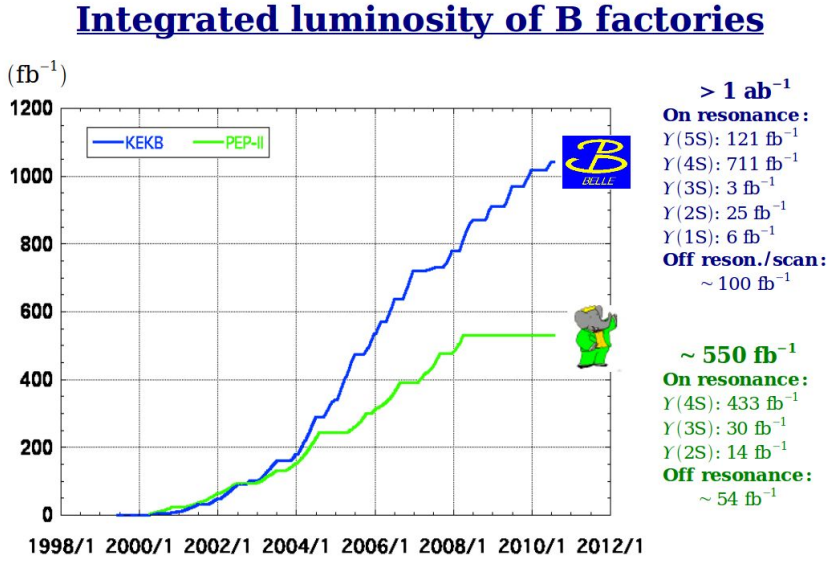
# Belle II

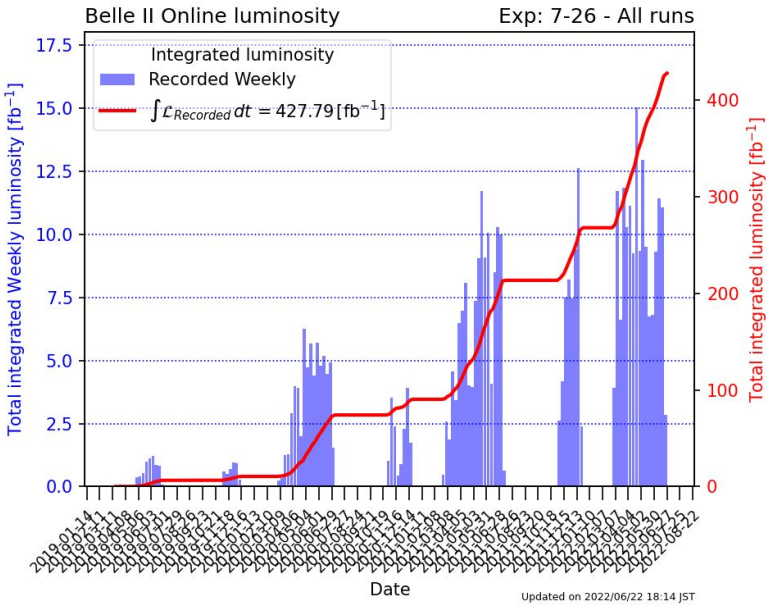
- PXD (2 layers) + SVD (4 layers) ⇒ Vertex Reco.
- ARICH+TOP ⇒ Particle ID (K/π)
- ECL ⇒ With waveform sampling readout electronics ($\gamma$ and e)
- CDC ⇒ Small cell, long lever arm
- KLM ⇒ Scintillator + RPC




Belle TDR: T. Abe et al., arXiv:1011.0352 [physics.ins-det] (2002)

