Radiative and Electroweak Penguin *B* Decays at Belle II

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(On Behalf of the Belle II Collaboration)

Outline

- Motivation and Introduction (Belle II and SuperKEKB)
- b $\rightarrow$ (s,d) γ
- b $\rightarrow$ (s,d)l+l-
- b $\rightarrow$ (s,d) $\nu\nu$
- Status and Summary

Belle II Experiment

- (Belle and BaBar) had a successful operational period $\Rightarrow$ 1.5 ab^{-1} (1.25 x 10^9 Bpairs).
  - Observation of CPV in B meson system and confirmation of CKM picture, first evidence for mixing in the D meson system, first evidence for exotic states X(3872) ….
  - Still room for NP.

See Belle Talks by Nibedita Dash and Giacomo Caria

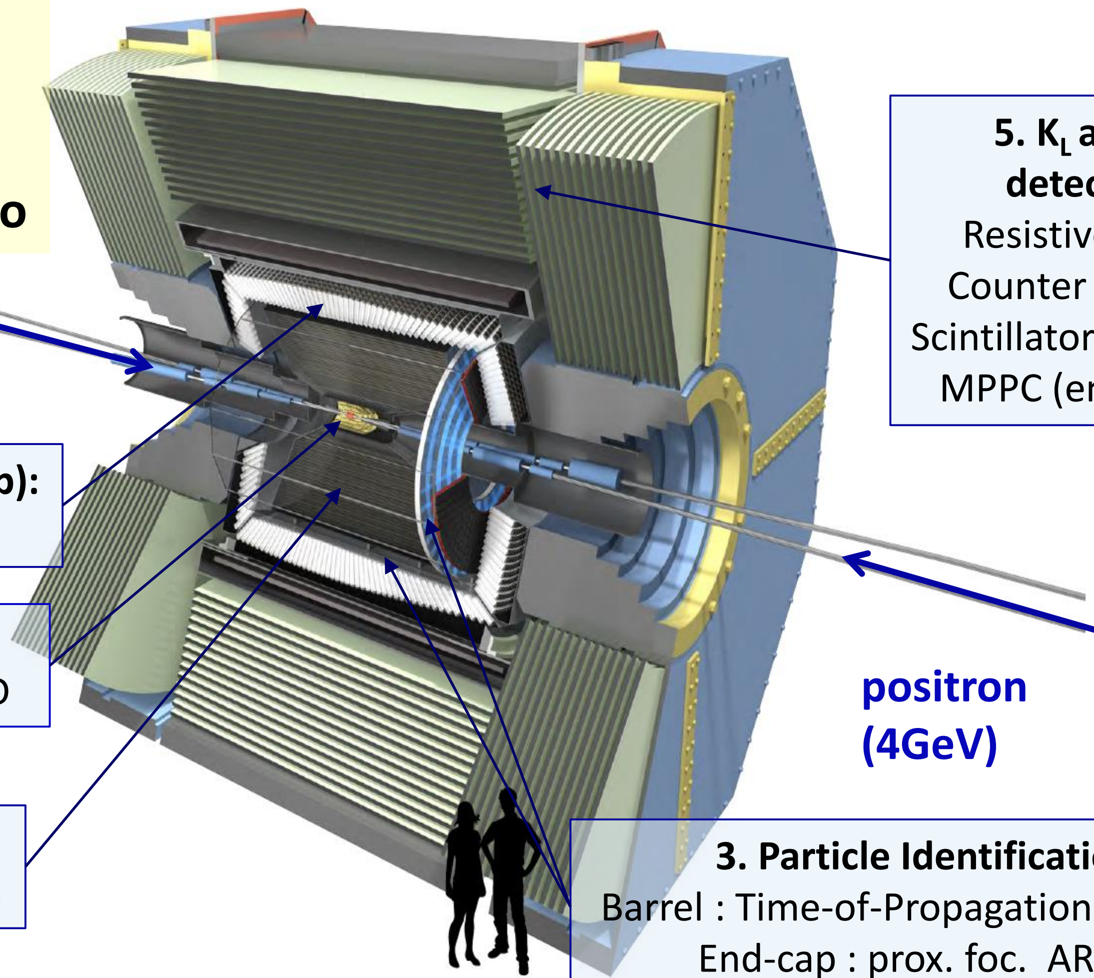
- Belle II, as a next generation flavor factory, aims to search for NP in the flavour sector, and to further reveal the nature of QCD.

Advantages of SuperKEKB and Belle II

- Very clean sample of quantum correlated B-meson pairs.
- Low background environment $\rightarrow$ efficient reconstruction of neutrals (π^0, η, ..)
- Dalitz plot analyses, missing mass analyses straight-forward.
- Systematics quite different from those at LHCb. If true NP is seen by one of the experiments, confirmation by the other would be important.
- Belle II goal: to increase the sample sizes over what Belle has achieved by a factor of 50 (> 5.0 x 10^{10} B-meson pairs).

