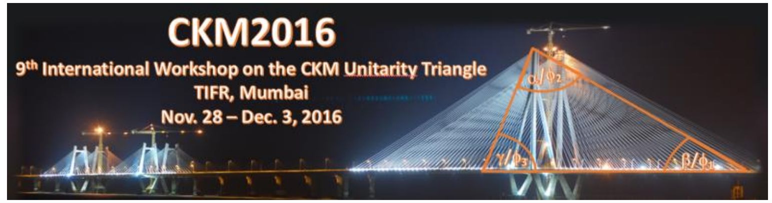


Prospects for Rare Decays at Belle II

Saurabh Sandilya
(On Behalf of the Belle II Collaboration)

Outline

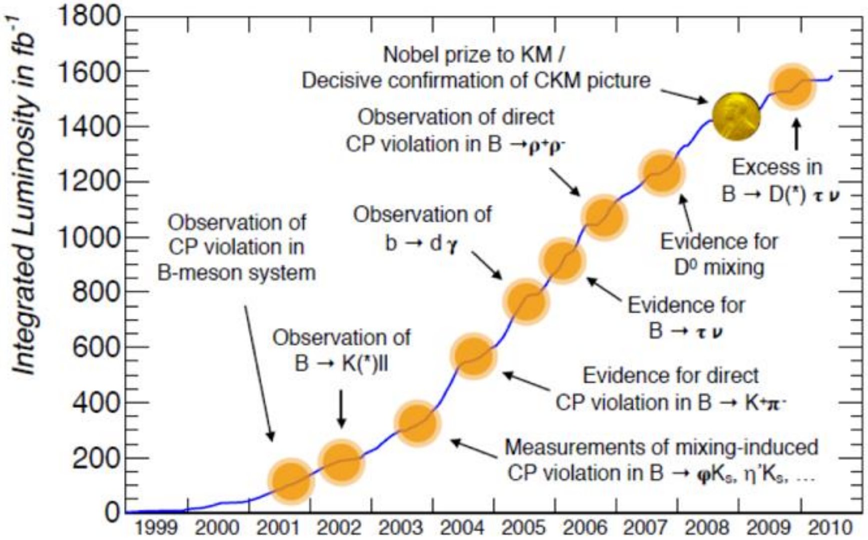
- Motivation and Introduction (Belle II and SuperKEKB)
- b $\rightarrow$ (s,d) γ
- b $\rightarrow$ (s,d)l+l-
- b $\rightarrow$ (s,d) $\nu\nu$
- Double radiative decays
- Status and Summary

Motivation

Success of B-factories:

(Belle and BaBar) had a successful operational period with a total recorded sample over 1.5 ab^{-1} (1.25 x 10^9 B-meson pairs).

- Observation of CPV in B meson system and confirmation of CKM picture.
- Still room for NP.

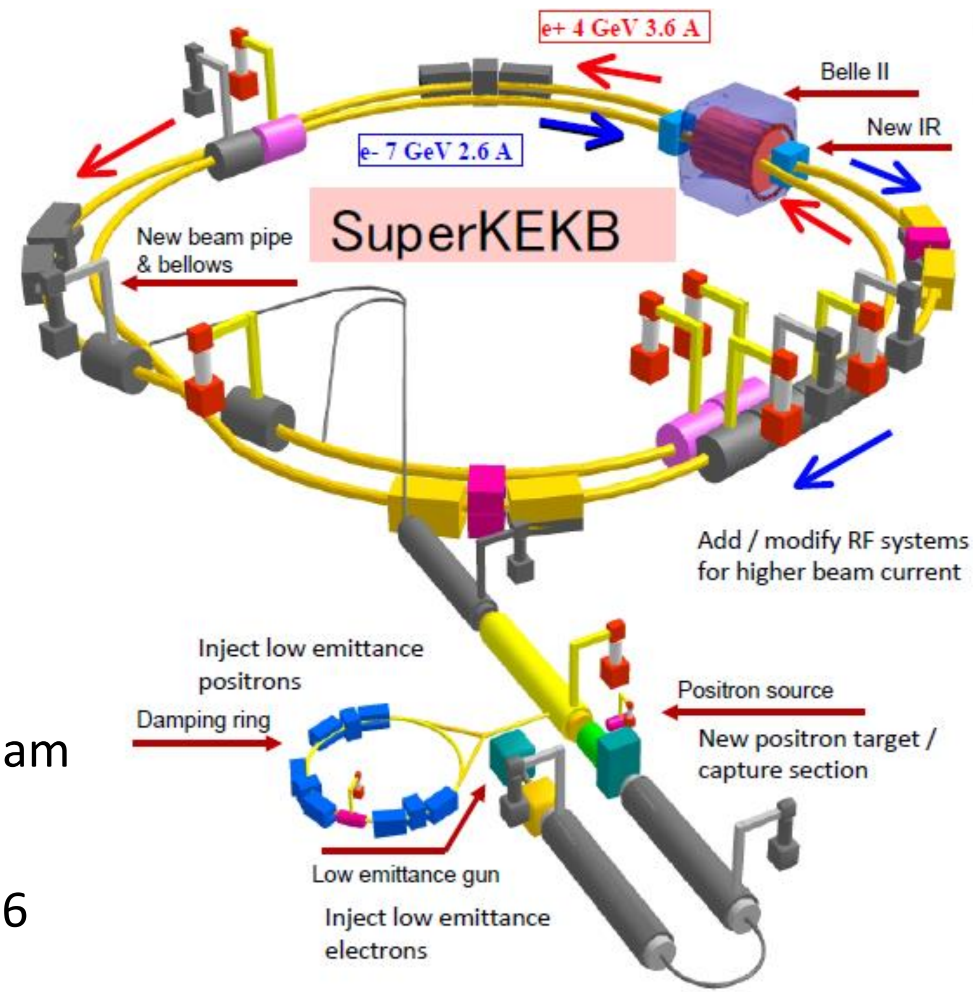


Advantages of SuperKEKB and Belle II

- 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).