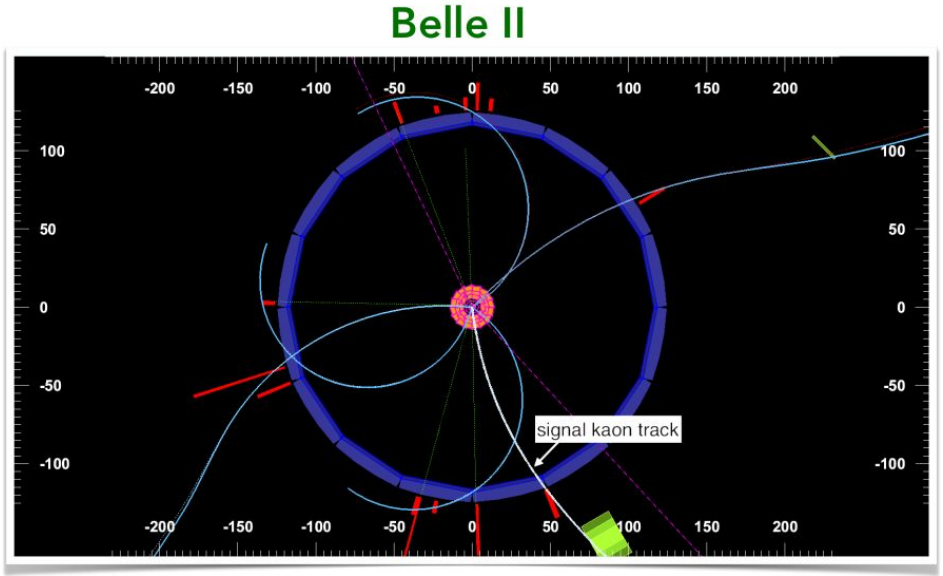
# Belle/Belle II status

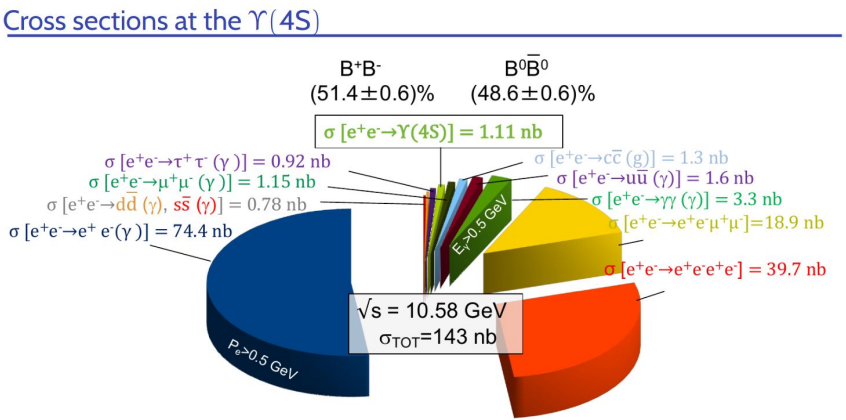



Belle II collected 362 fb-1 at $\Upsilon$(4S) — equivalent to BaBar and ~1/2 of Belle sample
Belle II collected 42 fb-1 of off-resonance data [60 MeV below $\Upsilon$(4S)] compared to ~90 fb-1 from Belle

# Events at B factories

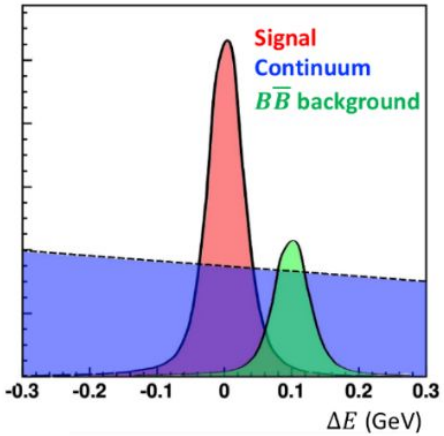



- Clean environment with on average ~10-15 tracks, 3-4 $\pi^0$
- Known initial state kinematics
- Principle background from light quarks