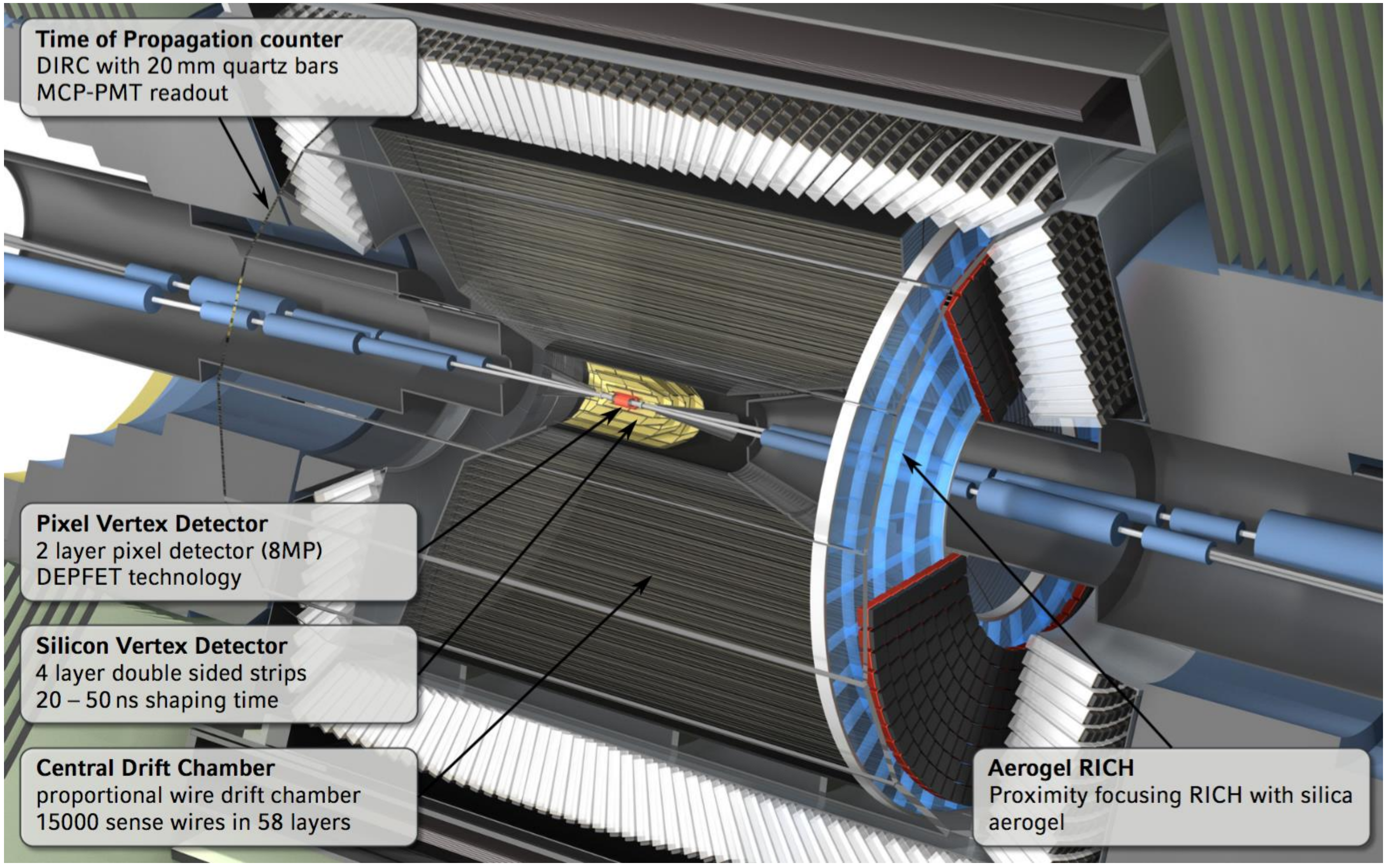
Belle II Detector

- See talks of **M. Nayak, A. Fodor** this conference.
- More in tomorrow's Plenary Talk by **P. Urquijo**



- All sub-detectors are upgraded from Belle II:
  - Except for ECL crystals and a part of Barrel KLM

Belle II Detector : a closer look



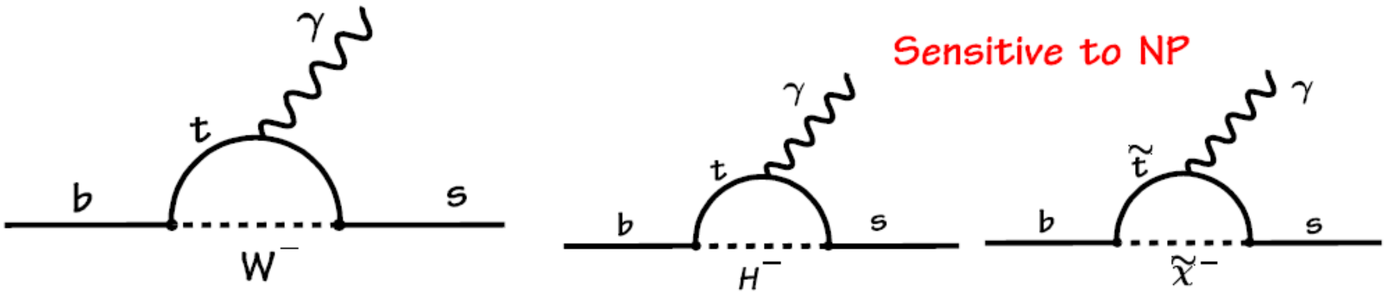
- First Pixel layer closer to IP $\rightarrow$ Better vertex resolution
- Larger Vertex Detector $\rightarrow$ Better Ks efficiency for TDCPV in B $\rightarrow K_s\pi^0\gamma$
- TOP and ARICH provide better K/π separation.
- Similar or better performance than Belle even under 20 times higher backgrounds.

Introduction

- FCNC $b \to s$ and $b \to d$ processes continue to be of great importance to precision flavor physics.
- Belle II physics program in this area will focus on fully-inclusive measurements of $B \to X_{(s,d)}\gamma$, $B \to X_{(s,d)}\ell\ell$ as well as decays such as $B_{d,s} \to \gamma\gamma$ and $B_{d,s} \to \tau^+\tau^-$.
- Belle II will provide an independent test of anomalies recently uncovered by the LHCb and Belle experiments in the angular analysis of $B \to K^*\mu^+\mu^-$ and in the determination of R(K).
- At Belle II, we will have access to decays $B \to K^{(*)}\tau^+\tau^-$ and $B \to K^{(*)} \nu\bar{\nu}$.

$\overline{B} \to X_{(s,d)}\gamma$

- The inclusive $\overline{B} \to X_{(s,d)}\gamma$ decays provide important constraints on masses and interactions of many possible BSM scenarios and SUSY theories.



- The inclusive $\overline{B} \to X_{(s,d)}\gamma$ B.F. is sensitive to $|C_7|$ and in the new physics models such as 2HDM type II and SUSY.

- Precise prediction is available (for the CP- and isospin-averaged branching ratios) for $E_\gamma > 1.6$ GeV :

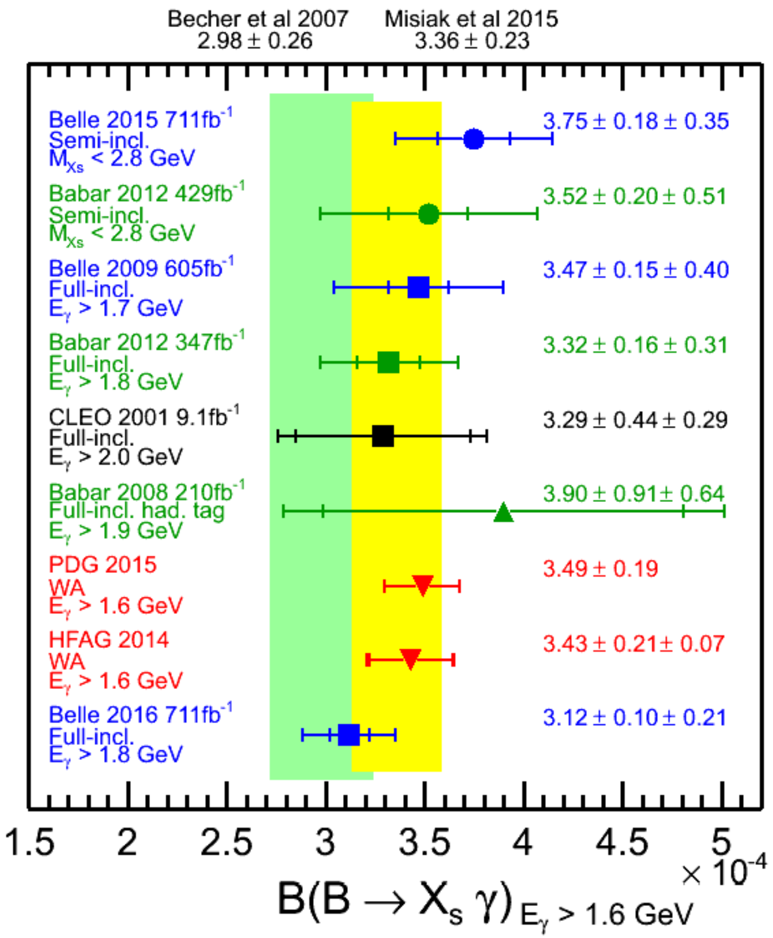
$$\mathcal{B}_{s\gamma}^{SM} = (3.36 \pm 0.23) \times 10^{-4}$$