SuperKEKB

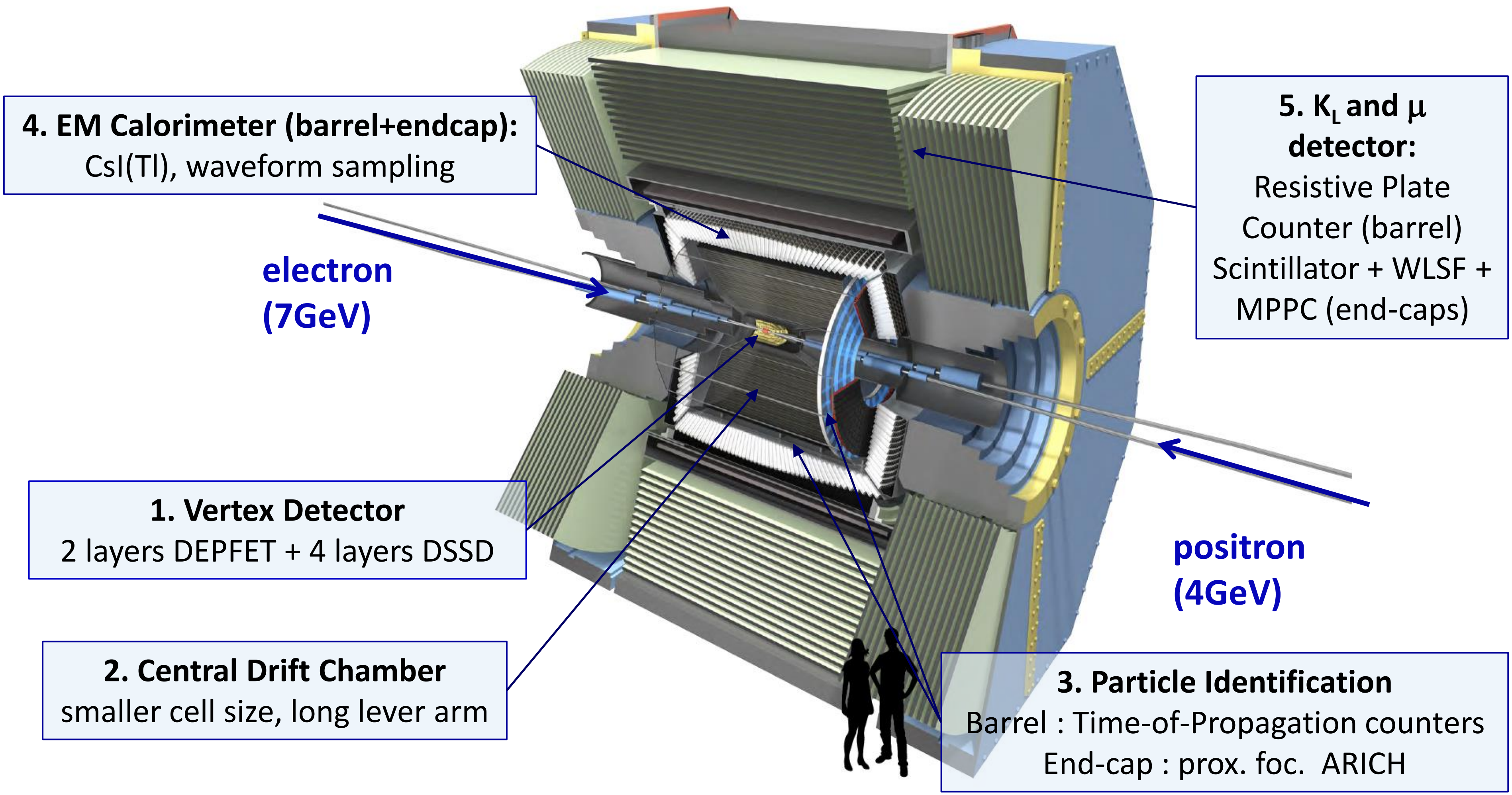
- Upgraded from KEKB
  - which is the world's highest luminosity e+e- machine.
- Design Luminosity : 8×10^{35} $cm^{-2}s^{-1}$
  - 40 times larger than KEKB.
    - 20 times smaller beam size
    - 2 times larger beam current
  - Large number of upgrades to RF, magnet, vacuum, etc. systems
- Asymmetric energy : 7GeV(e-) × 4GeV(e+)
  - Boost factor smaller to reduce beam background.
- Accelerator commissioning : June 2016 (successful.)
  - Phase 2: Starts in Nov 2017 (w/o vtx)
  - Phase 3 / Run 1: Fall 2018 (full det.)



