Radiative *B* Meson Decays at Belle and Belle II

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DESY

On behalf of the Belle and Belle II Collaborations

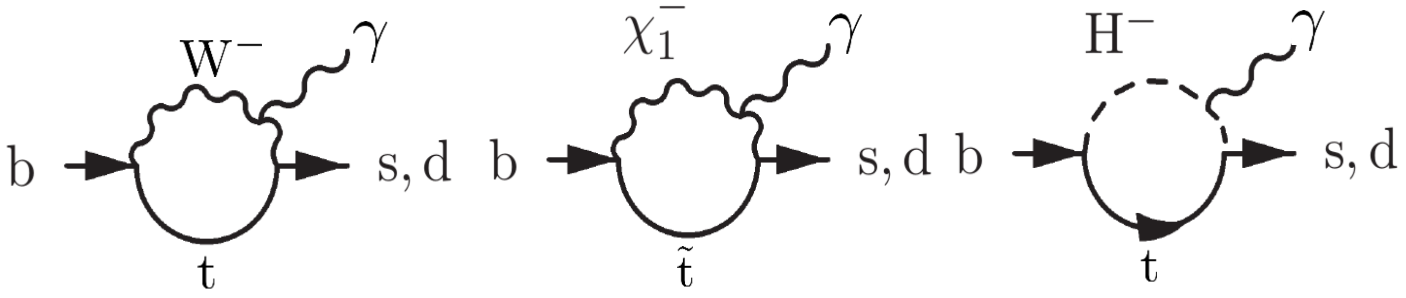
11th International Workshop on the CKM Unitarity Triangle
University of Melbourne, Australia
November 22-26, 2021

Overview

- Belle II BF measurement of $B \to K^*\gamma$ decays.
- Comparison to Belle's $B \to K^*\gamma$ measurement.
- Prospects on time-dependent measurements of $B \to K^*\gamma$ at Belle II.
- Measurement of the direct *CP* asymmetry of inclusive $B \to X_s\gamma$ decays with a lepton tag at Belle.
- Untagged analysis and photon energy spectrum of inclusive $B \to X_s\gamma$ decays at Belle II.
- Prospect of inclusive $B \to X_s\gamma$ measurements at Belle II.

Introduction to Radiative *B* Meson Decays

- Rare heavy flavor decays mediated by radiative penguin transitions provide sensitive probes for physics BSM:



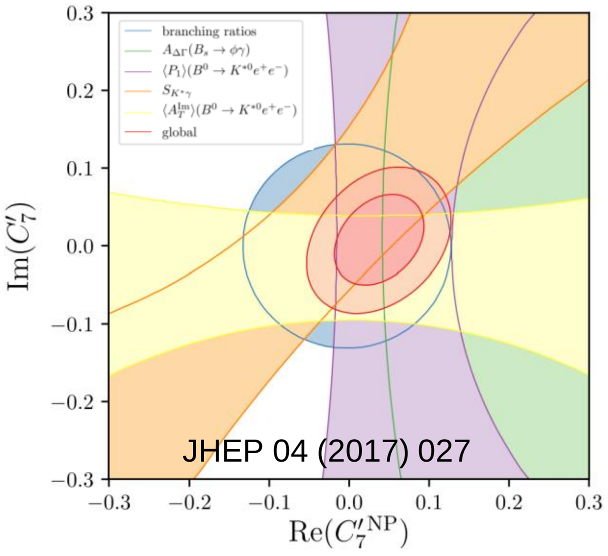
Radiative SM penguin

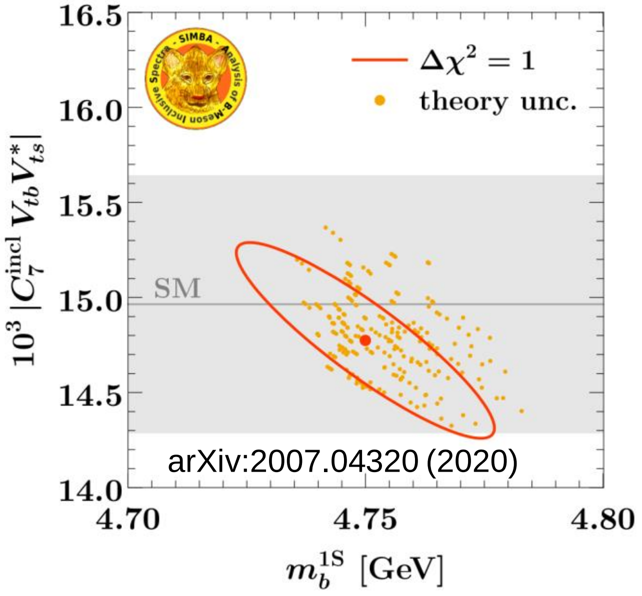
Examples of new physics entering the loops

- Various analysis approaches:
  - Exclusive decays (e.g. $B \to K^*\gamma$)
  - Sum-of-exclusive (adding many modes)
  - Inclusive $B \to X_s\gamma$

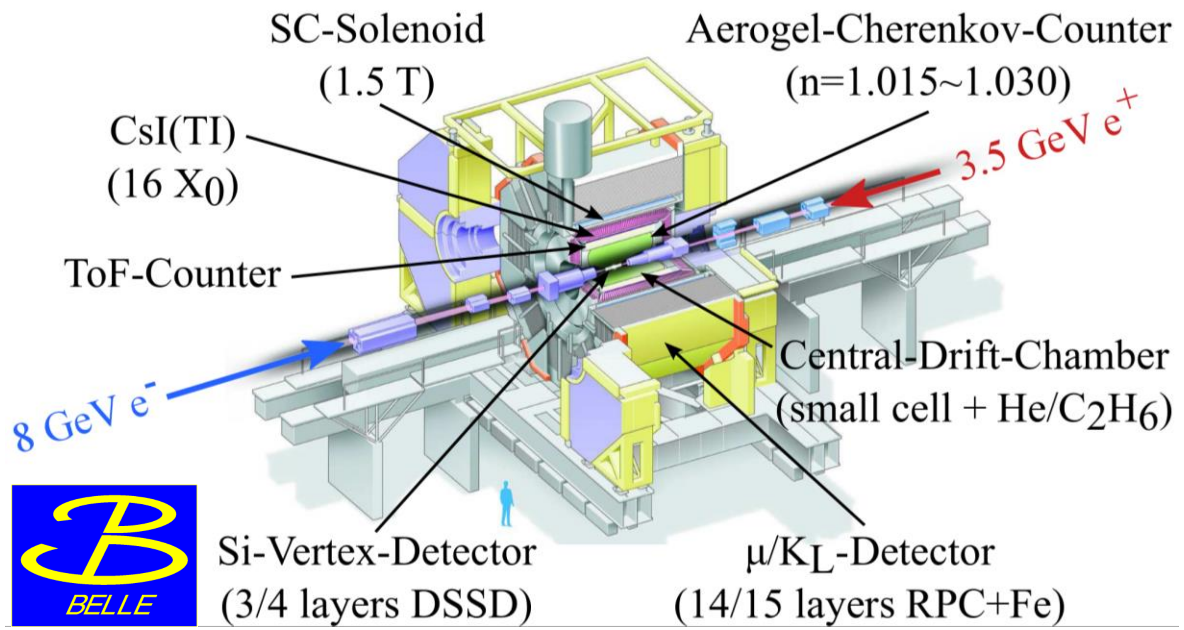
- Sensitive to Wilson coefficients C_7 and C_7'.
- Observables:
  - Branching fractions: $|C_7|^2 + |C_7'|^2$
  - Direct *CP* asymmetries: $\mathrm{Im}(C_7)$
  - Mixing-induced *CP* asymmetries + angular observables: C_7' (Right-handed currents, photon polarization)
  - Isospin asymmetries: Long distance effects.
  - Inclusive photon energy spectra: m_b
  - …

