Rare decays at Belle & Belle II

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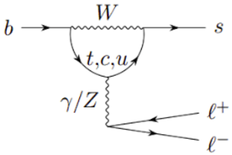
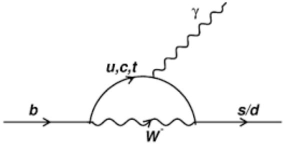
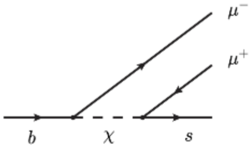
- Rare decays involving $b \to s(d)$ quark level transitions are FCNC processes
- These decays are forbidden at tree level in the SM and occur through electroweak loop diagrams



$b \to s\ell\ell$ loop



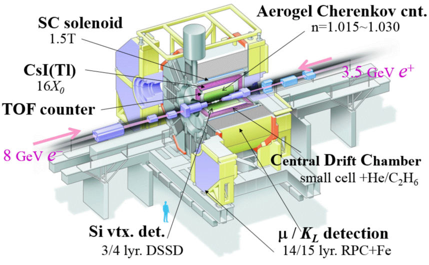
$b \to s\gamma$ loop

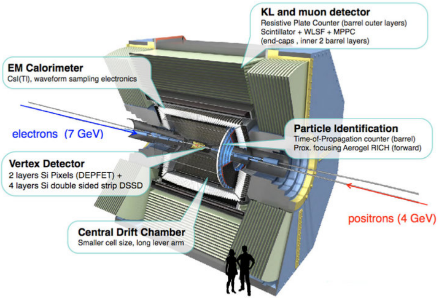


NP contribution

- Resulting B decays are rare having $\mathcal{B}_{\mathrm{SM}} = \mathcal{O}(10^{-7} - 10^{-4})$
- Amplitude from the NP contribution can interfere with the SM amplitude, altering physical observables like:
  lepton-flavor-universality ratios, isospin asymmetries, forward-backward asymmetries, total or differential branching fractions, angular observables, etc
- Many opportunities to probe the SM and explore the BSM physics

Belle & Belle II detectors

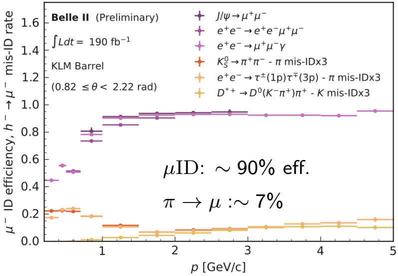


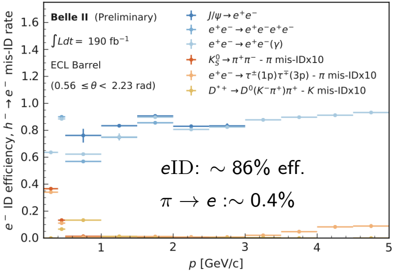


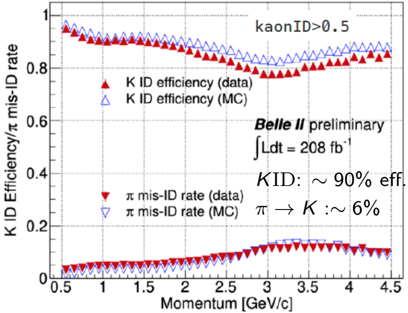
- Asymmetric e^+ (3.5 GeV) - e^- (8 GeV) collider
- Collected 711 fb^{-1} at $\Upsilon(4S)$ resonance
- Data taken from 1999 to 2010
- Collected 1 ab^{-1} of data

- Asymmetric e^+ (4 GeV) - e^- (7 GeV) collider
- So far collected 362 fb^{-1} at $\Upsilon(4S)$ resonance
- Data taken between 2019 - 2022
- Recorded 424 fb^{-1} of data: $\sim$ equivalent to BaBar and 1/2 of Belle data sample
- Aims to collect multi-ab^{-1} of data