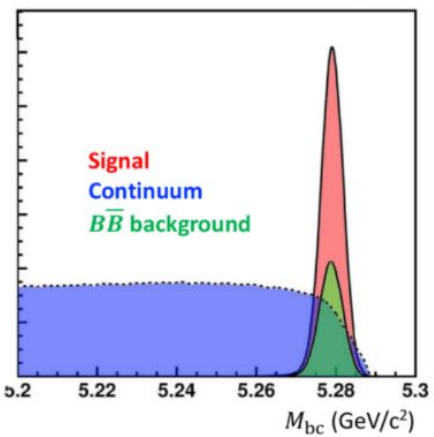
# Event kinematics

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

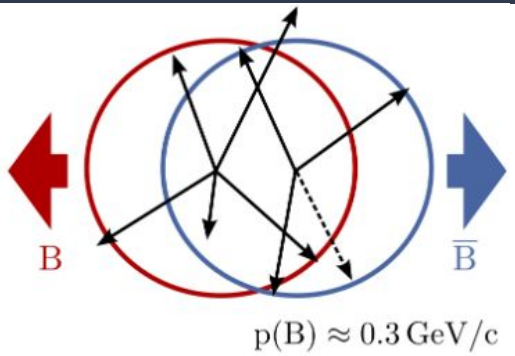


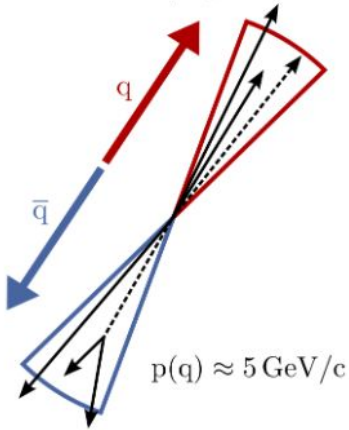

Expected $\Delta E \simeq 0$

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




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

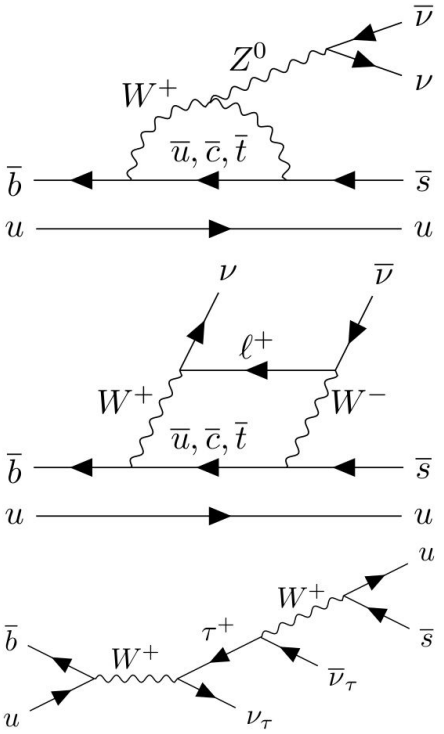
- $B^+ \to K^+ \nu \bar{\nu}$ is a challenging due to a single charged track in the final state
- $\mathcal{B}$(SM) = (5.58 ± 0.37) x $10^{-5}$ [PRD 107, 014511]
- New physics could significantly increase the rate

**Advantages at Belle II:**

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

**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)]



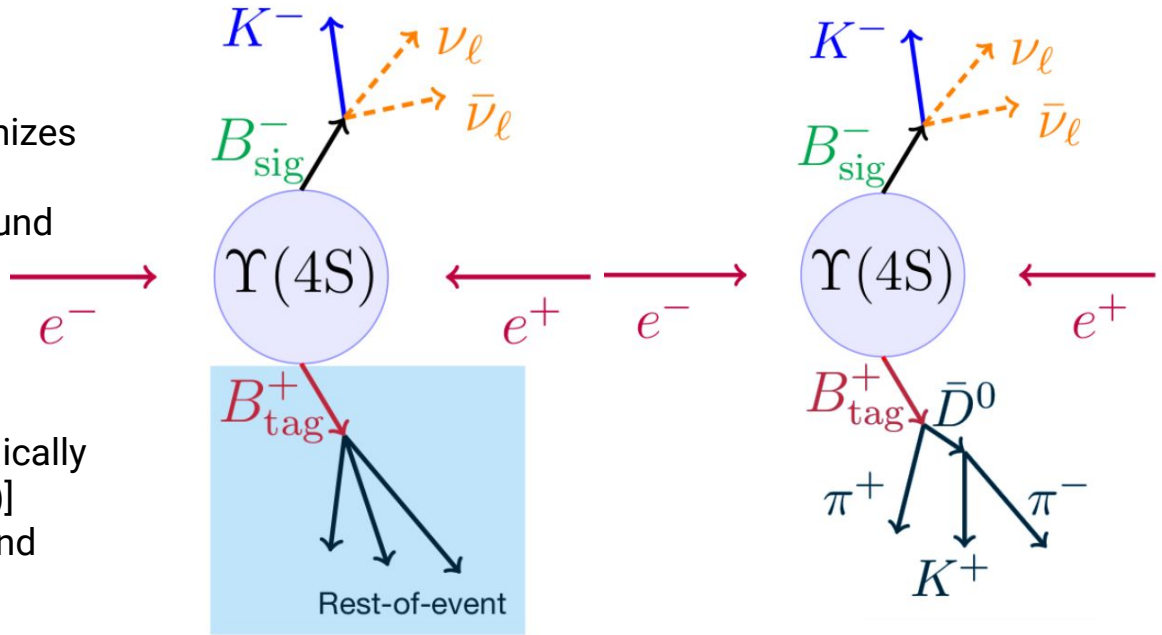
# $B \to K \nu \bar{\nu}$ : Reconstruction

Inclusive tag analysis (ITA)

- Select first signal kaon that minimizes $q^2_{rec}$ (computed as $K^+$ recoil)
- Nested BDT to suppress background
- Binned fit to $q^2_{rec}$ and BDT output simultaneously for on and off resonance

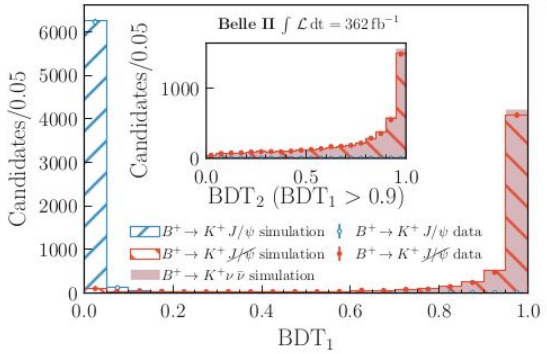
Hadronic tag analysis (HTA)