***Gray: recycled**

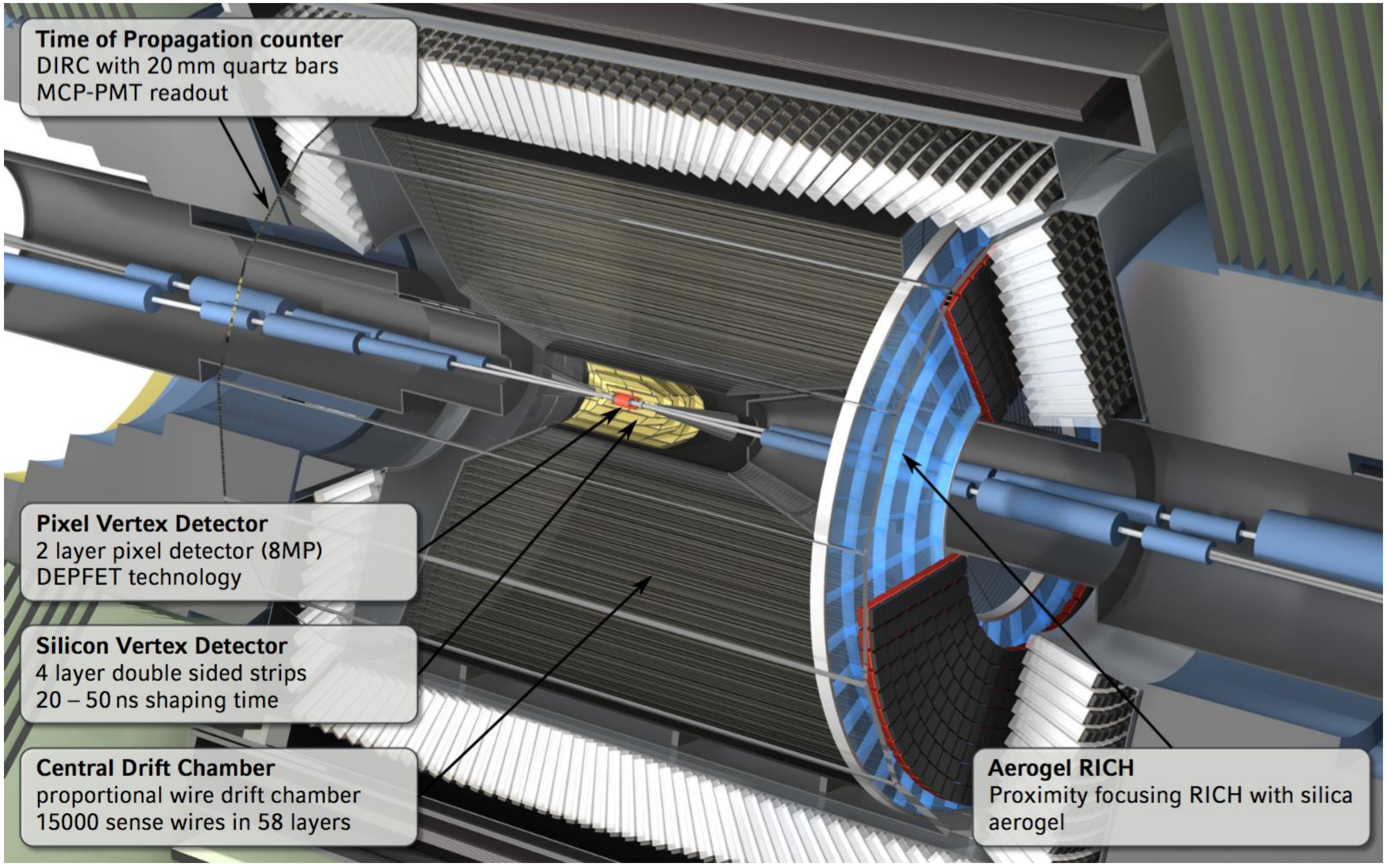
Colored : newly installed

Belle II



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

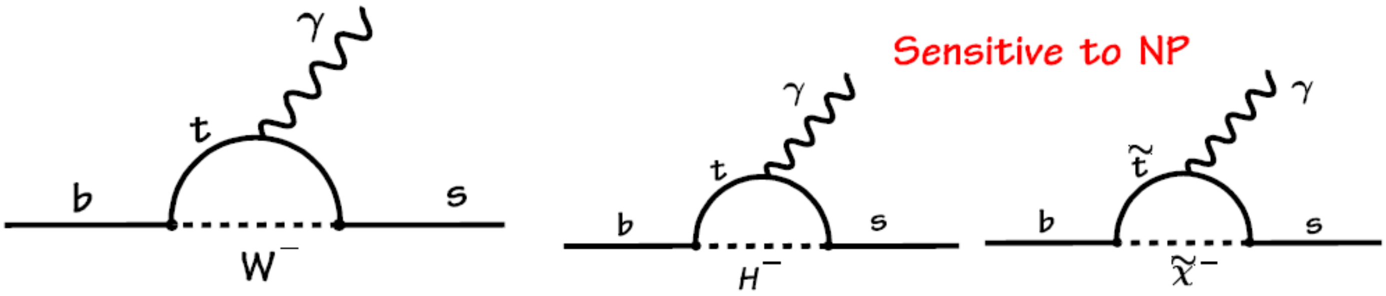
Belle II : a closer look



- 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.

$\overline{B} \to X_q\gamma$

- The inclusive $\overline{B} \to X_q\gamma$ decays provide important constraints on masses and interactions of many possible BSM scenarios.



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

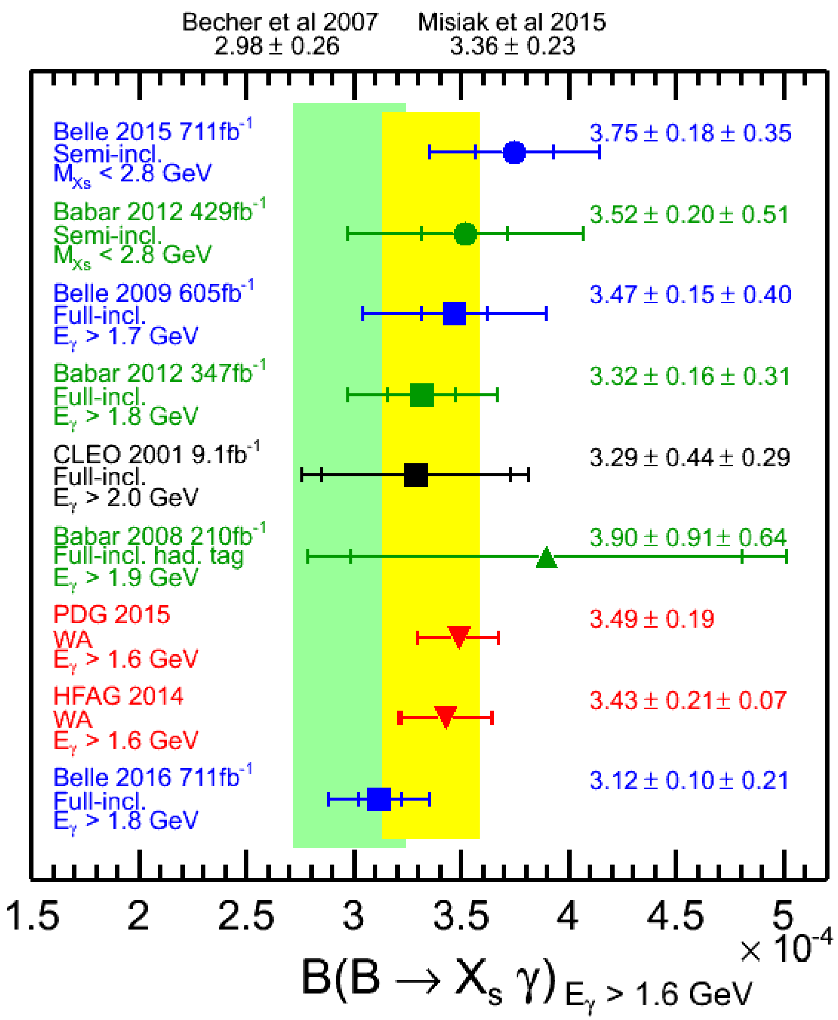
- Very precise prediction is available (for the CP- and isospin-averaged branching ratios) for $E_\gamma > 1.6$ GeV :

$$\mathcal{B}_{s\gamma}^{SM} = (3.36 \pm 0.23) \times 10^{-4}$$ **6.8% precision**