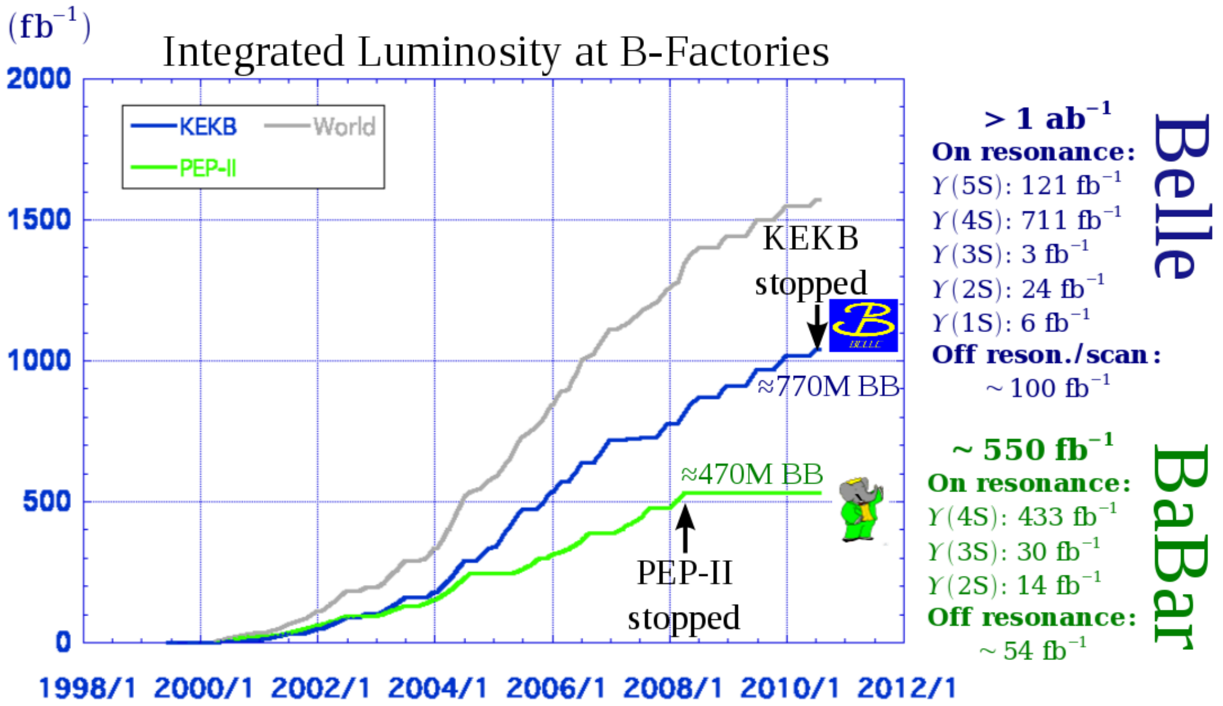
- Global fits:





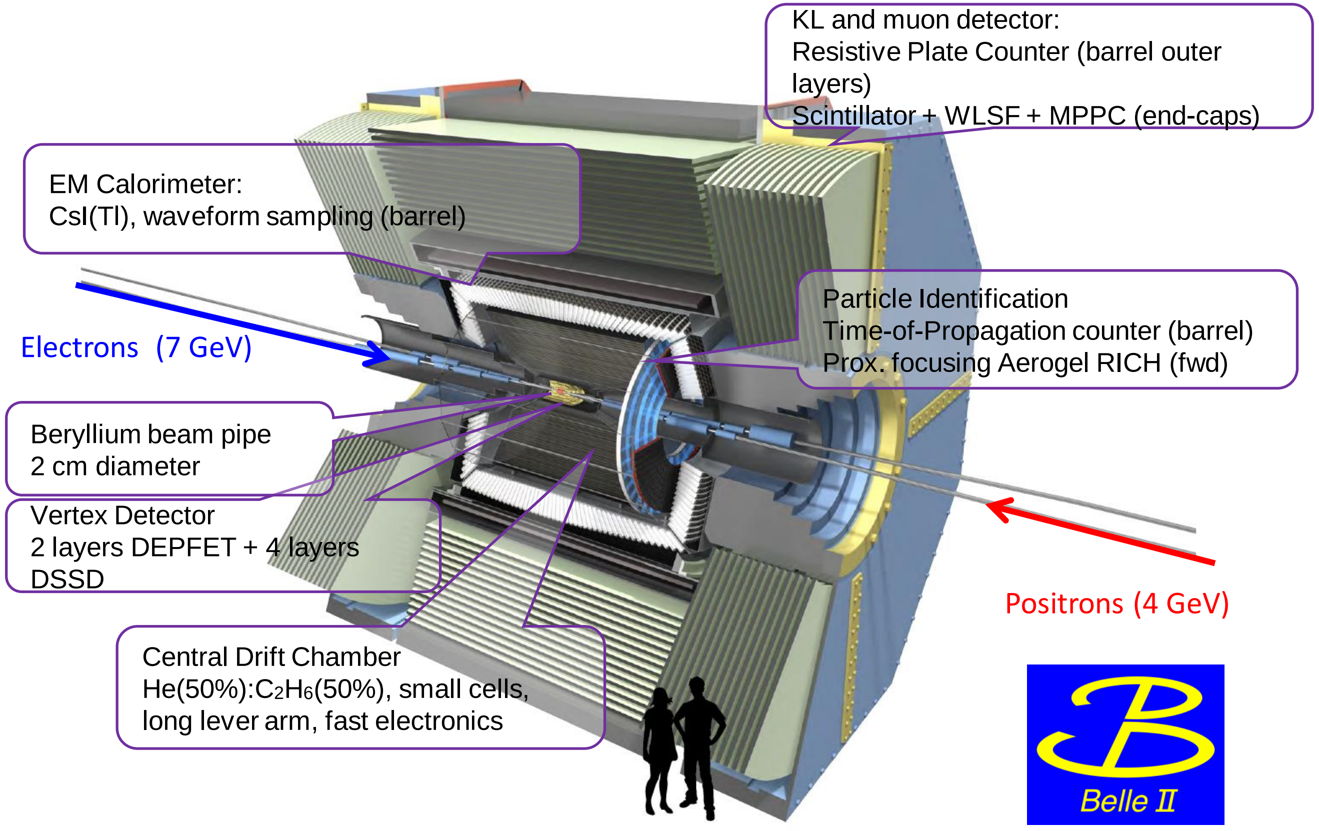
The Belle Experiment



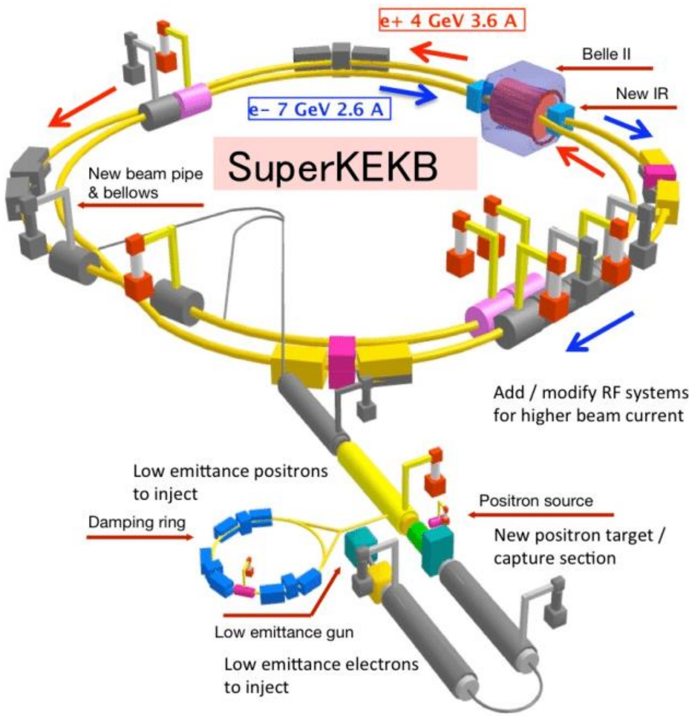


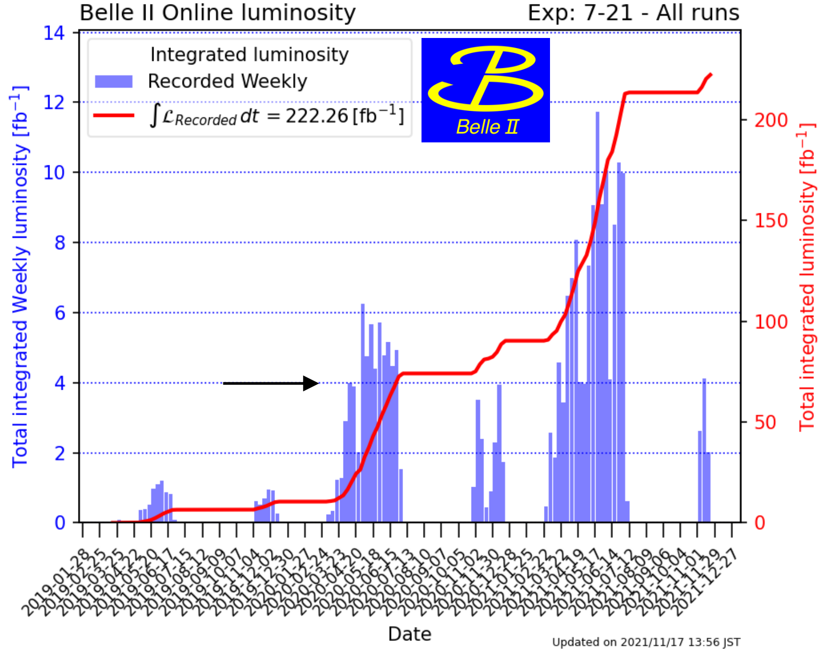
- The KEKB collider and the Belle experiment have been operated as an asymmetric-energy *B* factory until 2010.
- To date, Belle provides the largest data sample of *B* mesons produced in e^+e^- annihilations.
- The KEKB collider and the Belle detector have been upgraded to SuperKEKB and Belle II, that are designed to operate at 40x higher instantaneous luminosity.

The Belle II Experiment



[Belle II TDR, arXiv:1011.0352]





Exclusive Radiative *B* Decays

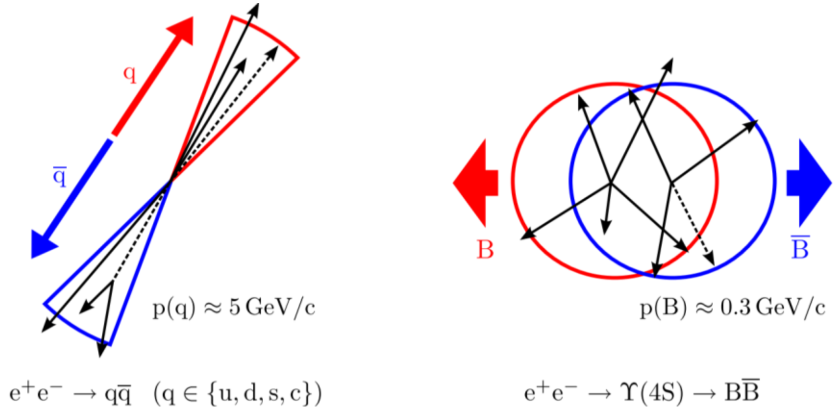
Belle II Measurement of $B \to K^* \gamma$

- Belle II performed a BF measurement of exclusive $B \to K^*\gamma$ decays using 62.8 fb^{-1}. [BELLE2-CONF-PH-2021-014]
- Neutral and charged *B* mesons are reconstructed in 4 decay modes, by combination of K^* mesons with hard γ s.

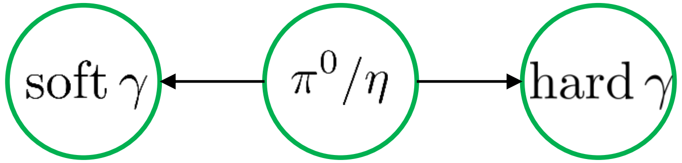
$$B^0 \to K^{*0}\left[K^+\pi^-\right]\gamma \qquad B^+ \to K^{*+}\left[K^+\pi^0\right]\gamma$$

$$B^0 \to K^{*0}\left[K_S^0\pi^0\right]\gamma \qquad B^+ \to K^{*+}\left[K_S^0\pi^+\right]\gamma$$

- The dominant sources of background are $e^+e^- \to q\bar{q}\,(q = u, d, s, c)$ continuum events and photons from the decays of light neutral hadrons like π^0 and η mesons.
  - The continuum background is suppressed using a BDT trained on event shape variables.

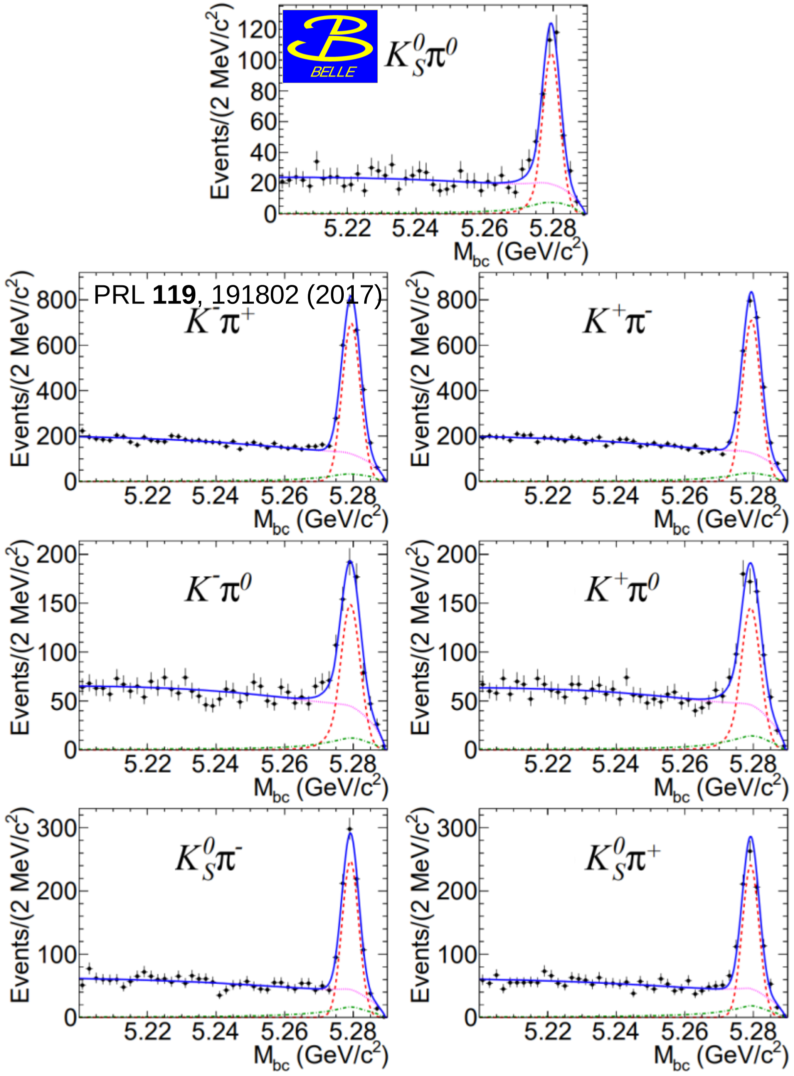


  - The photons from π^0 and η decays are veto-ed by a MVA classifier trained on kinematic variables.