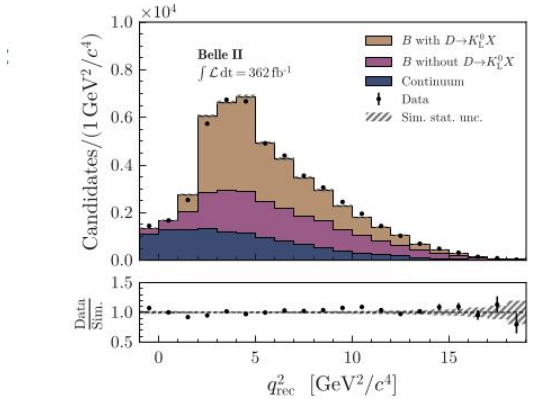
- Select first tag B decaying hadronically [Comput Softw Big Sci 3, 6 (2019)]
- Single BDT to suppress background
- Fit BDT output



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

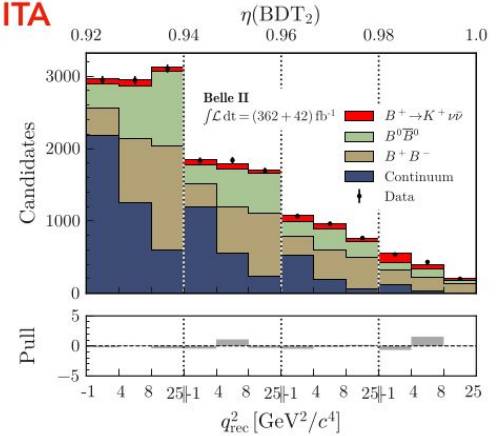




- Continuum validated with off-resonance
- $B \to X_c(\to K^0_L)$ validated from pion enriched sideband
- Signal like $B \to K^+ K^0_L K^0_L$ checked with $B \to K^+ K^0_S K^0_S$ [PRD 85 112010]
- Similar treatment for $B \to K^+ K^0_S K^0_L$ and $B \to K^+ nn$

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

## ITA



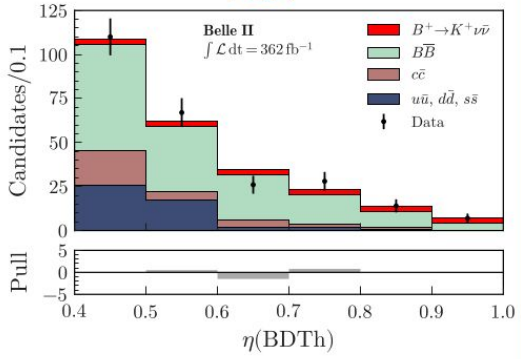

$\mu = 5.4 \pm 1.0(\mathrm{stat}) \pm 1.1(\mathrm{syst})$

corresponding to

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

- 3.5 $\sigma$ compatibility wrt bkg only
- 2.9 $\sigma$ compatibility wrt to the SM

## HTA



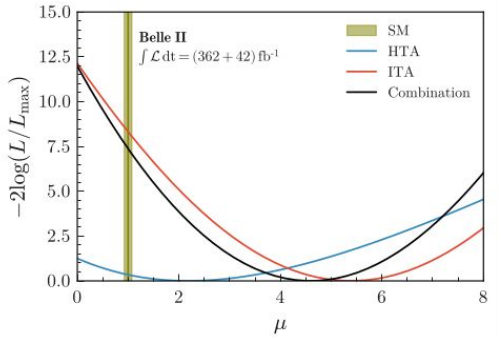

$\mu = 2.2^{+1.8}_{-1.7}(\mathrm{stat})^{+1.6}_{-1.1}(\mathrm{syst})$

corresponding to

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

- 1.1 $\sigma$ compatibility wrt bkg only
- 0.6 $\sigma$ compatibility wrt to the SM

## Combination




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

corresponding to

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

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

# First measurement of B->K*(892)$\gamma$ at Belle II

- Flavour changing neutral current decays sensitive to new physics
- CP ($A_{CP}$) and isospin ($\Delta_{+0}$) 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: $A_{CP}$ 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: $\Delta_{+,0}$ range from 2-8% with an uncertainty ~2%**