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

(Misiak et. al PRL 114, 221801 (2015))

$\overline{B} \to X_q\gamma$

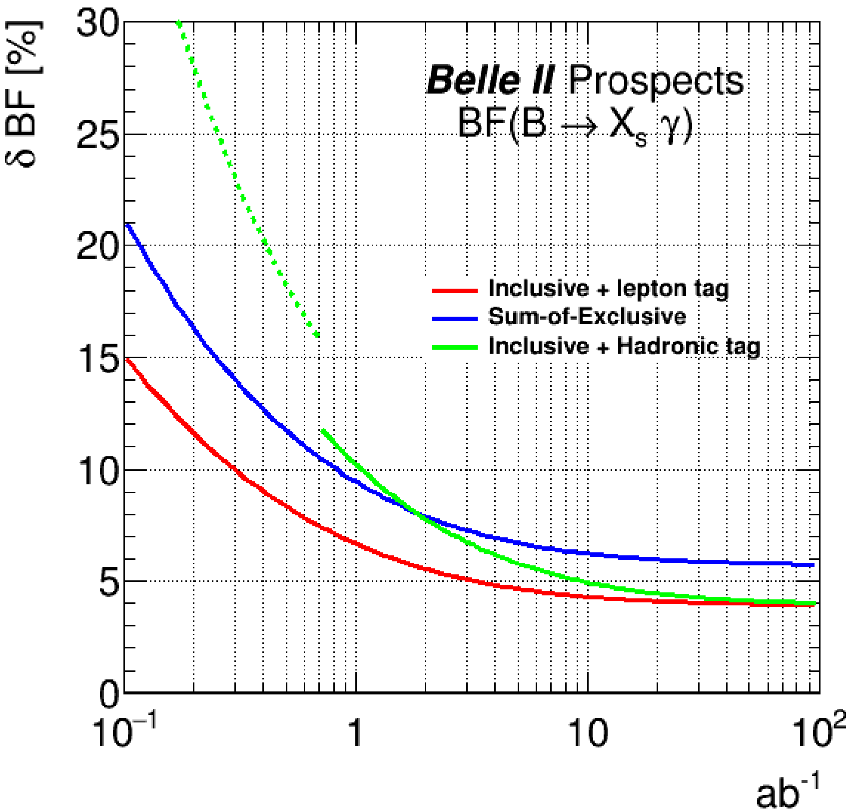


- Exp. and theory are consistent – puts a strong limit on new physics.
- Evaluation of constraint on BSM scenario depends crucially on both the central value and the uncertainties on the B.F.

  (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

$\bar{B} \to X_q\gamma$



- Mission at Belle II is to reduce the systematic uncertainty with huge 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).

$\bar{B} \to X_q\gamma$: Rate Asymmetry

- In addition to BFs, asymmetry in decay rates (isospin asym. and CP asym.) are also sensitive to BSM contributions.

- Isospin asymmetry (IA) can be 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: $\bar{a}_I = (a_I^{\bar{0}-} + a_I^{0+})/2$

$\bar{a}_I^{SM}(K^*\gamma) = (4.9 \pm 2.6)\%$ $\bar{a}_I^{exp}(K^*\gamma) = (5.2 \pm 2.6)\%$

$\bar{a}_I^{SM}(\rho\gamma) = (5.2 \pm 2.8)\%$ $\bar{a}_I^{exp}(\rho\gamma) = (30^{-13}_{+16})\%$ **slight tension with considerable uncertainty**

PRD 88 (2013), 094004 **HFAG 2015**

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

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

$\delta_{aI}^{exp} = -4.0 \pm 3.5$ $\rightarrow$ **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

$\overline{B} \rightarrow X_q\gamma$: Rate Asymmetry

- 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 $\overline{B} \rightarrow X_s\gamma$ and $\overline{B} \rightarrow X_d\gamma$.

$$A_{CP}(B \to X_s\gamma) = (+0.44\ ^{+0.24}_{-0.14}) \times 10^{-2}$$
$$A_{CP}(B \to X_d\gamma) = (-10.2\ ^{+3.3}_{-5.8}) \times 10^{-2}$$

- However, the sum of $b \rightarrow s\gamma$ and $b \rightarrow d\gamma$ is predicted to be very small (close to zero, thanks to the unitarity of the CKM matrix).

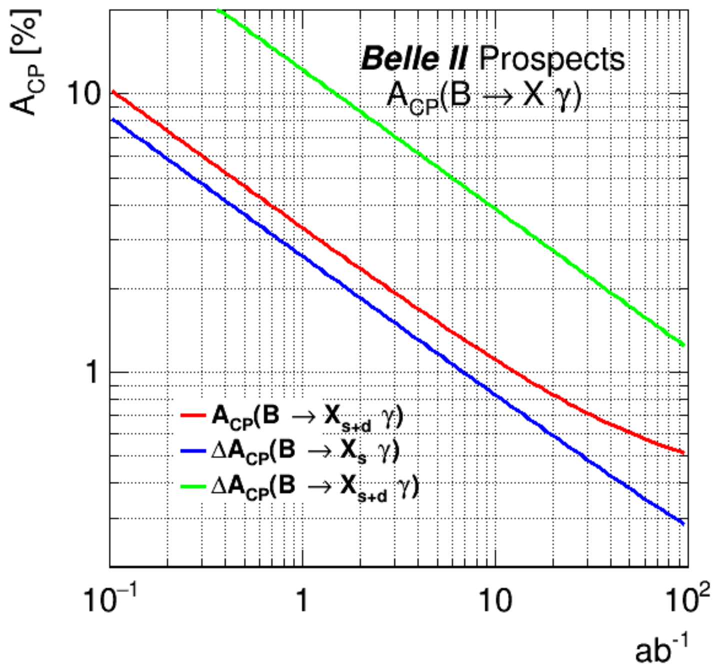
- Further, difference of $A_{CP}(B \rightarrow X_s\gamma)$ between charged and neutral B mesons ΔA_{CP} is sensitive to phases in C_7 and C_8 .
  - In the SM , phases in C_7 and C_8 are zero $\rightarrow \Delta A_{CP} = 0$.