Belle Measurement of $B \to K^* \gamma$

- $B \to K^*\gamma$ measurement by Belle using $772 \times 10^6\ B\bar{B}$.



$$M_{\rm bc} = \sqrt{E^{*2}_{\rm beam} - p^*_B}$$

Mode	$N_S^{\bar{B}}$	N_S^{B}
$B^0 \to K^0_S\pi^0\gamma$	$349 \pm 23 \pm 15$	
$B^0 \to K^+\pi^-\gamma$	$2295 \pm 56 \pm 27$	$2339 \pm 56 \pm 30$
$B^+ \to K^+\pi^0\gamma$	$572 \pm 32 \pm 12$	$562 \pm 31 \pm 11$
$B^+ \to K^0_S\pi^+\gamma$	$745 \pm 32 \pm 8$	$721 \pm 32 \pm 9$

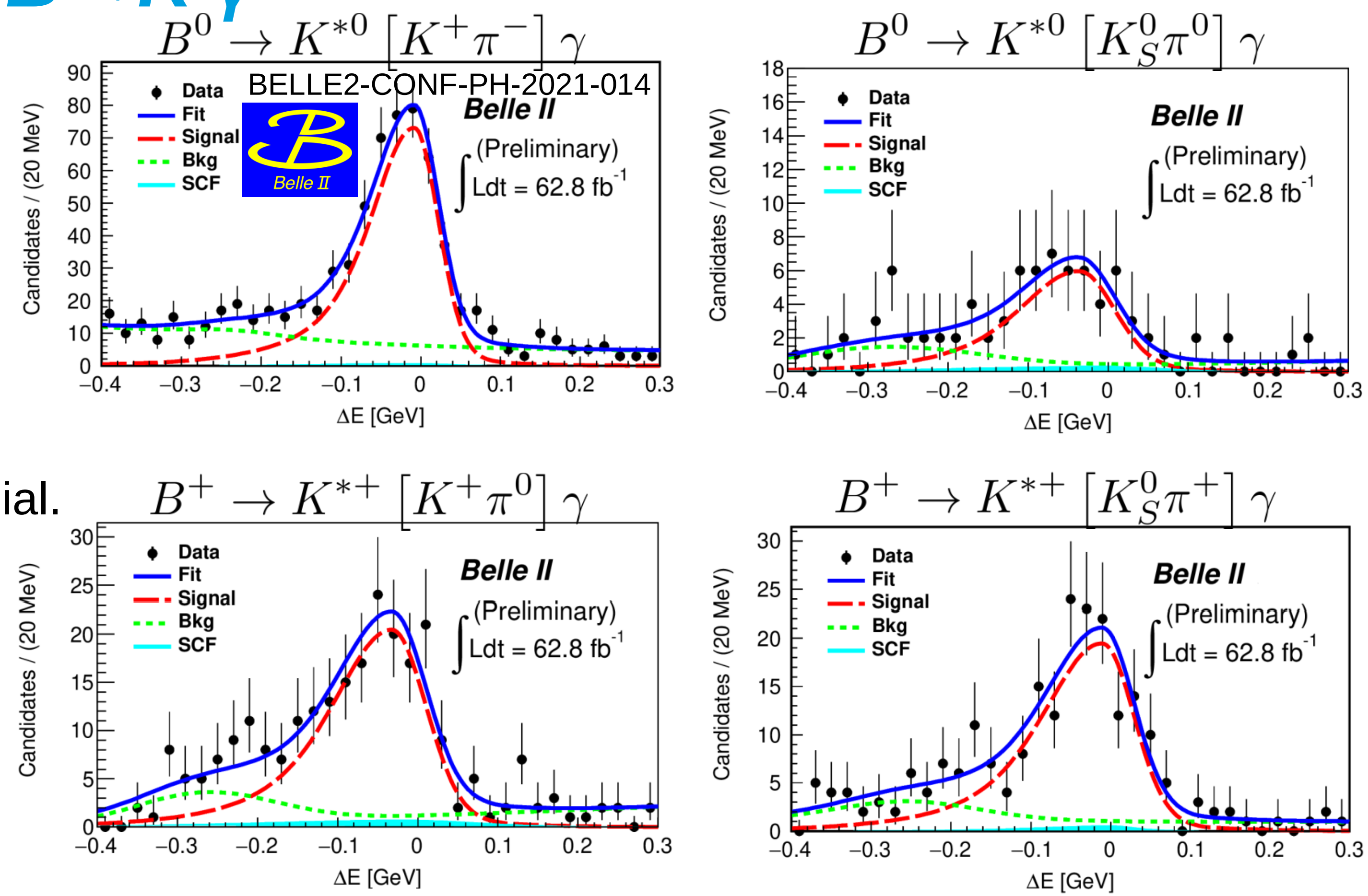
Belle with $772 \times 10^6\ B\bar{B}$ PRL **119**, 191802 (2017)

$$\mathcal{B}(B^0 \to K^{*0}\gamma) = (3.96 \pm 0.07 \pm 0.14) \times 10^{-5},$$
$$\mathcal{B}(B^+ \to K^{*+}\gamma) = (3.76 \pm 0.10 \pm 0.12) \times 10^{-5},$$
$$\mathcal{A}_{CP}(B^0 \to K^{*0}\gamma) = (-1.3 \pm 1.7 \pm 0.4)\%,$$
$$\mathcal{A}_{CP}(B^+ \to K^{*+}\gamma) = (+1.1 \pm 2.3 \pm 0.3)\%,$$
$$\mathcal{A}_{CP}(B \to K^{*}\gamma) = (-0.4 \pm 1.4 \pm 0.3)\%,$$
$$\Delta_{0+} = (+6.2 \pm 1.5 \pm 0.6 \pm 1.2)\%,$$
$$\Delta\mathcal{A}_{CP} = (+2.4 \pm 2.8 \pm 0.5)\%,$$
$$\bar{\mathcal{A}}_{CP} = (-0.1 \pm 1.4 \pm 0.3)\%,$$

- Evidence for isospin violation at the 3.1σ level.
- Belle results still more precise than Belle II to date.

Belle II Measurement of $B \to K^* \gamma$

- The signal is extracted by unbinned ML fits to the ΔE distributions (with $\Delta E = E_B^* - E_{\mathrm{beam}}^*$):
  - Signal: Cruijff + Gaussian functions.
  - Self-cross-feed (SCF): Cruijff.
  - Continuum bkg.: Chebyshev polynomial.
  - Partially reconstructed *B* decays: Gaussian



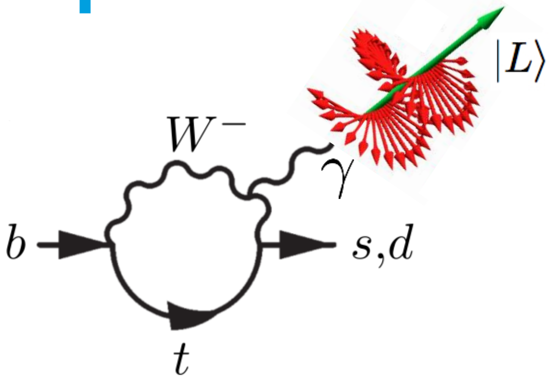
- Belle II using 62.8 fb^{-1}:
- The results agree with the world averages at the 1-2σ level:

Mode	Signal yield	Efficiency (%)	$\mathcal{B}_{\mathrm{meas}}$ $[10^{-5}]$
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	454 ± 28	15.22 ± 0.03	$4.5 \pm 0.3 \pm 0.2$
$B^0 \to K^{*0}[K_S^0\pi^0]\gamma$	50 ± 10	1.73 ± 0.01	$4.4 \pm 0.9 \pm 0.6$
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	169 ± 18	4.84 ± 0.02	$5.0 \pm 0.5 \pm 0.4$
$B^+ \to K^{*+}[K_S^0\pi^+]\gamma$	160 ± 17	4.23 ± 0.02	$5.4 \pm 0.6 \pm 0.4$