# B->K*(892)$\gamma$: Analysis

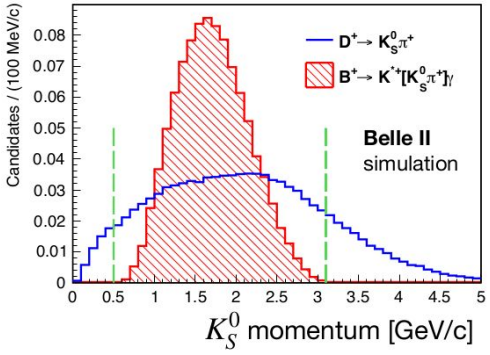
- Analysis based on run 1 data (362 $fb^{-1}$)
- Reconstruct K* → $K^+ \pi^-$ , $K^0_S \pi^0$ , $K^+ \pi^0$ , $K^0_S \pi^-$
- Combine K* with a prompt photon to get B candidate
- Dedicated BDTs to suppress continuum, π → γγ, and η → γγ decays

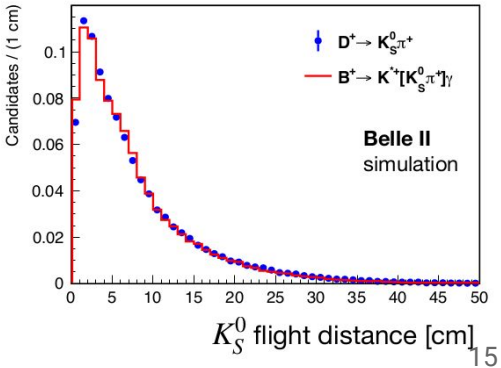
**Fit strategy**

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

**Control sample study**

- Employed B → $D^0 \pi^-$ to calibrate continuum, π → γγ, and η → γγ BDTs
- Hadron identification calibrated using $D^0 \rightarrow K^- \pi^+$
- Significant effort towards $K^0_S$ systematics using $D^+ \rightarrow K^0_S \pi^+$



# B->K*(892)$\gamma$ : Results

- Consistent with World average and SM
- Asymmetries are statistically limited
- Similar sensitivity to Belle result despite half the data
  $\Delta_{0+}$ = 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)

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

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

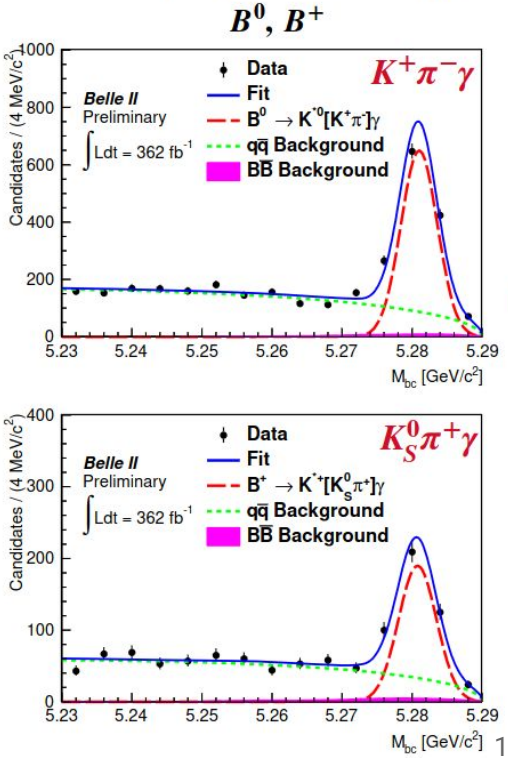
$$\mathcal{B}[B^+ \to K^{*+}\gamma] = (4.04 \pm 0.13 \pm 0.13) \times 10^{-5},$$

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

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

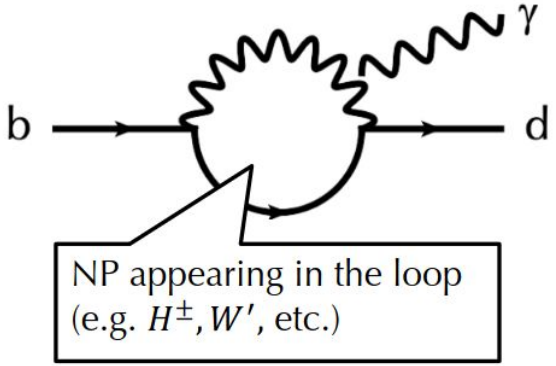
$$\Delta\mathcal{A}_{CP} = (2.2 \pm 3.8 \pm 0.7)\%,$$