6.8% precision

$$\mathcal{B}_{d\gamma}^{SM} = (1.73^{+0.12}_{-0.22}) \times 10^{-5}$$

- **M. Czakon, P. Fiedler, T. Huber, M. Misiak, T. Schutzmeier, and M. Steinhauser, JHEP, 04, 168 (2015),**
- **M. Misiak et. al PRL 114, 221801 (2015)**

$\bar{B} \to X_{(s,d)}\gamma$



$$\mathcal{B}_{s\gamma}^{\text{exp}} = (3.27 \pm 0.14) \times 10^{-4}$$

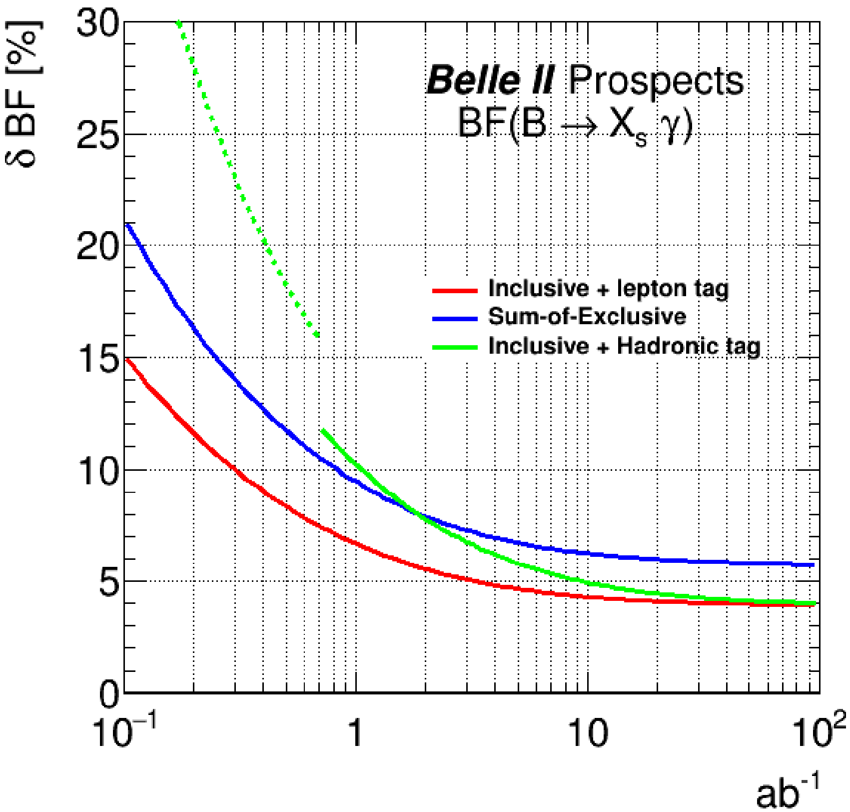
$$\mathcal{B}_{d\gamma}^{\text{exp}} = (1.41 \pm 0.57) \times 10^{-5}$$

- Exp. and theory are consistent – puts a strong limit on new physics.
- Evaluation of constraint on BSM scenario depends crucially on both the central value and the uncertainties on the B.F.

  (Misiak et. al PRL 114, 221801 (2015))
- The newest Belle result with fully inclusive method has only 7.3% uncertainty.

  → Charged Higgs mass > 580 GeV at 95% CL
- The uncertainties of the measured branching ratios are systematically dominated

$\overline{B} \to X_{(s,d)}\gamma$



(5-10 ab^{-1} will be recorded in ~2-3 years)

- Mission at Belle II is to reduce the systematic uncertainty with more data.
- Conservatively estimated, 3.9% total error will be reachable with 50 ab^{-1} which is comparable to uncertainty due to non-perturbative effect (which is hard to reduce) in theory. [**Misiak et. al PRL 114, 221801 (2015)**].
- We can also measure the BF with E_γ>1.6GeV (w/o extrapolation).

  Lowering the photon energy threshold will however increase the size of the systematic uncertainty due to hadronic backgrounds.

$\overline{\mathrm{B}} \to X_{(s,d)}\gamma$: Rate Asymmetry

- In addition to BFs, asymmetry in decay rates (isospin asym. and CP asym.) are also sensitive to BSM contributions.
- The direct CP asymmetry in the time-integral rates is defined as:

$$A_{CP} = \frac{\Gamma(\overline{B} \to \overline{X}) - \Gamma(B \to X)}{\Gamma(\overline{B} \to \overline{X}) + \Gamma(B \to X)}$$

- SM predicts quite different asymmetries for $\overline{\mathrm{B}} \to X_s\gamma$ and $\overline{\mathrm{B}} \to X_d\gamma$.

$$A^{SM}_{\mathrm{CP}(s\gamma)} = [-0.6, 2.8]\%$$

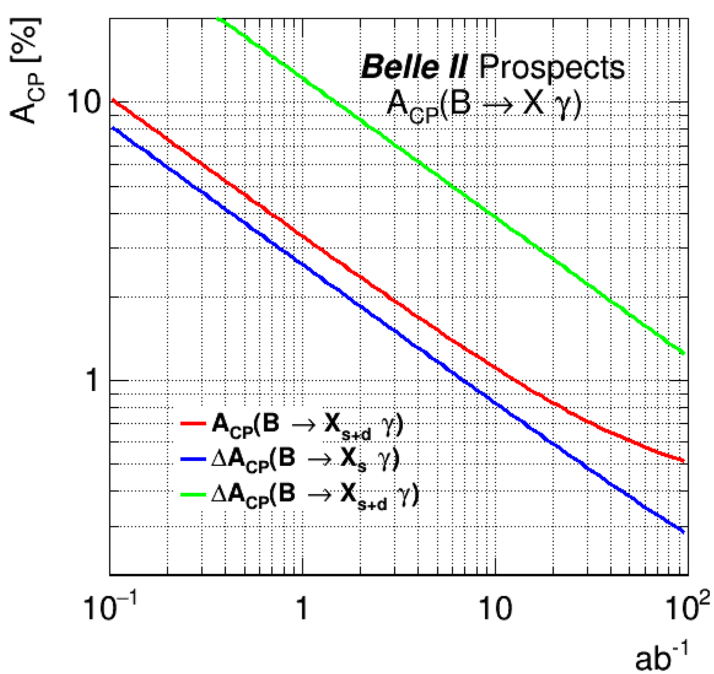
$$A^{SM}_{\mathrm{CP}(d\gamma)} = [-62, 14]\%$$