[BELLE2-CONF-PH-2021-014]

Prospects of $B \to K^* \gamma$ Time-Dependent Measurements

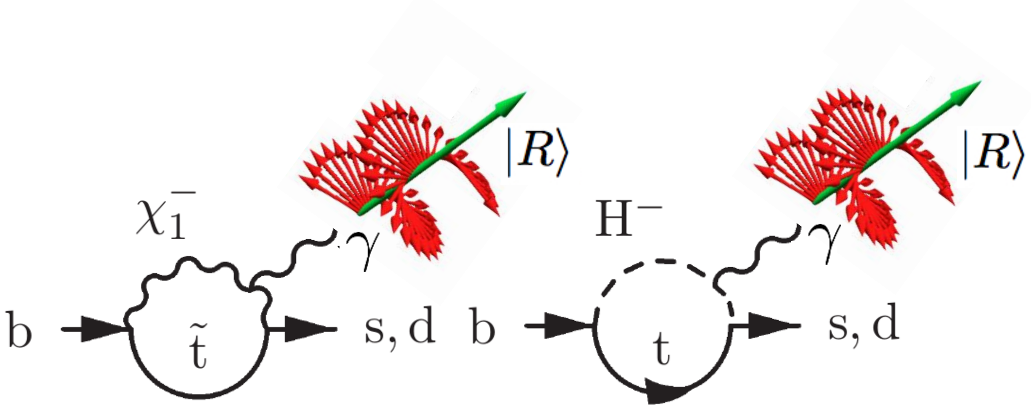
- Radiative penguins $b \to s\gamma$ provide unique probes to the photon polarization:



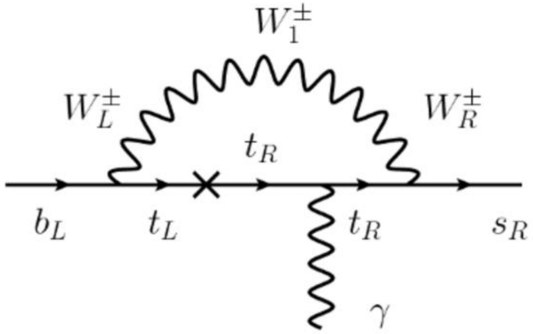
- W^- bosons couple only to left-handed quarks, chirality flip suppressed: $b \to \gamma_L + \frac{m_s}{m_b}\gamma_R$

  → Photon is dominantly left-handed (right-handed) in b ($\bar{b}$) decays.

- New physics effects can give rise to a right-handed photon polarization:



arXiv:0705.4458



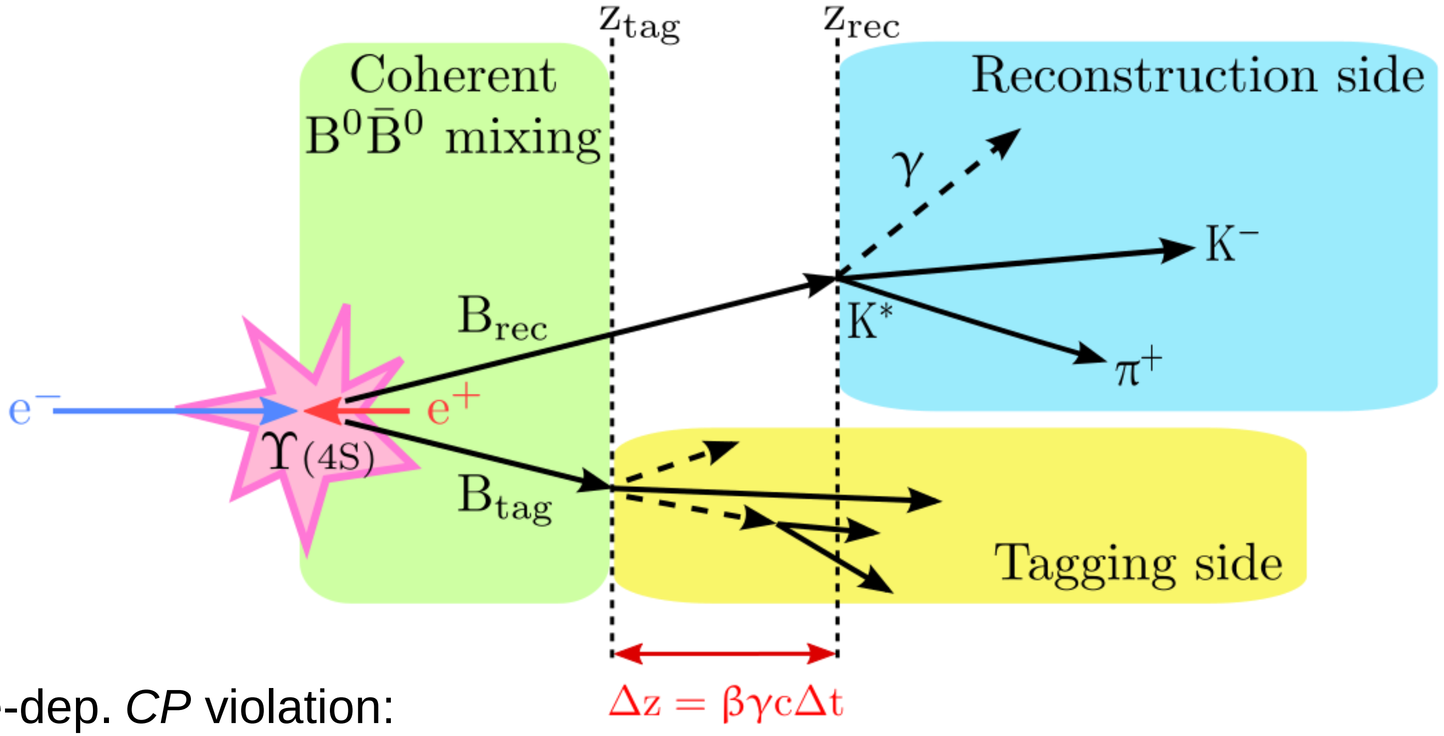
JHEP **12**, 102 (2013)

New heavy particles and flavor couplings (SUSY, extended Higgs sector, …)

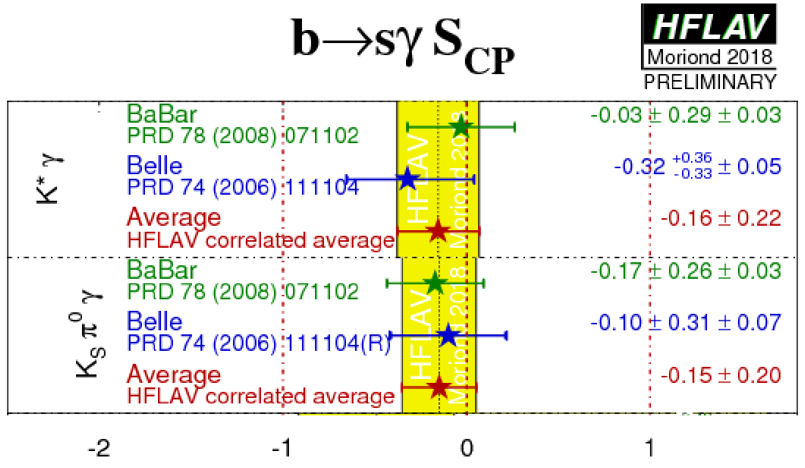
Models restoring the Left↔Right symmetry and right-handed interactions ($W_R^\pm$, V_{CKM}^R).