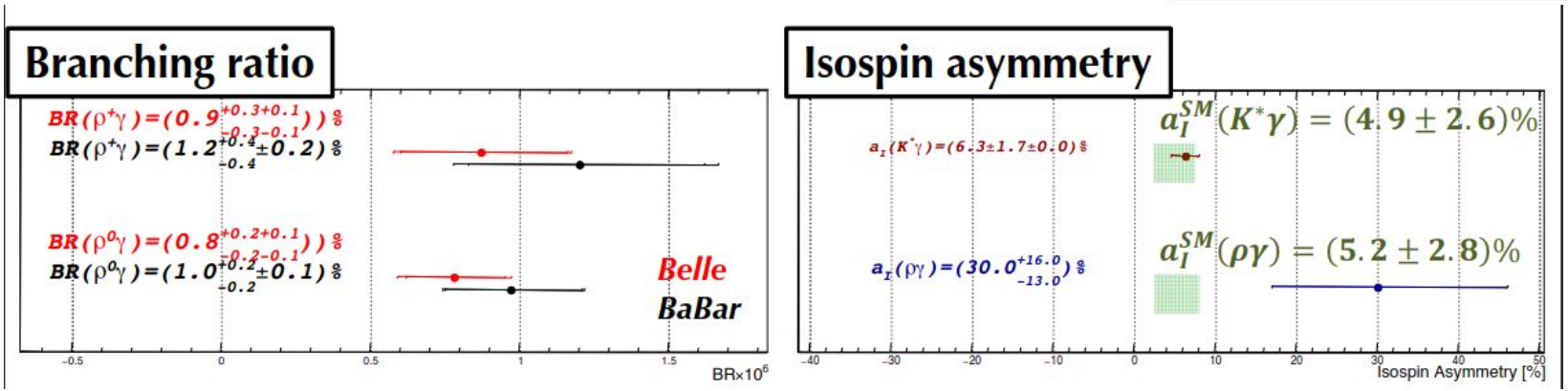
$$\Delta_{0+} = (5.1 \pm 2.0 \pm 1.0 \pm 1.1)\%$$



# Exclusive measurement of B→ργ at Belle and Belle II

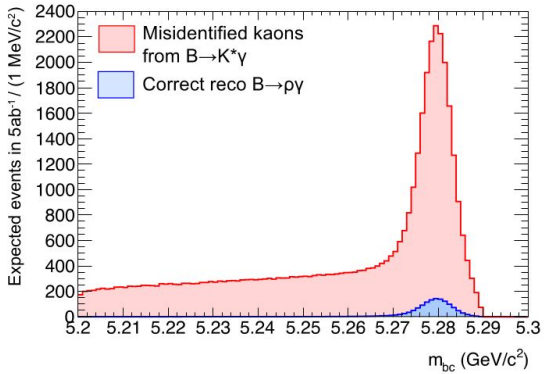
- Flavor changing neutral current with b → d transition
- Independent search for NP
- SM branching fraction suppressed by |Vtd /Vts | ~ 0.04 with respect to $B->K^*(892)\gamma$
- The first “charmless” study with Belle and Belle II joint data
- Earlier results from Belle [Phys. Rev. Lett. 101, 111801]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



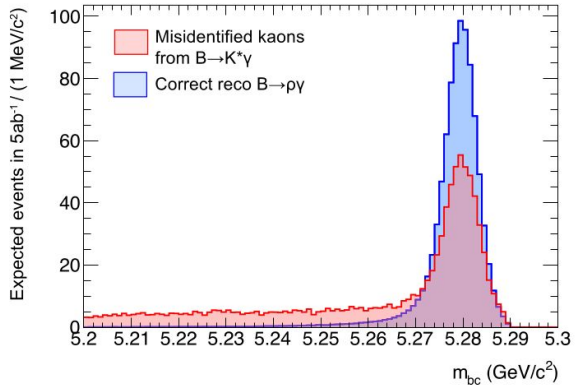



# B→ργ : Analysis

- Select high energy photon candidate 1.8< $E_\gamma^B$ < 2.8 GeV with shower shape consistent to an isolated photon.
- Reconstruct $\rho^0 \to \pi^+\pi^-$ and $\rho^+ \to \pi^+\pi^0$ for neutral and charged modes of B.
- Define $M_{K\pi}$ as the invariant mass calculated assuming $\pi^+$ is $K^+$
- The $M_{K\pi}$ helps separate $K^*\gamma$ background better compared to $M_{\pi\pi}$
- Dedicated BDTs to suppress continuum, π → γγ, and η → γγ decays




⇐ Without PID
Impact of PID ⇒



# $B \to \rho\gamma$ : Observables and Fit strategy

- $B^0$-> $K^*(892)[K^+\pi^-]\gamma$ taken as a control channel.
  - Calibrate the signal PDF modelling
  - Efficiency corrections due to application of BDTs
- Simultaneous 3D fitting with 3x2=6 samples to determine target observables.
- $\Delta E$, $M_{bc}$ and $M_{K\pi}$ for $(B^+, B^-, B^0) \times$ (Belle, Belle II)