Advantages of Belle & Belle II for rare decays

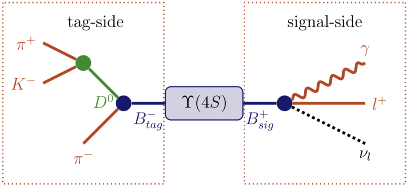


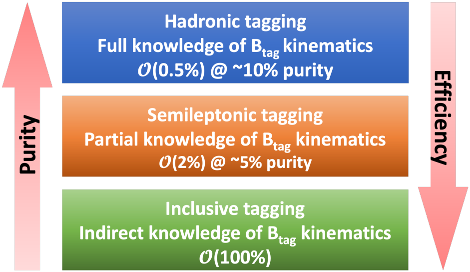




- Low background environment
- Good particle identification and performance
- PID performance of Belle II is similar to Belle
- High photon detection efficiency

Advantages of Belle & Belle II for rare decays





- Good hermiticity: useful for the channels with missing energy
- B-tag reconstruction: Reconstruction of tag side B allows to infer the properties of the signal-side with missing energy, and also good control over background
- Full Event Interpretation (FEI) [Comput. Softw. Big Sci. 3 (2019) 6] algorithm using machine learning for Hadronic/semileptonic $B_{\rm tag}$ has high purity but low efficiency
- Inclusive tagging benefits has higher background contamination but higher efficiency

Outline

- **Belle (711 fb^{-1})**
  - $B^+ \to K^+\tau\ell$, $\ell = e$ or μ **[PRL 130 (2023) 261802]**
  - $B^0 \to K^{*0}\tau\tau$ **[PRD 108 (2023) L011102]**
- **Belle II (189 fb^{-1})**
  - Towards R_{K^*}: $B \to K^*\ell\ell$, $\ell\ell = ee$ or $\mu\mu$ **[arXiv:2206.05946]**
  - Inclusive $B \to X_s\gamma$ **[arXiv:2210.10220]**
- **Belle & Belle II (711 fb^{-1} & 362 fb^{-1})**
  - Exclusive $B \to \rho\gamma$ **[EPS HEP 2023]**

- Also see Roberta's talk on rare $B^+ \to K^+\nu\bar{\nu}$ decay from Belle II **[arXiv:2311.14647]**

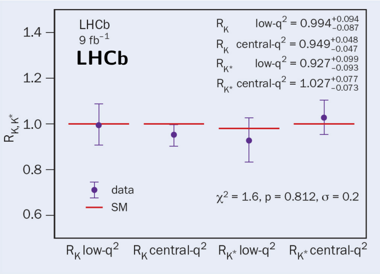
Let's start with Penguin decays...

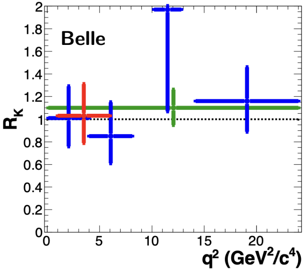
Introduction on $b \to s\ell\ell$ decays

- SM $\mathcal{B}$ for $B \to K^{(*)}\ell\ell$ decay is $\mathcal{O}(10^{-7})$
- Test of LFU: $R_{K^{(*)}}$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$$

- According to SM this ratio should be 1 [EPJC **76**, 440 (2016)], as the coupling of lepton to gauge boson is independent of flavor





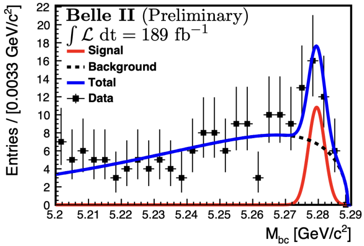
- $R_{K^{(*)}}$ results from LHCb [PRL 131 (2023) 051803] and Belle [JHEP 03 (2021) 105, PRL 126 (2021) 161801] are consistent with SM expectations
- LFU can uniquely tested using Belle II data

Towards R_{K^*}: $B \to K^* \ell\ell$ at Belle II [arXiv:2206.05946]

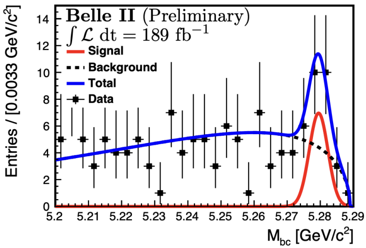
- Decay modes reconstructed: $B^0 \to K^{*0}(K^+\pi^-)\ell\ell$ and $B^+ \to K^{*+}(K^+\pi^0, K^0_S\pi^+)\ell\ell$
- Background from continuum and $B\overline{B}$ is suppressed using event shape, vertex quality, and kinematic variables in a BDT
- Performed 2D unbinned ML fit in $M_{\rm bc}$ and ΔE to extract the signal yield

$$M_{\rm bc} = \sqrt{(E_{\rm beam}/c^2)^2 - (p_B/c)^2},\ \Delta E = E_B - E_{\rm beam}$$