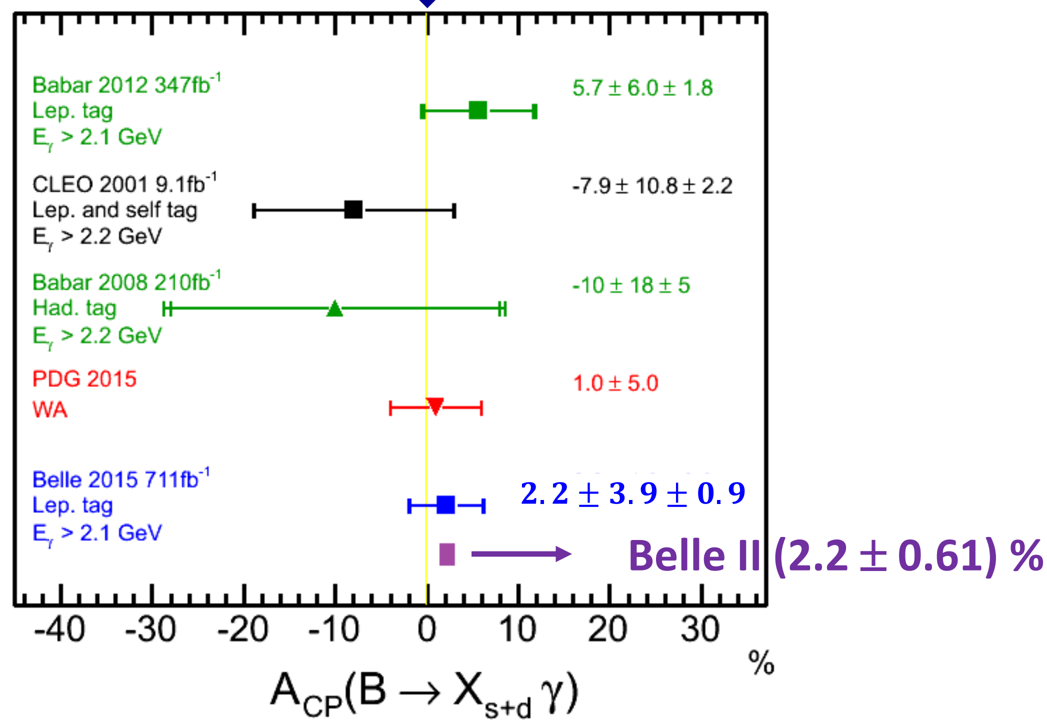
- However, the sum of $b \to s\gamma$ and $b \to d\gamma$ is predicted to be very small (close to zero, thanks to the unitarity of the CKM matrix).
- Further, difference of $A_{CP}(B \to X_s\gamma)$ between charged and neutral B mesons ΔA_{CP} is sensitive to phases in C_7 and C_8 .
  - In the SM , phases in C_7 and C_8 are zero $\to \Delta A_{CP} = 0$.
- If either is deviated from null, clear NP signal!

T. Hurth, E. Lunghiand W. Porod, Nucl.Phys. B704 (2005) 56–74, M. Benzke et. al, PRL 106, 141801 (2011)

$\bar{B} \to X_{(s,d)}\gamma$: Rate Asymmetry

- In asymmetry (difference) measurements, most of systematic error cancels out, it will be statistically dominated at Belle II with 50 ab^{-1}.
- Uncertainty in A_{CP} to be $\pm$0.5 % $\rightarrow$ 4.4σ if the central value not change





- Uncertainty in ΔA_{CP} to be $\pm$0.37 % $\rightarrow$ 13.5σ if the central value not change [from BaBar's measurement $\Delta A_{CP}(X_s\gamma)$ = +(5.0 ± 3.9 ± 1.5)%] [Belle II : +(5.0 ± 0.37)%]

b→ qγ Exclusive modes

- Isospin asymmetry is sensitive to BSM, defined as :

$$a_I^{\bar{0}-} = \frac{c_V^2\,\Gamma(\bar{B}^0 \to \bar{V}^0\gamma) - \Gamma(B^- \to V^-\gamma)}{c_V^2\,\Gamma(\bar{B}^0 \to \bar{V}^0\gamma) + \Gamma(B^- \to V^-\gamma)}$$

for $c_{\rho^0}^2$ = 2 and $c_{K^*}^2$ = 1

- To accumulate more statistics, CP-averaged IAs can be defined as: $\bar{a}_I = (a_I^{\bar{0}-} + a_I^{0+})/2$

$\bar{a}_I^{SM}(K^*\gamma) = (4.9 \pm 2.6)\%$

$\bar{a}_I^{SM}(\rho\gamma) = (5.2 \pm 2.8)\%$

PRD 88 (2013), 094004

$\bar{a}_I^{exp}(K^*\gamma) = (5.2 \pm 2.6)\%$

$\bar{a}_I^{exp}(\rho\gamma) = (30^{-13}_{+16})\%$

HFLAV 2017

slight tension with considerable uncertainty

- The observable with reduced uncertainty $\delta_{a_I} = 1 - \frac{\bar{a}_I(\rho\gamma)}{\bar{a}_I(K^*\gamma)}\sqrt{\frac{\bar{\Gamma}(B \to \rho\gamma)}{\bar{\Gamma}(B \to K^*\gamma)}}\left|\frac{V_{ts}}{V_{td}}\right|$

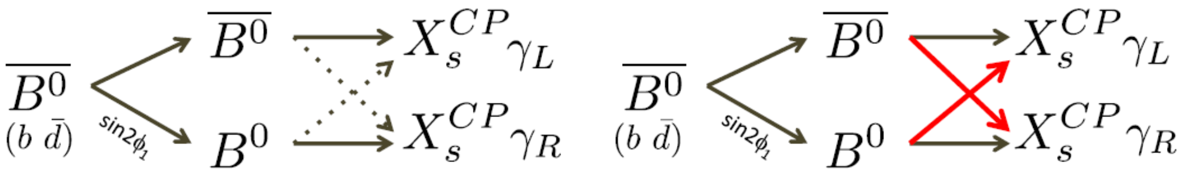
$\delta_{aI}^{SM} = 0.10 \pm 0.11$

$\delta_{aI}^{exp} = -4.0 \pm 3.5$ → **Can be improved at Belle II with more statistics.**

The sensitivity of δ_{aI} to BSM physics has been studied in PRD 88 (2013), 094004 in a model-independent fashion

b→ sγ :Time dependent CPV

- Mixing-induced CP asymmetry in an exclusive b → sγ CP eigenstate mode such as B → $K^*(K_s\pi^0)\gamma$ is an excellent probe for particular class of NP scenario.
- In the SM, expected asymmetry $|S_{CP}| \approx \frac{2m_s}{m_b}\sin(2\phi_1)$ ~ a few %.