– Floating parameters:

- $A_I \equiv \frac{rc_\rho^2 BR(B^0 \to \rho^0\gamma) - BR(B^\pm \to \rho^\pm\gamma)}{rc_\rho^2 BR(B^0 \to \rho^0\gamma) + BR(B^\pm \to \rho^\pm\gamma)}$, where $c_\rho = \sqrt{2}$ and $r \equiv \frac{f_{+-}}{f_{00}} \frac{\tau_{B^\pm}}{\tau_{B^0}}$
- $A_{CP} \equiv \frac{BR(B^+ \to \rho^+\gamma) - BR(B^- \to \rho^-\gamma)}{BR(B^+ \to \rho^+\gamma) + BR(B^- \to \rho^-\gamma)}$
- $\Gamma \equiv rc_\rho^2 BR(B^0 \to \rho^0\gamma) + BR(B^\pm \to \rho^\pm\gamma)$

- $BR(B^\pm \to \rho^\pm\gamma) = \frac{\Gamma}{2}(1 - A_I)$
- $BR(B^0 \to \rho^0\gamma) = \frac{\Gamma}{4r}(1 + A_I)$

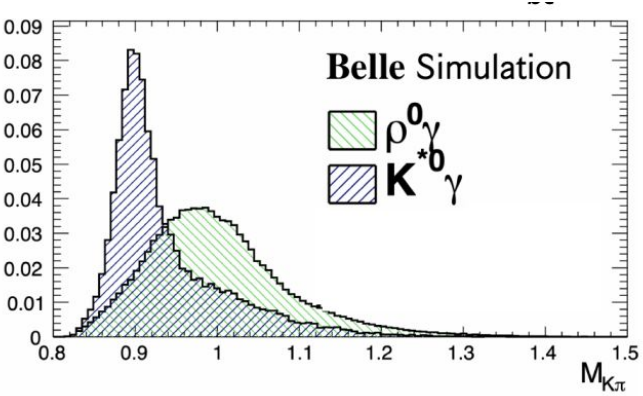
# B→ργ : Results

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

Signal enriched region

$M_{\rm bc} > 5.27$ GeV/c$^2$

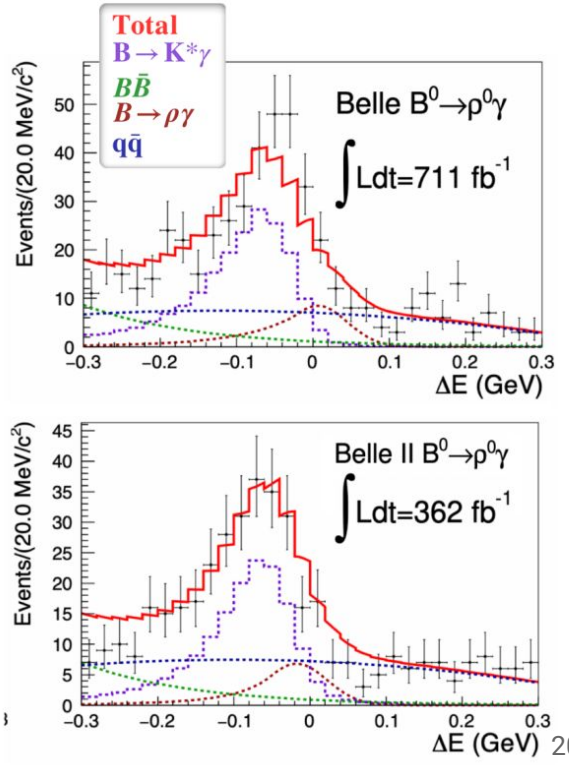
$M_{K\pi} > 0.92$ GeV




Uncertainty:

stat. + sys. + $f_{+-}/f_{00}$ (for $A_l$)

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



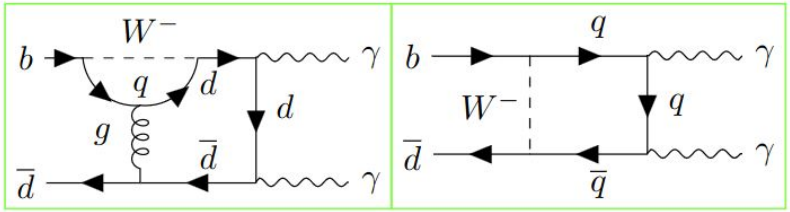
# Double radiative B->$\gamma\gamma$ at Belle + Belle II

- 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 Bs → γγ
- 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 $pb^{-1}$ | $3.9 \times 10^{-5}$ |
| Belle | 104 $fb^{-1}$ | $6.2 \times 10^{-7}$ |
| Babar | 426 $fb^{-1}$ | $3.2 \times 10^{-7}$ |