$B \to K^* \mu\mu$



$B \to K^* ee$

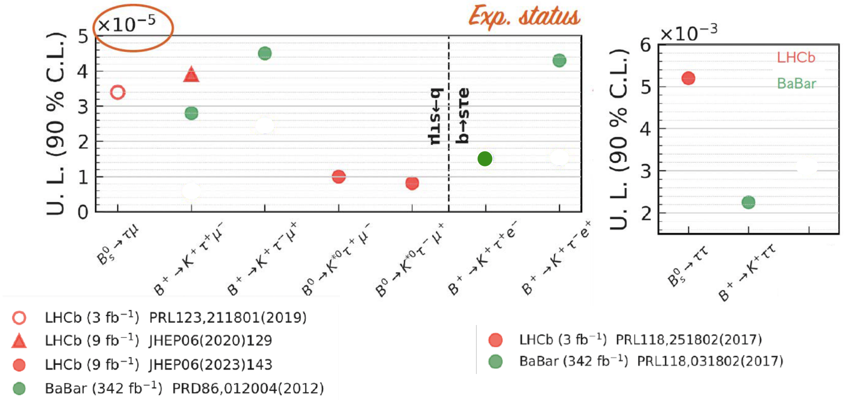


$$\mathcal{B}(B \to K^*(892)\mu^+\mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*(892)e^+e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*(892)\ell^+\ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6},$$

- Similar performances for electrons and muons
- Results are compatible with world averages within the uncertainties

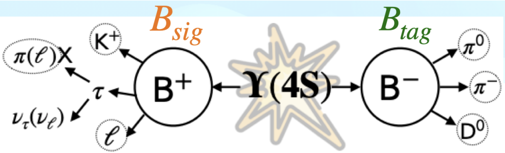
- Observation of these decays is the first step towards LFU test (R_{K^*}) at Belle II

- $b \to s\tau\ell$ and $b \to s\tau\tau$ are expected to be more sensitive to NP which has a coupling proportional to lepton or only couples to the third generation
- According to theory [PRL 114 (2015) 091801]: violation of LFU predict LFV processes



- SM prediction is $\mathcal{O}(10^{-7})$ [PRL 120 (2018) 181802] for the $\tau\tau$ final state
- $b \to s\tau\tau(\ell)$ are less studied compared to their $e - \mu$ counterparts
- Experimentally challenging due to two or more neutrinos in the final state

- FEI Hadronic B-tagging ($B_{\rm tag}$)



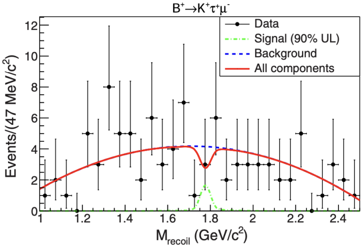
- Signal side: $B \to K\tau\ell$, $\tau \to e\nu\overline{\nu}, \mu\nu\overline{\nu}, \pi\nu$ ($\tau \to \rho\nu$ mode contribute $\sim$ 50% to $\tau \to \pi\nu$, because of large $\mathcal{B}$), combined 46% $\mathcal{B}$

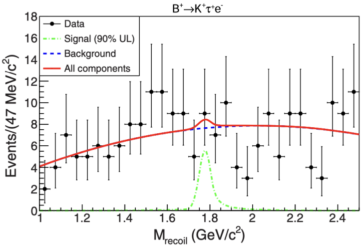
- Dominant background from semileptonic D decays $B^+ \to \overline{D^0}(\to K^+\ell^-\overline{\nu_\ell})X^+$ or semileptonic B decays $B^+ \to \overline{D^0}(\to K^+X^-)X\ell^+\nu_\ell$, are vetoed in $M_{K^+\ell^-}$ around D^0 mass region