Prospects of $B \to K^* \gamma$ Time-Dependent Measurements

- Principle of time-dependent measurements:



- Current status on time-dep. *CP* violation:



- Prospects at Belle II:

Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\Delta_{0+}(B \to K^*\gamma)$	2.0%	0.70%	0.53%
$A_{CP}(B^0 \to K^{*0}\gamma)$	1.7%	0.58%	0.21%
$A_{CP}(B^+ \to K^{*+}\gamma)$	2.4%	0.81%	0.29%
$\Delta A_{CP}(B \to K^*\gamma)$	2.9%	0.98%	0.36%
$S_{K^{*0}\gamma}$	0.29	0.090	0.030

[The Belle II Physics Book, BELLE2-PAPER-2018-001]

Inclusive Radiative *B* Decays

Inclusive Measurements

Several tagging techniques are possible at the *B* factory experiments for inclusive analyses.

- Important effects:

← Tagging efficiencies, achievable signal yields

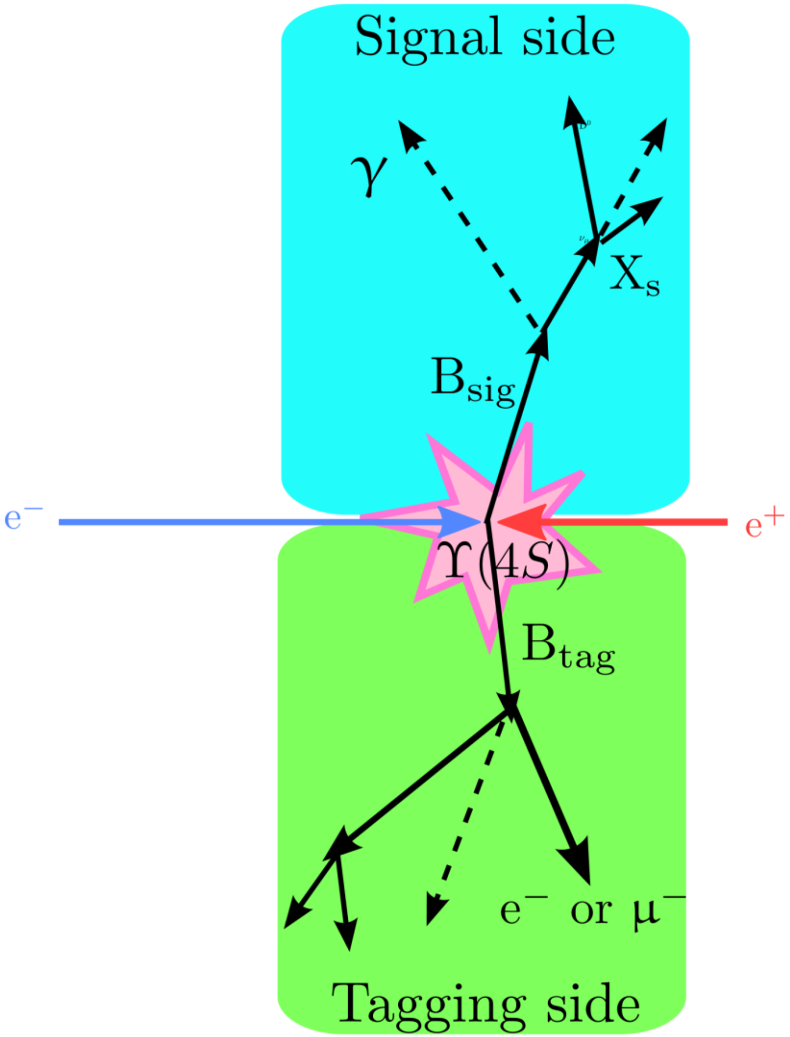
Purities of the tagged samples →

Amount of accessible physics information →

Fully inclusive, no tagging	Lepton tagging	Semileptonic tagging	Hadronic tagging
$B \to \text{anything}$	$B \to lX$	$B \to \bar{D}^{(*)} l \nu \text{n}\pi$	$B \to \text{hadrons}$, e.g. $B \to \bar{D}^{(*)}\text{n}\pi$
$\epsilon \approx \mathcal{O}\,(10\%)$	$\epsilon \approx \mathcal{O}\,(1\%)$	$\epsilon \approx \mathcal{O}\,(0.2\%)$	$\epsilon \approx \mathcal{O}\,(0.1\%)$
PRL **93**, 061803 (2004) BELLE2-NOTE-PL-2021-004	PRL **103**, 241801 (2009) PRL **114**, 151601 (2015)		

Measurement of the Direct *CP* Asymmetry w/ a Lepton Tag by Belle

- Belle performed a measurement of the direct *CP* asymmetry in $\bar{B} \to X_{s+d}\gamma$ decays with a lepton tag.



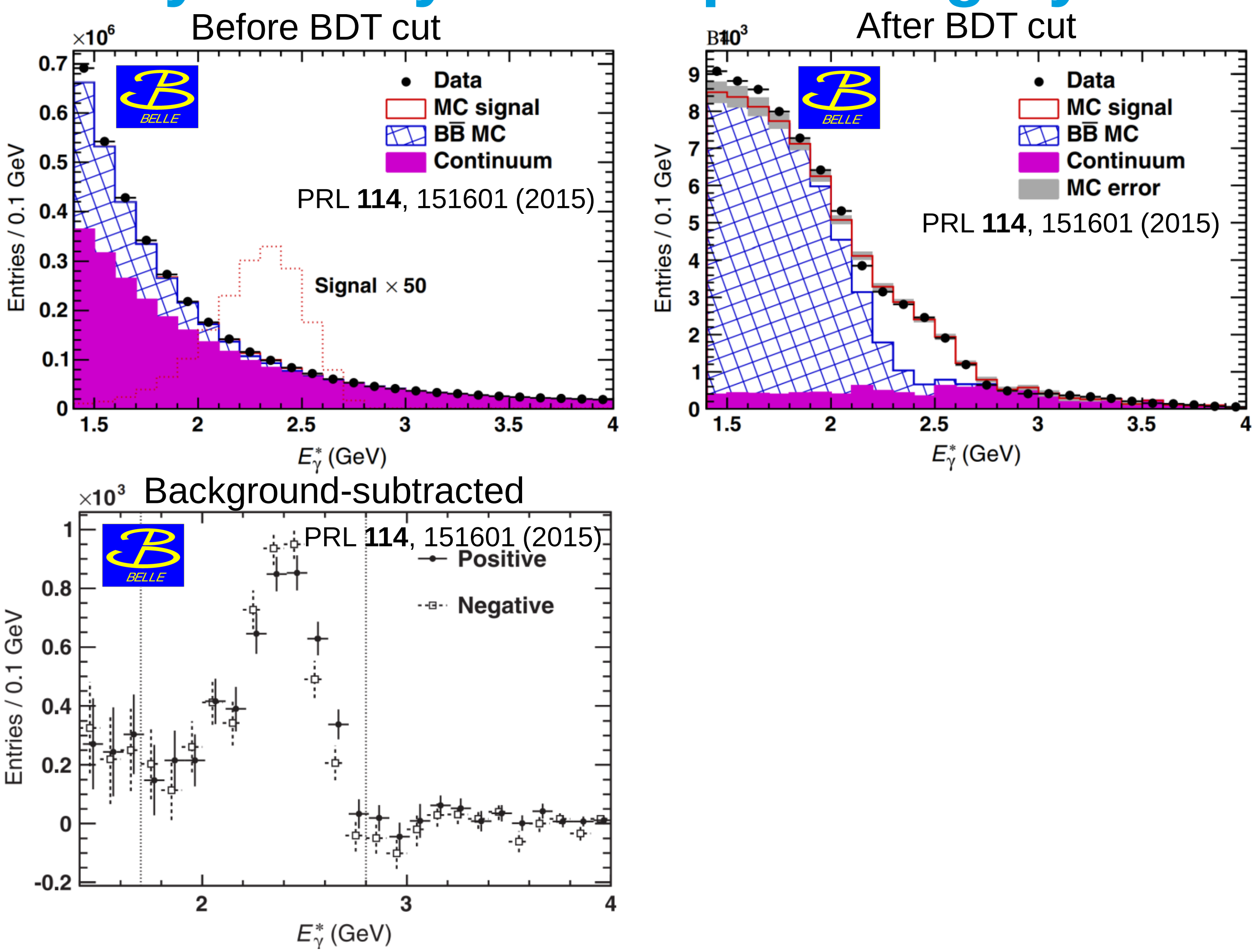
- Reconstruct only one high-energetic photon on the signal side.
- From the tagging side, reconstruct only the high-momentum lepton from the second *B* meson from the $\Upsilon(4S)$ decay.
- The *B* flavor can be inferred from the charge of the lepton.
- Definition of the direct *CP* asymmetry:

$$\mathcal{A}_{CP}(\bar{B} \to X_{s+d}\gamma) \equiv \frac{\Gamma(\bar{B} \to X_{s+d}\gamma) - \Gamma(B \to X_{\bar{s}+\bar{d}}\gamma)}{\Gamma(\bar{B} \to X_{s+d}\gamma) + \Gamma(B \to X_{\bar{s}+\bar{d}}\gamma)}$$