# B->γγ : Analysis

- Analysis based on combined Belle (362 $fb^{-1}$) + Belle II (711 $fb^{-1}$) 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, π → γγ, and η → γγ decays

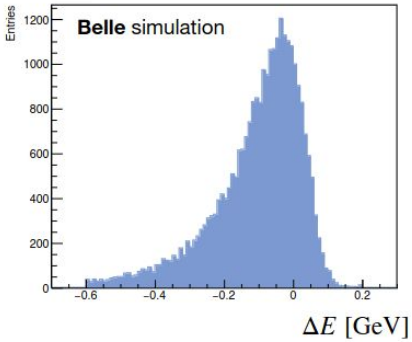
**Fit strategy**

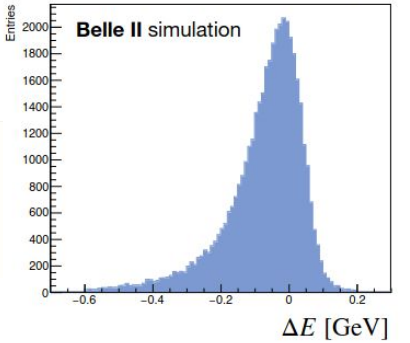
- 3D fit to ΔE, $M_{bc}$ and transformed continuum BDT output ($C'_{BDT}$)
- Use $B^0 \to K^*(892)[K^+\pi^-]\gamma$ as control sample

**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->γγ : Results

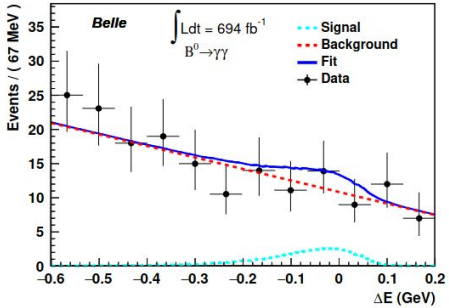
- Combined signal yield = $11.0^{+6.5}_{-5.5}$
- Since no significant signal ⇒ set 90% C.L. limits
- Sensitivity approaching SM prediction

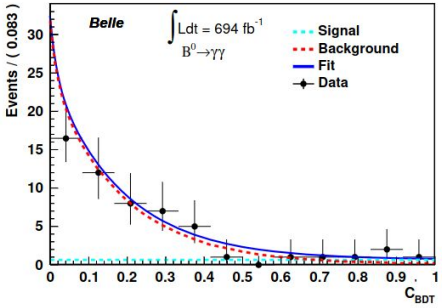
→ **best upper limit with Belle II data**

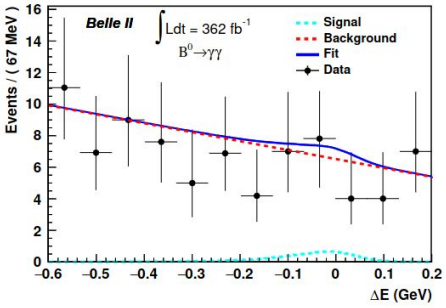
| | $\mathcal{B}(B^0 \to \gamma\gamma)$ | $\mathcal{B}(B^0 \to \gamma\gamma)$ (at 90% CL) |
|---|---|---|
| Belle | $(5.4^{+3.3}_{-2.6} \pm 0.5) \times 10^{-8}$ | $< 9.9 \times 10^{-8}$ |
| Belle II | $(1.7^{+3.7}_{-2.4} \pm 0.3) \times 10^{-8}$ | $< 7.4 \times 10^{-8}$ |
| Combined | $(3.7^{+2.2}_{-1.8}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

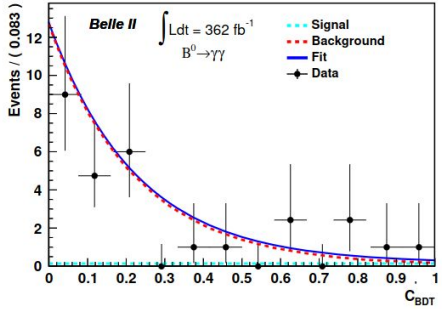
Expected 90 C.L. $4.4 \times 10^{-8}$

- Uncertainties are comparable between Belle and Belle II, despite Belle II having a smaller dataset.
- 5x improvement over previous best UL.




ΔE

$C'_{BDT}$

# 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 (711 fb-1) and Belle II (362 fb-1) data.
- First measurement of $B \to K^*(892)\gamma$ with Belle II data
- Best upper limit for $B \to \gamma\gamma$, rarest decay measured with Belle II data so far