- Background is suppressed using BDTs having kinematic and topology of the $B_{\rm sig}$ and ECL energy from extra clusters (not associated with $B_{\rm sig}$ or $B_{\rm tag}$)

- Signal yield is extracted by unbinned extended ML fit to $M_{\rm recoil}$: should peak at the mass of the τ lepton

$$M_{\rm recoil} = \sqrt{m_B^2 + m_{K\ell}^2 - 2(E^*_{\rm beam}E^*_{K\ell} + p^*_{B_{tag}}p^*_{K\ell}\cos\theta)},$$
$$\text{here, } p^*_{K\ell} = p^*_K + p^*_\ell$$

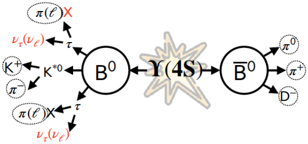




- Four channels:
  2 charge configurations $\times$ 2 flavours

channel	$N_{\rm sig}$	$\mathcal{B}^{\rm UL}$ (10^{-5})
$K^+\tau^+\mu^-$	-2.1 ± 2.9	< 0.59
$K^+\tau^+e^-$	1.5 ± 5.5	< 1.51
$K^+\tau^-\mu^+$	2.3 ± 4.1	< 2.45
$K^+\tau^-e^+$	-1.1 ± 7.4	< 1.53

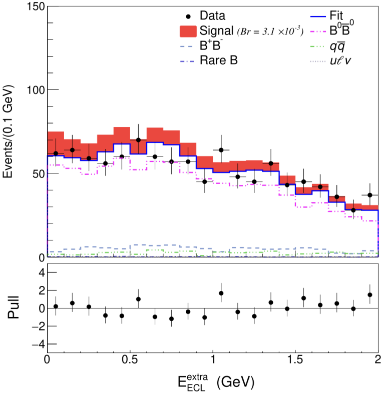
- World's best limits for $B^+ \to K^+\tau\ell$ decays



- FEI Hadronic B-tagging (B_{tag})
- $\tau^- \to e^-\overline{\nu_e}\nu_\tau, \mu^-\overline{\nu_\mu}\nu_\tau, \pi^-\nu_\tau$
- 6 different decay modes: $K^{*0}e^+e^-$, $K^{*0}e^\mp\mu^\pm$, $K^{*0}\mu^+\mu^-$, $K^{*0}e^\mp\pi^\pm$, $K^{*0}\mu^\mp\pi^\pm$, $K^{*0}\pi^+\pi^-$
- $B^0 \to D^{(*)-}(K^{*0}\pi^-(\pi^0))\ell^+\nu_\ell$ background for $K^{*0}\pi^+\pi^-$ and $K^{*0}\ell^\pm\pi^\mp$ are rejected by $M_{K^{*0}\pi^-} \notin [1.84 - 1.94]$ GeV$/c^2$
- Signal yield is extracted by binned extended ML fit to $E_{\text{ECL}}^{\text{extra}}$, sum of the energy from cluster not associated with B_{sig} or B_{tag}, with a bin width of 0.1 GeV
- Fit result on data

$$N_{\text{sig}} = -4.9 \pm 6.0$$
$$\mathcal{B}^{\text{UL}} < 3.1 \times 10^{-3} \text{ at 90\% CL}$$

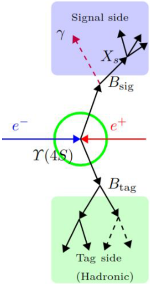
- First experimental limit on the decay $B^0 \to K^{*0}\tau\tau$

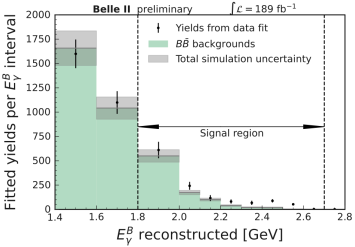


Radiative decays ...