- In the SM, the direct *CP* asymmetry is predicted to vanish.
  [A.L. Kagan and M. Neubert, PRD **58**, 094012 (1998)]
- In BSM models, the direct *CP* asymmetry could be as large as 10%.
  [T. Hurth, E. Lunghi and W. Porod, Nucl. Phys. **B704**, 56 (2005)]

Measurement of the Direct *CP* Asymmetry w/ a Lepton Tag by Belle

- The dominant background originates from $e^+e^- \to q\bar{q}\,(q = u, d, s, c)$ continuum events and is suppressed by a BDT classifier trained on event shape variables:

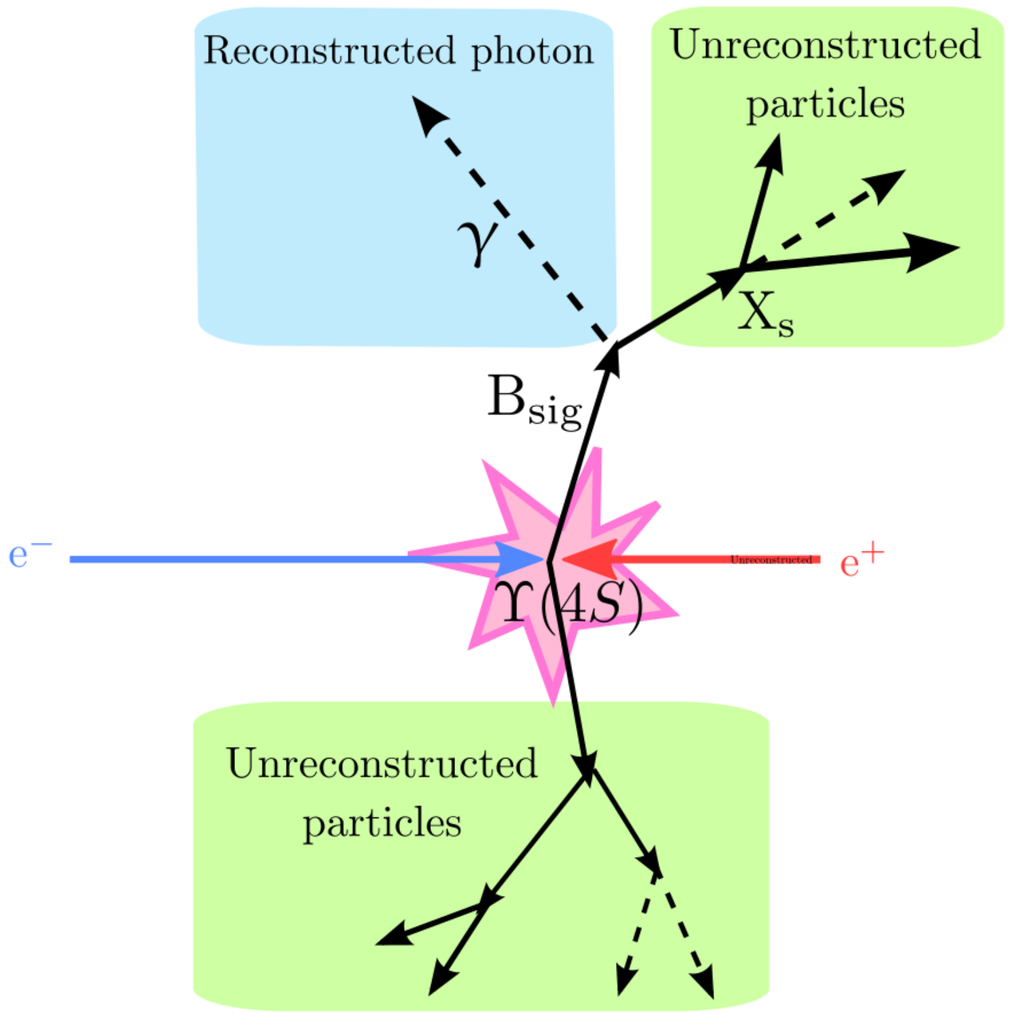


- The $\bar{B} \to X_{s+d}\gamma$ signal is obtained by subtracting the continuum and $B\bar{B}$ contributions:

- The result using $772 \times 10^6\ B\bar{B}$ is: $\boxed{\mathcal{A}_{CP}(\bar{B} \to X_{s+d}\gamma) = (2.2 \pm 3.9 \pm 0.9)\%}$ PRL **114**, 151601 (2015)

Observation of Inclusive $B \to X_s\gamma$ Decays by Belle II

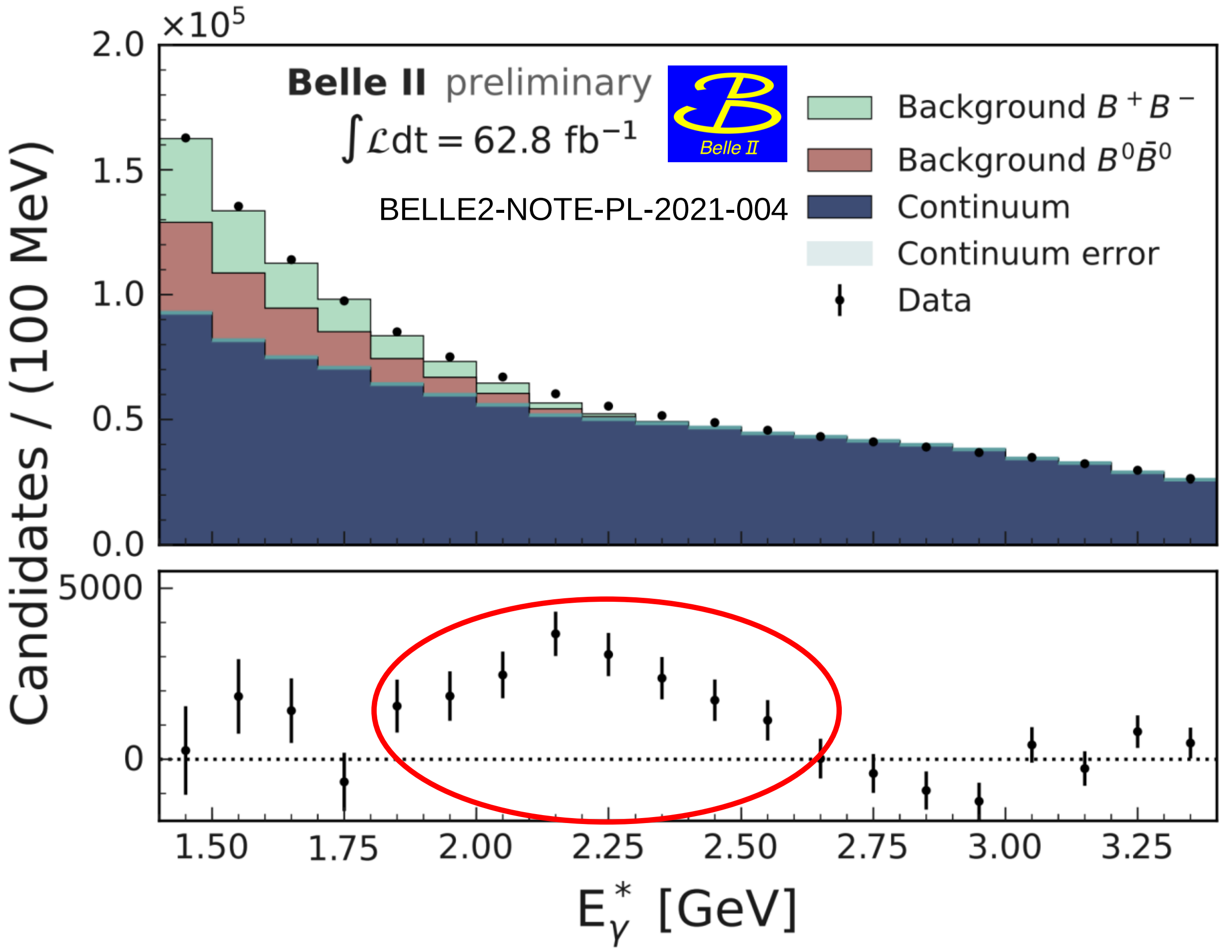
- Belle II performed a measurement of the inclusive $B \to X_s\gamma$ photon energy spectrum without any tagging.