dotted : helicity flip red : helicity flip+NP

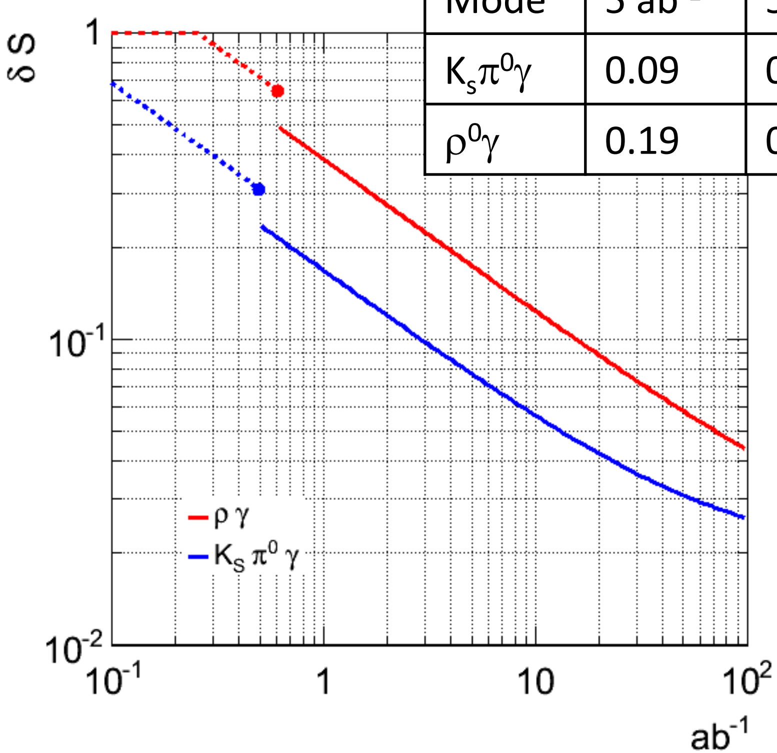
- New physics with right handed current increases the fraction of right handed photon.
  - Interfere with the SM occurs and large TDCPV possible
- Studies of these asymmetries are thus considered to be one of the most promising methods to search for non-SM right-handed currents

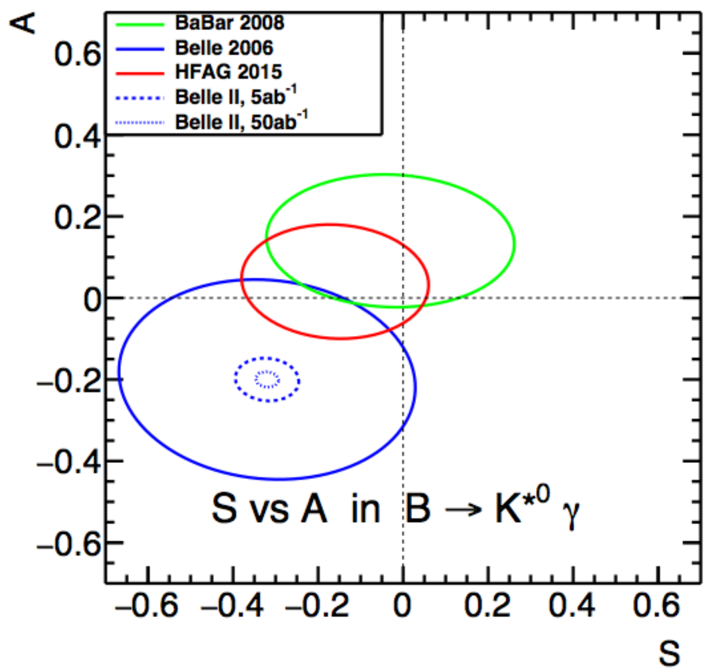
Time dependent CPV

- At Belle II, significant improvement in the determination of $A_{CP}(t)$ in $K_s\pi^0\gamma$ is expected.
  - $\rightarrow$ Belle II vertex detector is larger than Belle (6cm $\rightarrow$ 11.5cm).
  - $\rightarrow$ 30% more Ks with vertex hits available.
  - $\rightarrow$ Effective tagging efficiency is 13% better (conservative estimation).

- Expected errors for ***S*** measurements of $K_s\pi^0\gamma$ and $\rho^0\gamma$.

Mode	5 ab^{-1}	50 ab^{-1}
$K_s\pi^0\gamma$	0.09	0.030
$\rho^0\gamma$	0.19	0.064



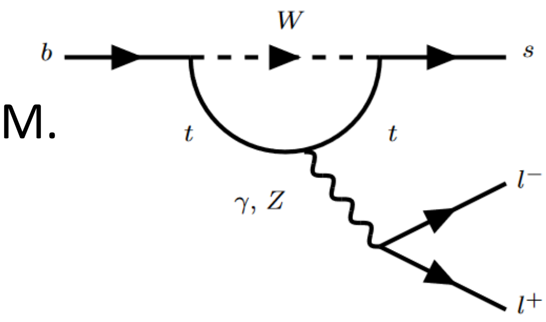


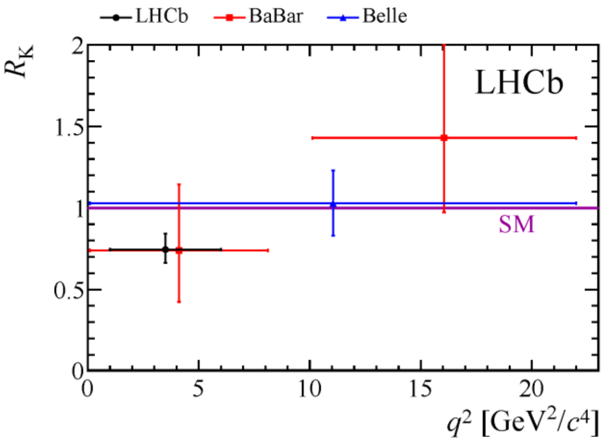
16σ deviation with 50 ab^{-1}.

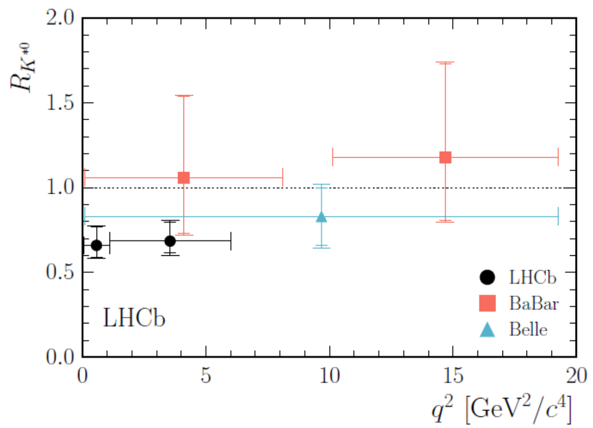
R(K), R(K*), R(X_s)

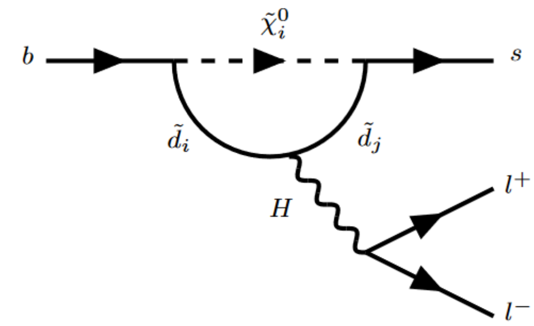
Ratio of B → $K^{(*)}\mu\mu$ and B → $K^{(*)}ee$

- B → $K^{(*)}ll$ proceeds via one loop diagram, and LU holds in SM.