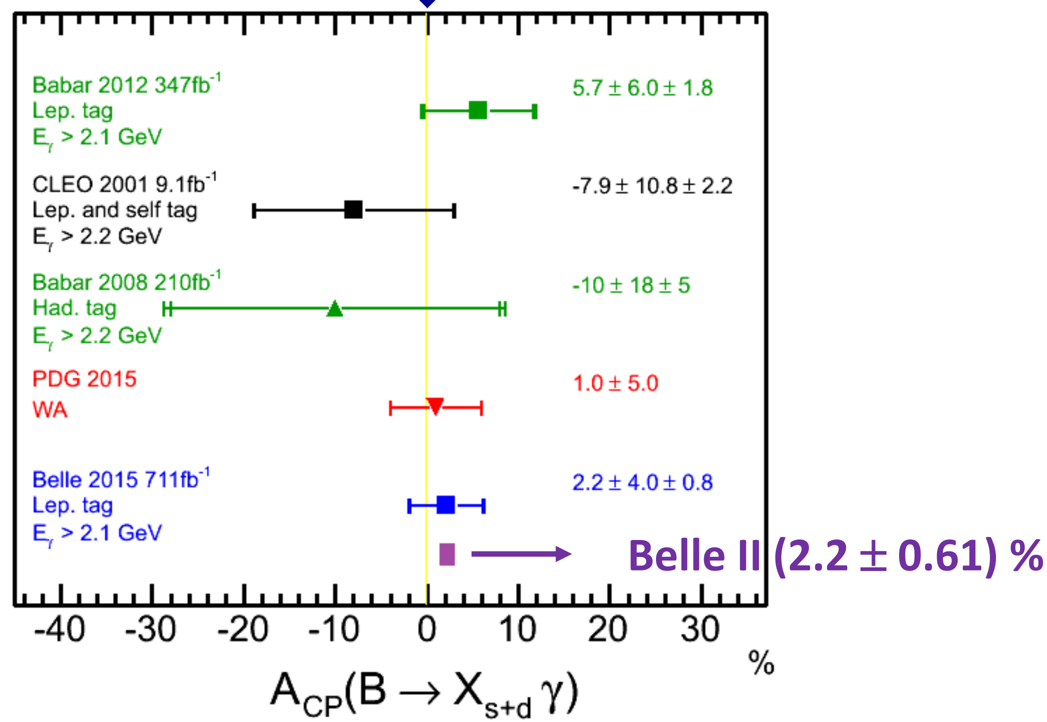
- If either is deviated from null, clear NP signal!

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

$\overline{B} \to X_q\gamma$: Rate Asymmetry

- In asymmetry (difference) measurements, most of systematic error cancels out, so both are still statistically dominated at Belle II with 50 ab^{-1}.
- Uncertainty in A_{CP} to be $\pm$0.61 % $\to$ 3.4σ if the central value not change

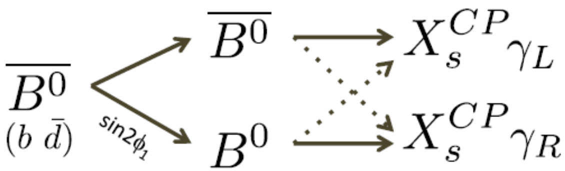




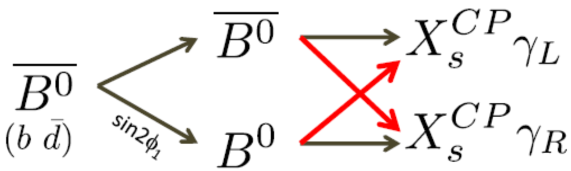
- Uncertainty in ΔA_{CP} to be $\pm$0.37 % $\to$ 13.5σ if the central value not change [from BaBar's measurement $\Delta A_{CP}(X_s\gamma)$ = +(5.0 $\pm$ 3.9 $\pm$ 1.5)%] [Belle II : +(5.0 $\pm$ 0.37)%]

Time dependent CPV

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



dotted : helicity flip



red : helicity flip+NP

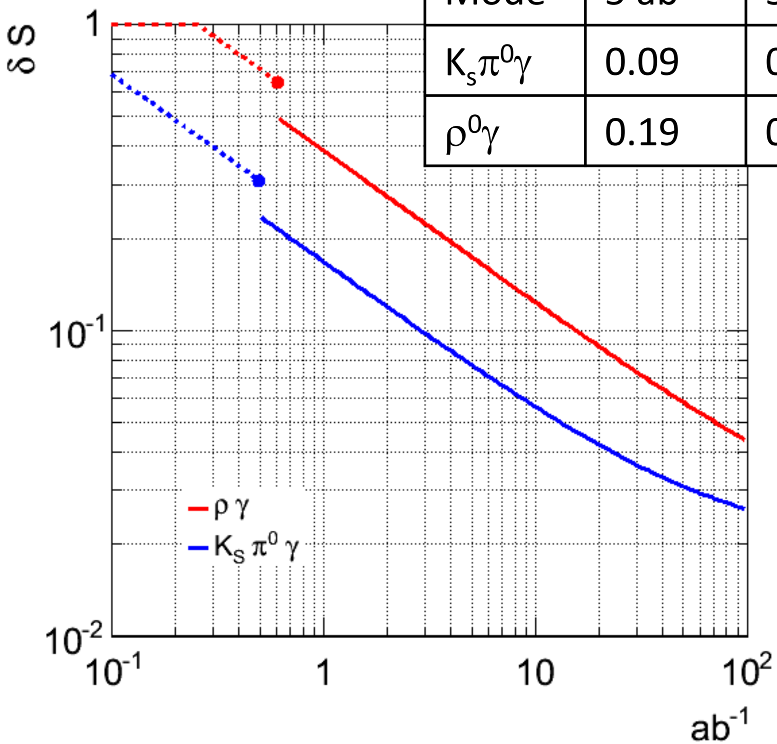
- New physics with right handed current increases the fraction of right handed photon.
  - Interfere with the SM occurs and large TDCPV possible
- Studies of these asymmetries are thus considered to be one of the most promising methods to search for non-SM right-handed currents