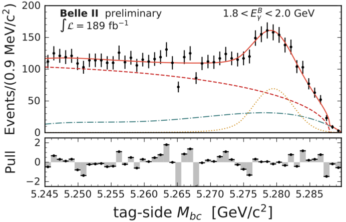
Inclusive $B \to X_s\gamma$ at Belle II [arXiv:2210.10220]

- $B \to X_s\gamma$ is sensitive to non-SM effects [EPJC 77 (2017) 201]
- Photon-energy spectrum offers access to the mass of the b quark and the function describing its motion inside the B meson [PRL 127 (2021) 102001, EPJC 77 (2017) 201]
- Measurement is possible in clean environment of B factories
- Fully inclusive measurement using hadronic B_{tag}
- Knowledge of kinematic properties of B_{tag} allows to access photon energy in the B_{sig} frame, E_γ^B
- Signal yield is extracted by fit to tag-side M_{bc} in bins of E_γ^B (8 bins with $E_\gamma^B > 1.8$ GeV)
- $b \to d\gamma$ contribution accounted for by assuming same shape and efficiency as signal but suppressed by a factor $|V_{td}/V_{ts}|^2 \approx 4.3\%$

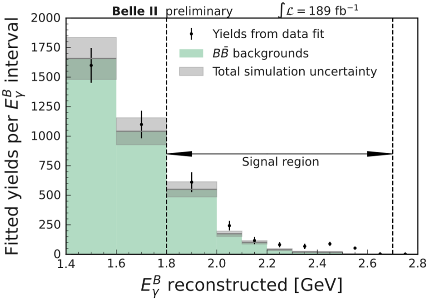




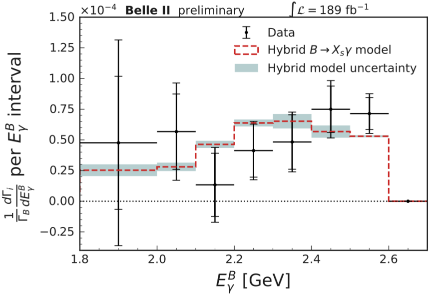
continuum, combinatorial, correctly rec. B



Inclusive $B \to X_s\gamma$ at Belle II [arXiv:2210.10220]



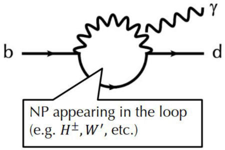
- Background subtracted distribution



E_γ^B (GeV) threshold	$\mathcal{B}$ (10^{-4})
1.8	$3.54 \pm 0.78 \pm 0.83$
2.0	$3.06 \pm 0.56 \pm 0.47$
2.1	$2.49 \pm 0.46 \pm 0.35$

- Provided partial $\mathcal{B}$ in bins of E_γ^B
- Results are consistent with the SM and world averages HFLAV (all tagging approached) $=$ $(3.49 \pm 0.19) \times 10^{-4}$
- Competitive with BaBar [PRD 77 (2008) 051103] result with hadronic tag method, on similar statistics

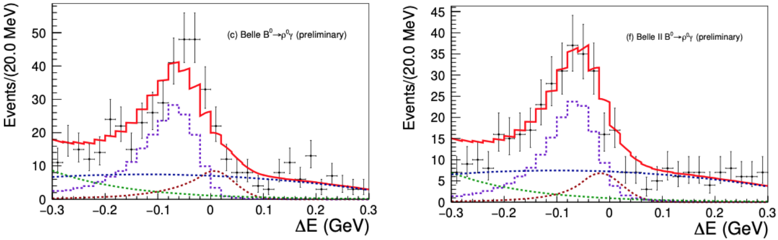
- $b \to d\gamma$ transition have one order of magnitude lower $\mathcal{B}$ compared to $b \to s\gamma$ processes and can be affected by NP independently



- $B \to \rho\gamma$ decay has been observed by the Belle [PRL 101 (2008) 200401] and BaBar [PRD 78 (2008) 112001]
- World average of isospin asymmetry lies about 2σ away from the SM expectation
- Reconstructed $\rho^0 \to \pi^+\pi^-$ and $\rho^+ \to \pi^+\pi^0$ for B^0 and B^+
- Experimentally challenging due to the presence of $B \to K^*\gamma$ background
- $M_{K\pi}$: invariant mass of ρ recalculated based on hypothesis that one of the π^+ is a K^+
- $M_{K\pi}$ helps separate $K^*\gamma$ background better compared to $M_{\pi\pi}$