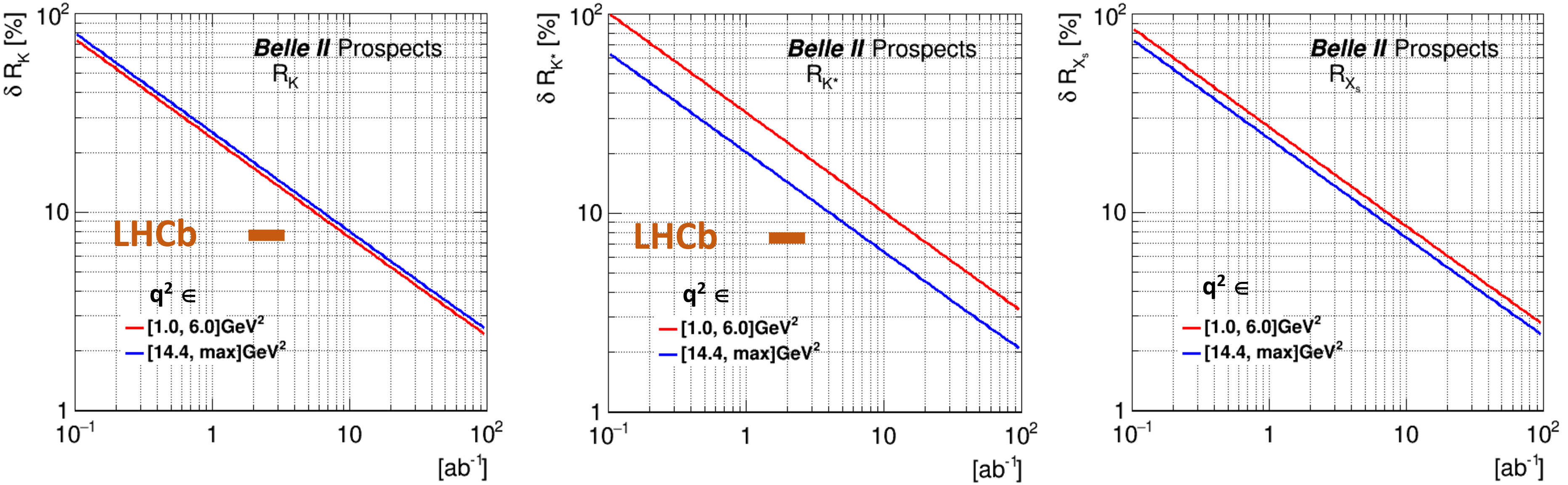


- However electron mode is challenging at LHCb, especially for high q^2.

- At Belle II:
  - electron and muon modes have similar efficiency.
  - Both low and high q^2 regions are possible.
  - All ratios R(K), R(K*), R(X_s) are possible.

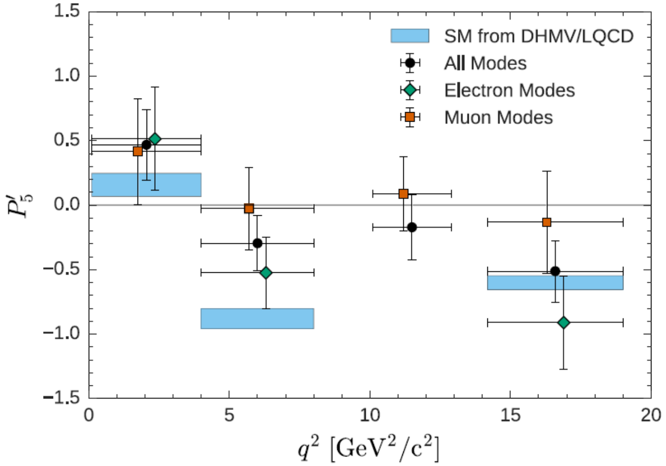
R(K), R(K*), R(Xs)

- The errors reach to 0.04 for all K, K* and Xs modes in Belle II.
- Errors are still statistically limited (systematic error ~ 0.4%)



- Belle II should be able to confirm the $R(K^{(*)})$ anomaly with a significance of 5σ, if it is indeed due to new physics.

Angular Analysis $B \to K^* \ell^+ \ell^-$ (at Belle II)

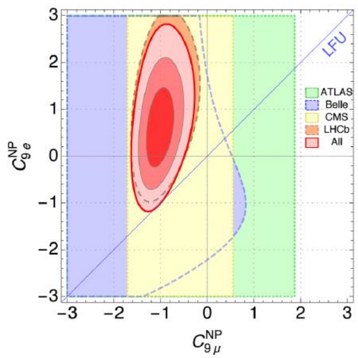


- First Lepton Flavor dependent angular analysis of $B \to K^* \ell^+ \ell^-$ performed at Belle.
- Similar central values for the P_5' anomaly with **2.5σ** (combined result) tension.
- The Largest deviation in the muon mode with **2.6σ**, electron mode is deviating with **1.1σ**.

- Belle II and LHCb will be comparable for this process.
- electron mode more efficiently and can also explore $Q_{4,5}$
- Projection of uncertainties at Belle II for P_5'

q^2 (GeV^{2}c^{-4})	Belle	Belle II
0.1 – 4	0.416	0.059
4 – 8	0.277	0.040
10.09 – 12	0.344	0.049
14.18 – 19	0.248	0.033

- Global fits including P_5' Q_5 $R(K^*)$, $B_s \to \mu\mu$, $b \to s\gamma$ suggests $C_{9\mu}^{NP} \approx -1.1$

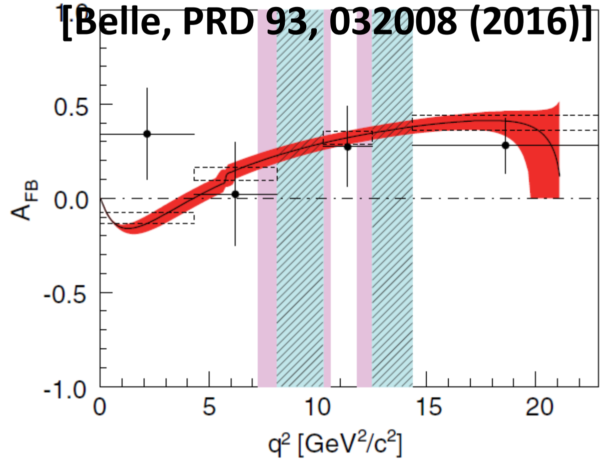


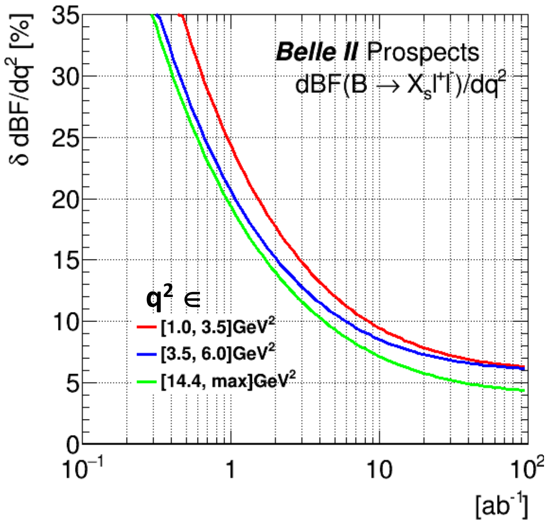
Capdevila, Crivellin, Descotes-Genon, Matias, Virto, arXiv:1704.05340