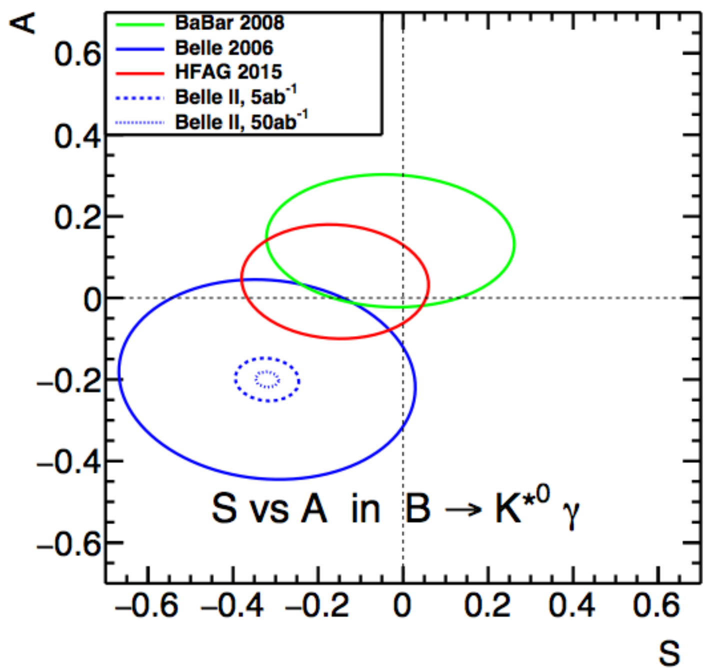
Time dependent CPV

- 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



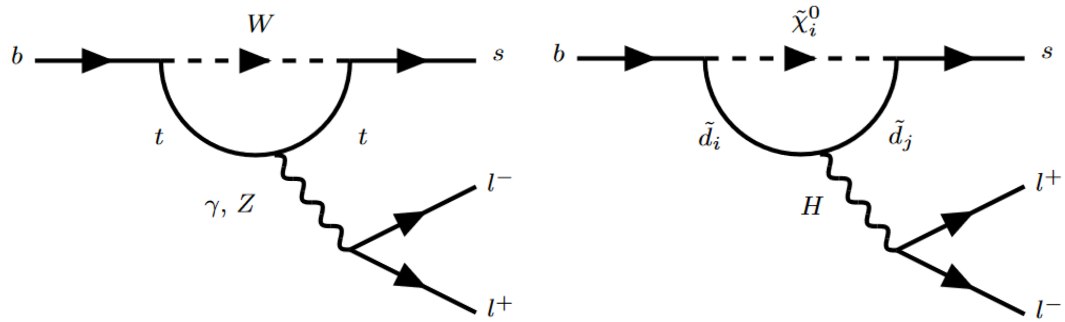


16σ deviation with 50 ab^{-1}.

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

Ratio of B → Kμμ and B → Kee

- B → Kll proceeds via one loop diagram, and LU holds in SM.

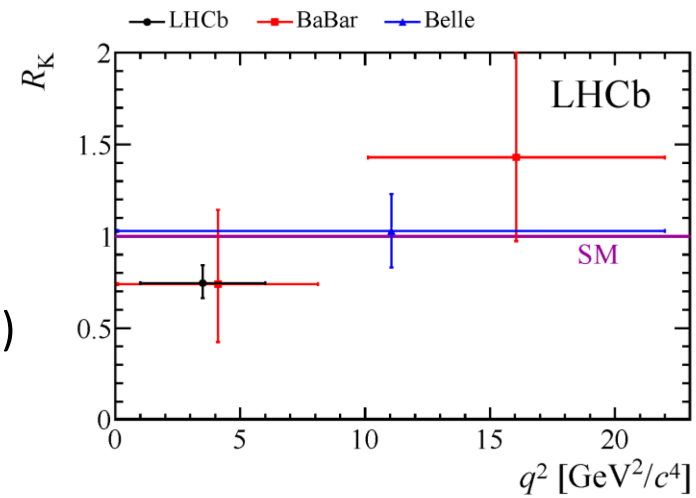


- LHCb reported 2.6σ deviation of ratio of BFs from unity.

$$R(K) = 0.745^{+0.090}_{-0.074} \pm 0.036$$

PRL 11, 151601 (2014)

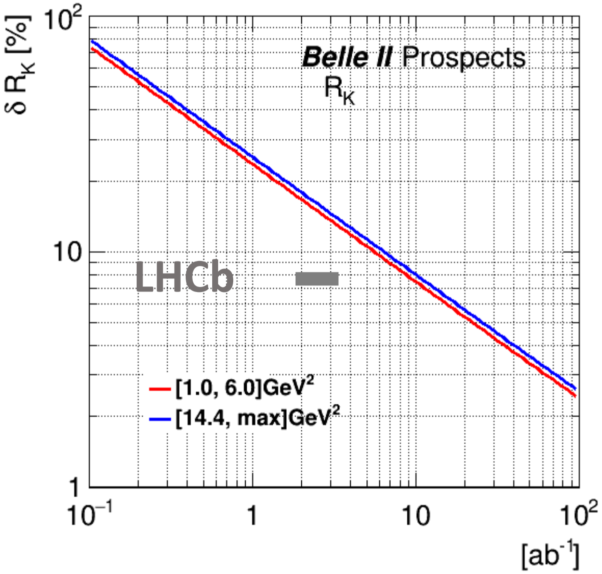
- However electron mode is challenging at LHCb, especially for high q^2.