- Simultaneous 3D fitting on M_{bc}, ΔE, and $M_{K\pi}$ with extended unbinned ML to 6 independent data sets: B^+, B^-, and B^0 in Belle and Belle II

signal + bkg, signal, continuum bkg, generic B, $B \to K^*\gamma$



$$\mathcal{B}(B^+ \to \rho^+\gamma) = (12.85^{+2.02+1.38}_{-1.92-1.13}) \times 10^{-7}$$

$$\mathcal{B}(B^0 \to \rho^0\gamma) = (7.45^{+1.33+0.97}_{-1.27-0.79}) \times 10^{-7}$$

$$A_{CP}(B^+ \to \rho^+\gamma) = (-7.1^{+15.3+1.4}_{-15.2-1.3})\%$$

$$A_I(B \to \rho\gamma) = (14.2^{+11.0+6.6+6.0}_{-11.7-6.4-6.5})$$

- Measured the $\mathcal{B}$, CP-asymmetry, and isospin asymmetry of $B \to \rho\gamma$ decays using Belle and Belle II combined data
- Improved isospin asymmetry A_I results, which is consistent with the SM prediction with 0.6σ CL
- Most precise measurement of observables for $B \to \rho\gamma$ to date

Summary

Belle

- Most stringent limit for $B \to K\tau\ell$ decays, $< (0.59 - 2.45) \times 10^{-5}$ at 90% CL
- First experimental limit on the decay $B \to K^{*0}\tau\tau$, $< 3.1 \times 10^{-3}$ at 90% CL

Belle II

- Heading towards $R_K - R_{K^*}$ measurement with larger data sample: $\mathcal{B}(B \to K^*\ell\ell)$ are consistent with PDG
- Inclusive $\mathcal{B}(B \to X_s\gamma)$ measurement in bins of E_γ^B, results are consistent with world averages

- World's most precise measurement of $B \to \rho\gamma$ decays branching fraction, isospin asymmetry and CP-asymmetry using Belle and Belle II data samples

Belle II data taking will restart in early 2024: many exciting results are on their way ...

Backup slides

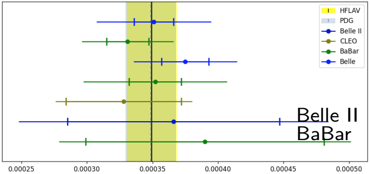
Systematic Uncertainties

TABLE II. Contributions to the systematic uncertainties of the measured signal yields and branching fractions.

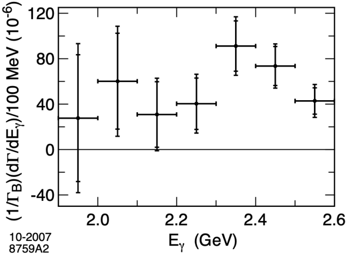
Source	$K^+\tau^+\mu^-$	$K^+\tau^+e^-$	$K^+\tau^-\mu^+$	$K^+\tau^-e^+$
Additive (events)				
PDF shape (mean)	0.09	0.01	0.08	0.08
PDF shape (width)	0.02	0.08	0.04	0.07
PDF shape ($f_{\rm sig}$)	0.28	0.16	0.11	0.16
Linearity	0.03	0.04	0.02	0.04
Total	0.30	0.18	0.14	0.20
Multiplicative (%)				
$B_{\rm tag}$ calibration	5.9	5.9	5.9	5.9
Track reconstruction	1.1	1.1	1.1	1.1
Kaon identification	1.3	1.4	1.3	1.3
Lepton identification	0.3	0.4	0.3	0.4
τ daughter identification	0.7	0.7	0.6	0.6
MC statistics	1.0	1.5	1.2	1.0
Number of $B\bar{B}$ pairs	1.4	1.4	1.4	1.4
BDT $B\bar{B}$ selection	10.6	10.0	12.7	12.6
BDT $q\bar{q}$ selection	8.8	8.6	9.2	6.6
f^{+-}	1.2	1.2	1.2	1.2
Total	15.3	14.8	17.0	15.7

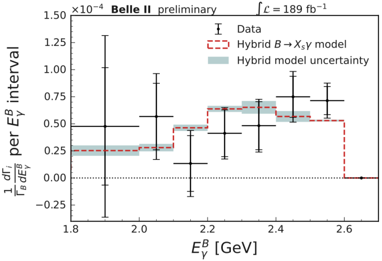
TABLE I. Systematic uncertainties for the branching fraction of the charged mode ($\mathcal{B}_{\rho^+\gamma}$), the neutral mode ($\mathcal{B}_{\rho^0\gamma}$), the isospin asymmetry, and the CP asymmetry.