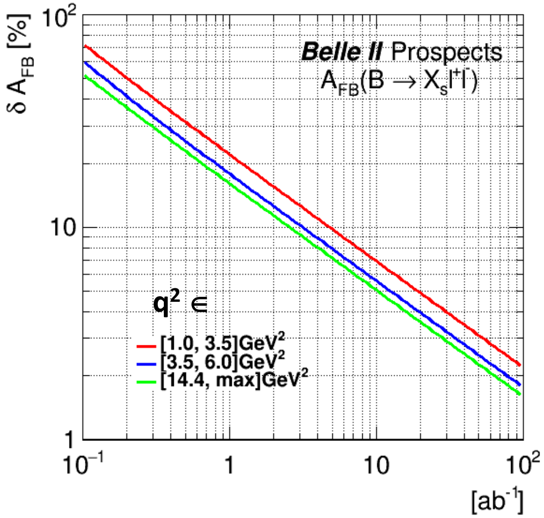
$B \to X_s\, l^+ l^-$

- Measurement of BF and A_{FB} in $B \to X_s\, l^+ l^-$ at Belle.
- Sum-of-exclusive method is utilized.
- Tension in low q^2 region.
- Measurement can be improved at Belle II.

[Belle, PRD 93, 032008 (2016)]

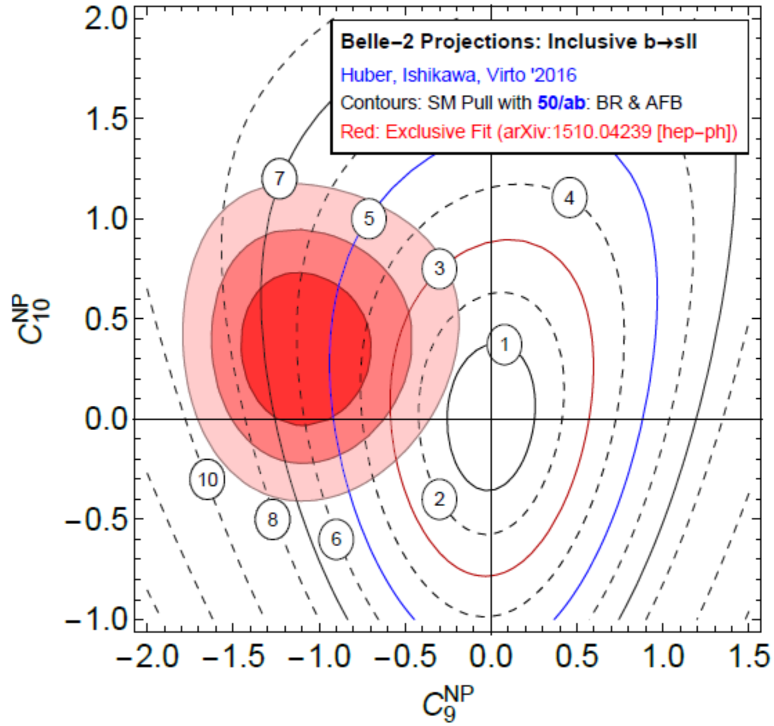




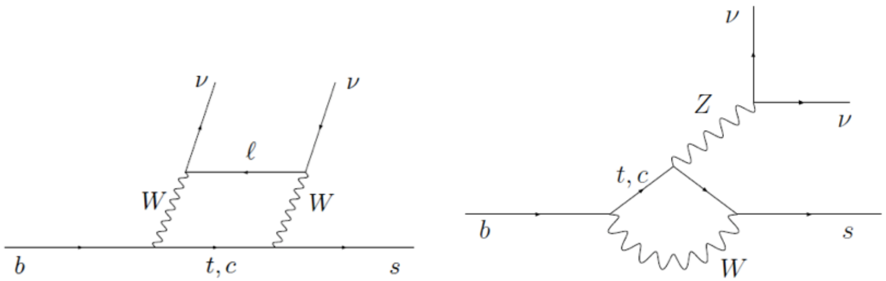


- Decay amplitude can be expressed in terms of C_7, C_9, and C_{10}.
- Precise theory prediction available.

T. Huber, J. Virto, A. Ishikawa →



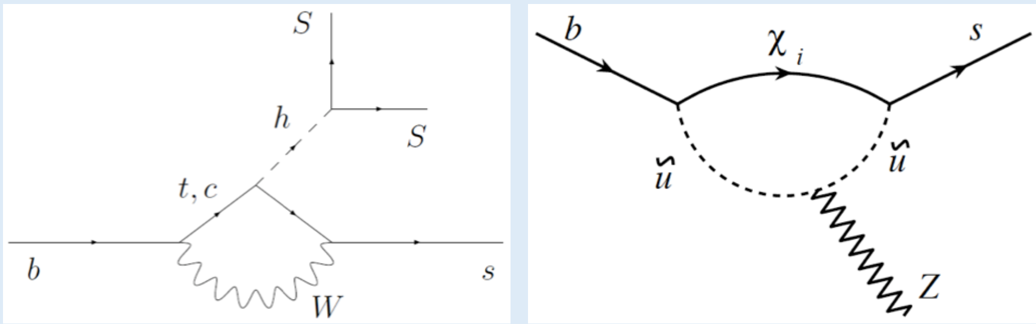
In the SM:

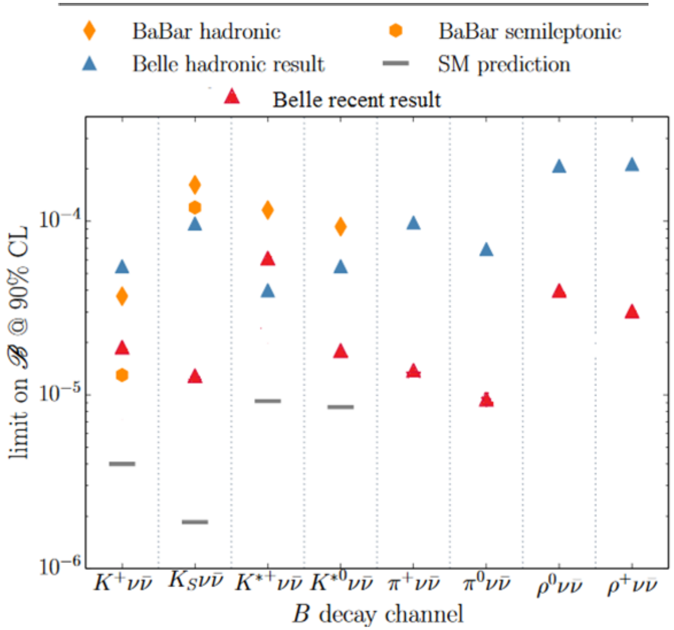


- SM predictions (JHEP 02 184, 2015) updated BELLE2-MEMO-2016-007 [D M Straub]

Mode	$\mathcal{B}$ $[10^{-6}]$
$B^+ \to K^+\nu\bar{\nu}$	$3.98 \pm 0.43 \pm 0.19$
$B^0 \to K^0_S\nu\bar{\nu}$	$1.85 \pm 0.20 \pm 0.09$
$B^+ \to K^{*+}\nu\bar{\nu}$	$9.91 \pm 0.93 \pm 0.54$
$B^0 \to K^{*0}\nu\bar{\nu}$	$9.19 \pm 0.86 \pm 0.50$

- NP scenario can be tested:
  - Non- standard Z-coupling
  - New sources of missing energy.