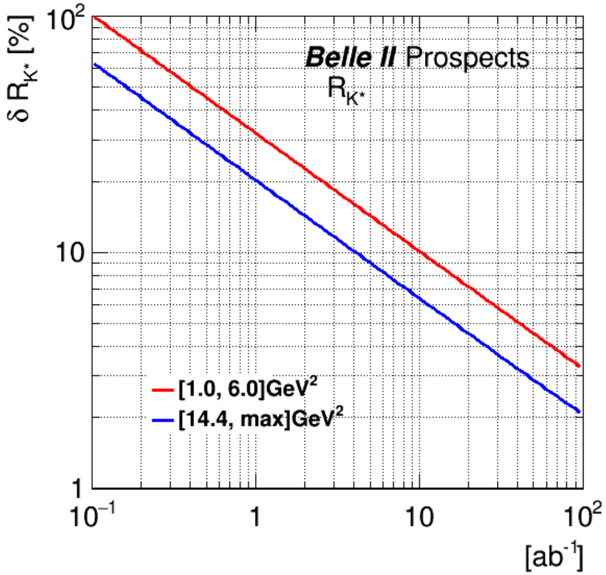


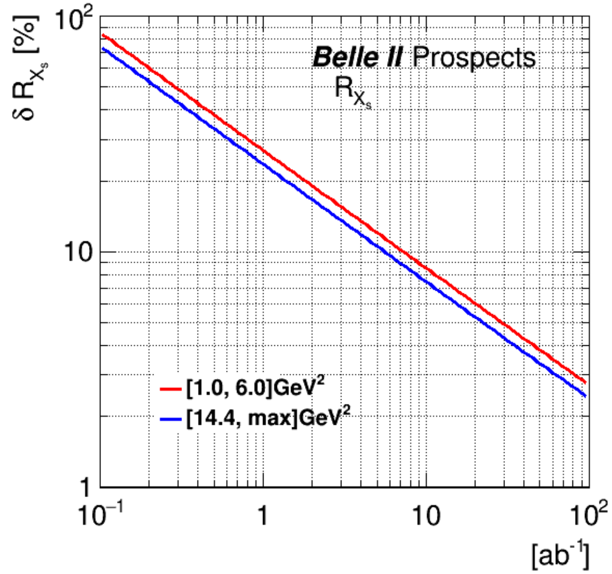
- At Belle II:
  - electron and muon modes have similar efficiency.
  - Both low and high q^2 regions are possible.
  - All ratios R(K), R(K*), R(X_s) are possible.

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

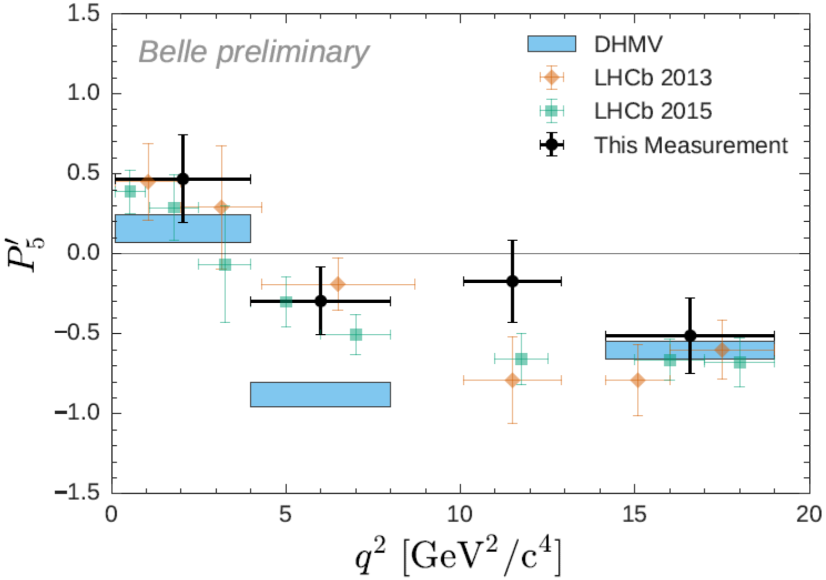
The errors reach to 0.04 for all K, K* and Xs modes in Belle II.
Errors are still statistical dominant (systematic error ~ 0.4%)







Angular Analysis $B \rightarrow K^* l^+ l^-$ (at Belle II)



Angular Analysis of $B \rightarrow K^* \ell^+ \ell^-$

- Demonstrated that Belle can make a contribution to the $b \rightarrow s\ell^+\ell^-$ puzzle
- Found 2.6σ deviation from the Standard Model prediction
- Shows P_5' anomaly is unlikely to be a statistical fluctuation
- No significant lepton flavor non-universality is found

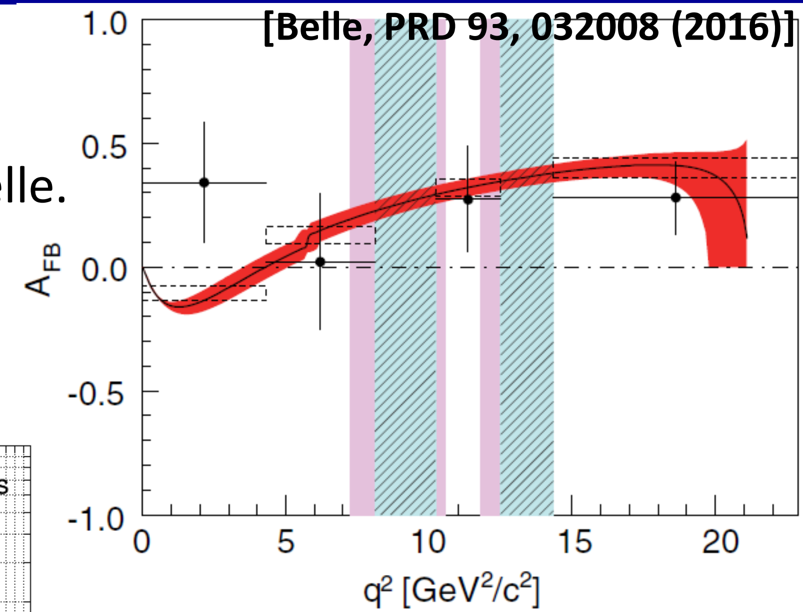
See Simon Wehle's talk in this conference

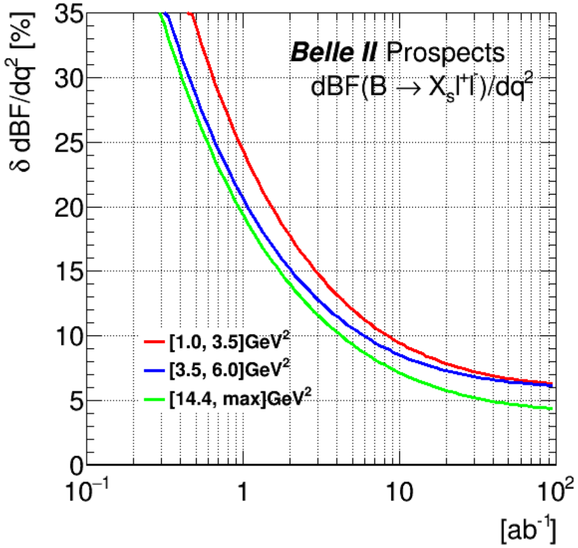
- Belle II and LHCb will be comparable for this process.
- electron mode more efficiently
- Belle II will be also be able to do isospin comparison (K^{*0}, K^{*+} or ground states K).