Source	$\mathcal{B}_{\rho^+\gamma} \times 10^8$	$\mathcal{B}_{\rho^0\gamma} \times 10^8$	$A_{\rm I}$	$A_{\rm CP}$
reconstruction eff.	4.1	1.2	1.5%	0.4%
cut eff.	8.9	3.3	4.0%	0.6%
Fixed PDF parameters	1.1	2.6	1.8%	0.2%
Signal shape	4.6	2.9	3.1%	0.5%
Histogram PDF	1.0	0.6	0.6%	0.2%
$K^*\gamma$ yield	3.4	5.4	3.2%	0.1%
$B\overline{B}$ peaking yield	2.2	0.7	0.9%	0.2%
$A_{\rm CP}$ of peaking	0.2	0.0	0.1%	1.0%
Number of $B\overline{B}$	1.7	1.4	0.3%	0.1%
Other parameters	4.0	3.6	6.3%	0.0%
Total	12.6	8.8	9.0%	1.3%

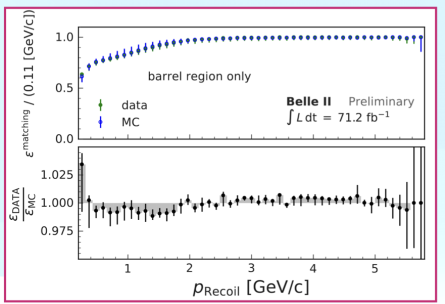


E_γ^B [GeV]	$\frac{1}{\Gamma_B}\frac{d\Gamma_i}{dE_\gamma^B}(10^{-4})$	Statistical	Systematic	Fit procedure	Signal efficiency	Background modelling	Other
1.8 – 2.0	0.48	0.54	0.64	0.42	0.03	0.49	0.09
2.0 – 2.1	0.57	0.31	0.25	0.17	0.06	0.17	0.07
2.1 – 2.2	0.13	0.26	0.16	0.13	0.01	0.11	0.01
2.2 – 2.3	0.41	0.22	0.10	0.07	0.05	0.04	0.02
2.3 – 2.4	0.48	0.22	0.10	0.06	0.06	0.02	0.05
2.4 – 2.5	0.75	0.19	0.14	0.04	0.09	0.02	0.09
2.5 – 2.6	0.71	0.13	0.10	0.02	0.09	0.00	0.04

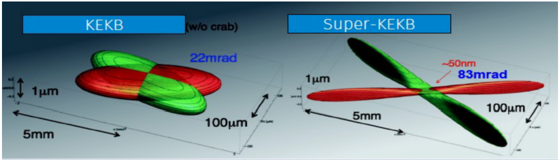




- Belle II (189 fb^{-1}) result is competitive with BaBar (210 fb^{-1}) data, HLFAV
- Main systematic uncertainties for $B \to X_s\gamma$ measurement from Belle II are coming from fit procedure (generic B background shape and $M_{\rm bc}$ end-point) and simulation statistics



- Belle II has good photon detection efficiency



	Energy (GeV) LER/HER	β_y^* (mm) LER/HER	ε_x (nm) LER/HER	ξ_y LER/HER	φ (mrad)	I_{beam} (A) LER/HER	Luminosity ($cm^{-2}s^{-1}$) x 10^{34}
KEKB Achieved	3.5/8.0	5.9/5.9	18/24	0.13/0.09	11	1.6/1.2	2.11
SuperKEKB	4.0/7.0	0.27/0.3	3.2/2.4	0.09/0.09	41.5	2.8/2.0	65

factor 20 factor 1.5

Factor ~30 in the luminosity

- Design peak luminosity of 6.5×10^{35} $cm^{-2}s^{-1}$ (30 times that of KEKB) to be achieved by:
  - reducing beam size by 20 times
  - increasing beam current by 1.5 times