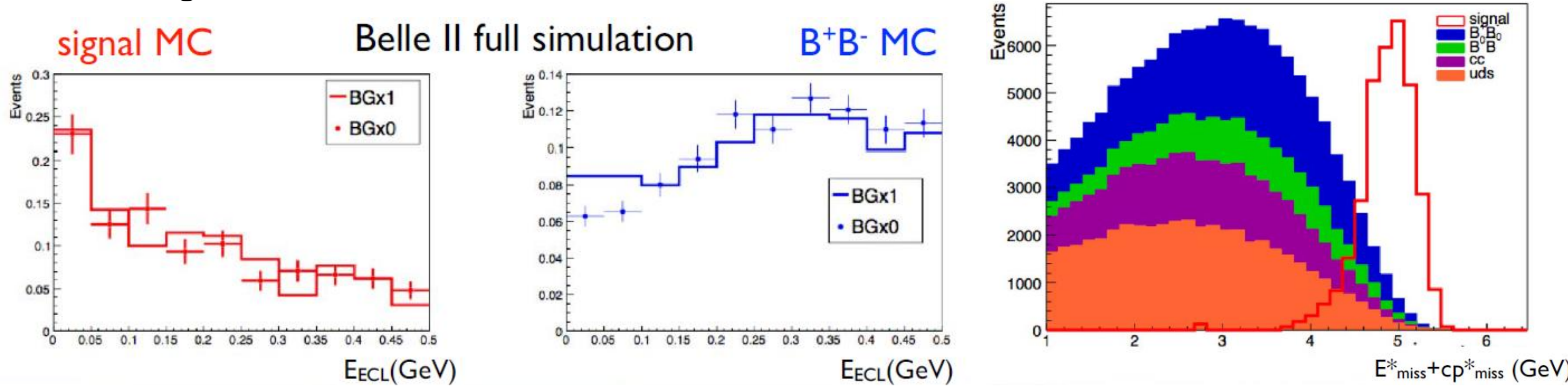




← Belle updated $b \to (s,d)\ \nu\bar{\nu}$ measurement with semileptonic tag. **PRD96, 091101(R)**

$b \to s\nu\bar{\nu}$: Belle II prospects

- Brighter prospects for Belle II to observe this decay.
- Analysis on Belle II Full simulation to establish machine background impact
  - → nominal machine bkg (BGx1) and machine bkg-free (BGx0) simulated samples analysed.
  - → Negligible impact of machine background both in terms of variables shape and signal significance



- Belle II extrapolation based on Belle hadronic and SL tag analyses, assuming 100% more had. tag eff. and 30% more K_s reco. eff.
- observation with about 18 ab^{-1}
- precision on the branching fraction at 50 ab^{-1}

	stat only	total
$B^+ \to K^+ \nu\nu$	9,5%	10,7%
$B^+ \to K^{*+} \nu\nu$	7,9%	9,3%
$B^+ \to K^{*0} \nu\nu$	8,2%	9,6%

Summary and Status

- Major upgrade at KEK represents an essentially new experiment:
  - Many detector components and electronics replaced, software and analysis also improved.
- Belle II has a rich physics program, complementary to existing experiments and energy frontier programs.
- With the better detector Belle II and higher luminosity machine SuperKEKB, we can intensely search for NP with Radiative and EW Penguin decays.
- Accelerator commissioning : June 2016 (successful.) $\rightarrow$ Phase 2: Starts in Summer 2018 (w/o vtx) $\rightarrow$ Phase 3 / Run 1: Early 2019 (full det.).
- Detector is now mostly (except VXD) installed. Gearing up for Phase II.

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New Physics searches with the Belle II Detector
Presented by **Phillip URQUIJO** on **15 Dec 2017** from **11:30 AM** to **12:00 PM**

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Double-radiative B decays

$B_q \to \gamma\gamma$:

SM prediction

$Br(B_s \to \gamma\gamma)_{SM} \in [0.5, 3.7] \times 10^{-6}$

$Br(B_d \to \gamma\gamma)_{SM} \in [1.0, 9.8] \times 10^{-8}$

Bosch and Buchalla, JHEP 08 (2002) 054

Exp. situation

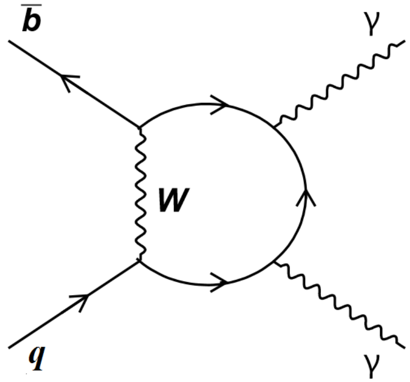
$Br(B_s \to \gamma\gamma)_{exp} < 3.1 \times 10^{-6}$

[Belle, PRD 91, 011101 (2015)]

$Br(B_d \to \gamma\gamma)_{exp} < 3.2\ \{6.2\} \times 10^{-7}$

BaBar, PRD 83, 032006 (2011)

{Belle, , PRD 73, 051107 (2006)}



- With the above comparison, Belle II will be able to discover $B_d \to \gamma\gamma$ with the anticipated 50 ab^{-1} at $\Upsilon(4S)$.
- Furthermore, in an appropriately large data at $\Upsilon(5S)$ $B_s \to \gamma\gamma$ can be observed.

$B \to X_s\gamma\gamma$:

- $B \to X_s\gamma\gamma$ decays are suppressed by $\alpha_s/4\pi$ compared to $B \to X_s\gamma$.

$$\mathrm{Br}(B \to X_s\gamma\gamma)^{c=0.02}_{\mathrm{SM}} = (1.7 \pm 0.7) \cdot 10^{-7}$$

Asatrian et al., PRD 93, 014037 (2016)

should be observable at Belle II.

- Measurements of the double-radiative decay mode would allow to put bounds on 1PI type corrections.
- One can study more complicated distributions like, double differential rate ($d^2\Gamma/dE_1dE_2$) and forward backward asymmetry $\to$ sensitive to BSM physics.