- Reconstruct only the hard photon from the $B \to X_s\gamma$ decay. In the reconstruction, ignore any other particles in the event.
- Veto photons from light neutral hadrons ($\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$).
- Suppress continuum background using global event shape variables.
- The remaining continuum background is subtracted using off-resonance data.
- Estimate/subtract the $B\bar{B}$ background from MC simulations.
- Determine the photon energy spectrum.

Observation of Inclusive $B \to X_s \gamma$ Decays by Belle II

- Belle II with 62.8 fb^{-1}:



- An excess of events is seen in the region expected for photons from $B \to X_s \gamma$ decays.

Prospects for Inclusive $B \to X_s \gamma$ at Belle II

- Prospects:

Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B \to X_s \gamma)^{\text{lep-tag}}_{\text{inc}}$	5.3%	3.9%	3.2%
$\mathrm{Br}(B \to X_s \gamma)^{\text{had-tag}}_{\text{inc}}$	13%	7.0%	4.2%
$\mathrm{Br}(B \to X_s \gamma)_{\text{sum-of-ex}}$	10.5%	7.3%	5.7%
$\Delta_{0+}(B \to X_s \gamma)_{\text{sum-of-ex}}$	2.1%	0.81%	0.63%
$\Delta_{0+}(B \to X_{s+d} \gamma)^{\text{had-tag}}_{\text{inc}}$	9.0%	2.6%	0.85%
$A_{CP}(B \to X_s \gamma)_{\text{sum-of-ex}}$	1.3%	0.52%	0.19%
$A_{CP}(B^0 \to X_s^0 \gamma)_{\text{sum-of-ex}}$	1.8%	0.72%	0.26%
$A_{CP}(B^+ \to X_s^+ \gamma)_{\text{sum-of-ex}}$	1.8%	0.69%	0.25%
$A_{CP}(B \to X_{s+d} \gamma)^{\text{lep-tag}}_{\text{inc}}$	4.0%	1.5%	0.48%
$A_{CP}(B \to X_{s+d} \gamma)^{\text{had-tag}}_{\text{inc}}$	8.0%	2.2%	0.70%
$\Delta A_{CP}(B \to X_s \gamma)_{\text{sum-of-ex}}$	2.5%	0.98%	0.30%
$\Delta A_{CP}(B \to X_{s+d} \gamma)^{\text{had-tag}}_{\text{inc}}$	16%	4.3%	1.3%

[Belle II Physics Book, arXiv:1808.10567]

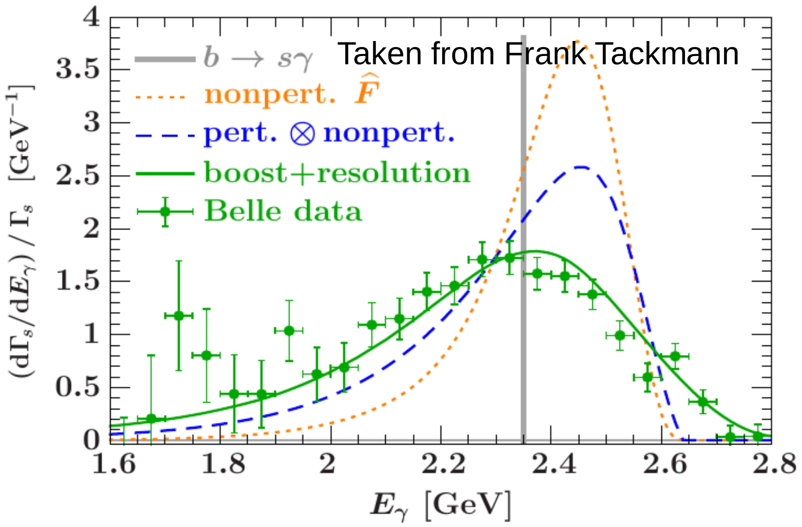
Summary

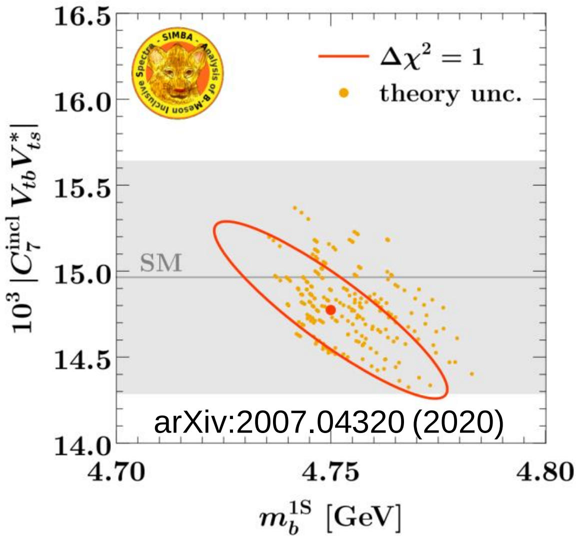
- Radiative B meson decays are very sensitive to physics BSM (2HDM, SUSY, Left$\leftrightarrow$Right symmetric models, …)
- All results are in agreement with the SM.
- Belle II started producing physics results. First results on exclusive and inclusive $b \to s\gamma$ mediated decays have been presented.

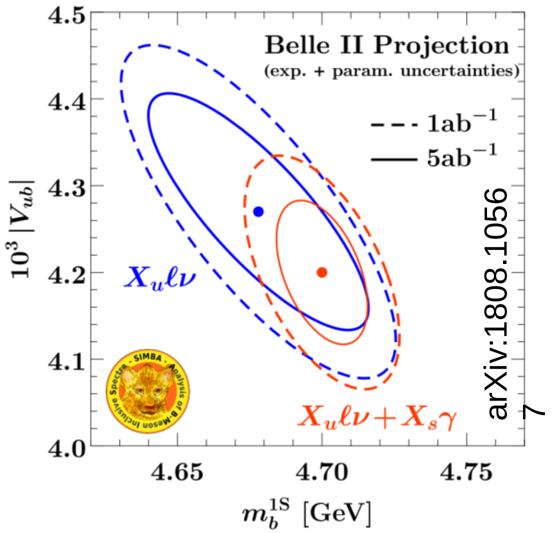
Supplementary Slides

SIMBA

- Sensitive observables are the inclusive $B \to X_s\gamma$ decay rate and the corresponding photon energy spectra.







- Inclusive $B \to X_s\gamma$ measurements are as well important for the estimation of SM parameters like m_b or $|V_{ub}|$.