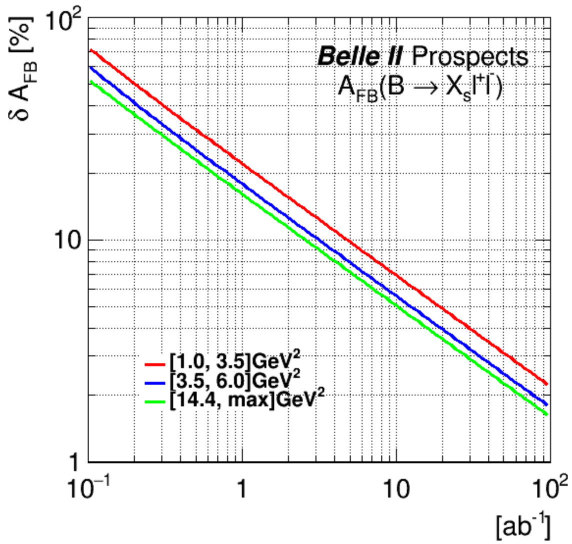
q^2 (GeV^2c^{-4})	Belle	LHCb ($3\ fb^{-1}$)	Belle II
0.1 – 4	0.416	0.109	0.059
4 – 8	0.277	0.099	0.040
10.09 – 12	0.344	0.155	0.049
14.18 – 19	0.248	0.092	0.033

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

- Inclusive measurement is theoretically cleaner than exclusive.
- 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.

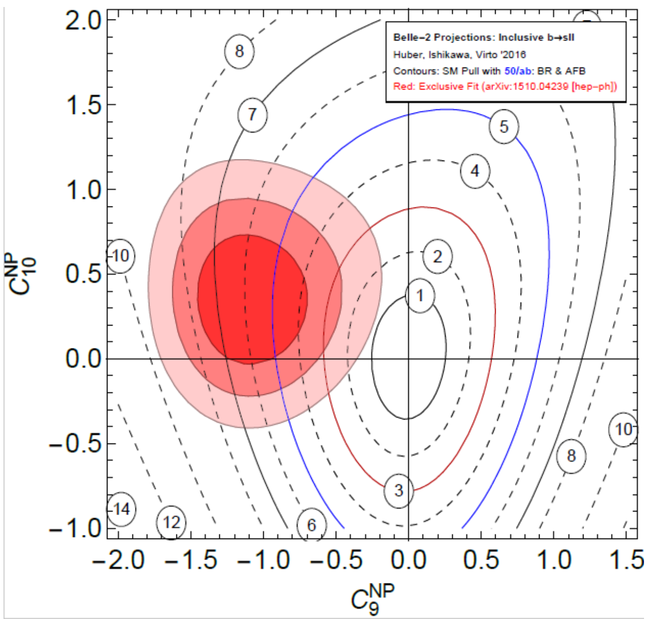






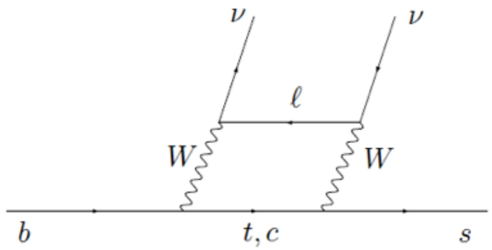
- Decay amplitude can be expressed in terms of C_7, C_9, and C_{10}.
- Precise theory prediction available.

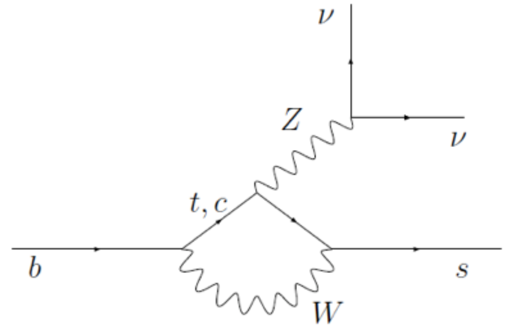
T. Huber, J. Virto, A. Ishikawa →



$b \to s\nu\bar{\nu}$

In the SM:

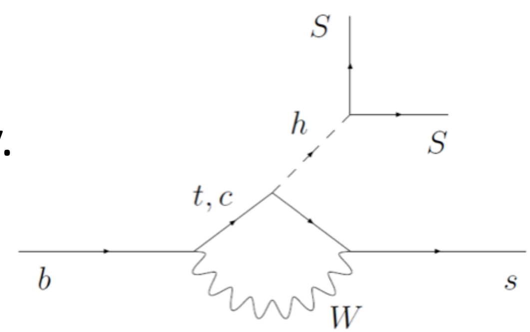


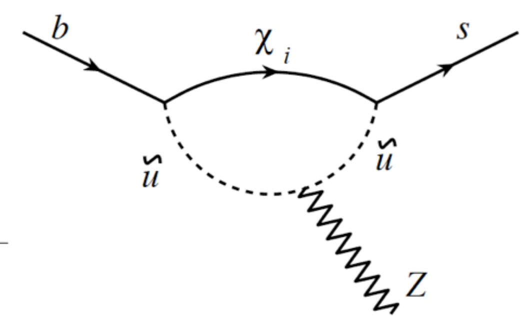


- SM predictions ([1] JHEP 02 184, 2015) updated BELLE2-MEMO-2016-007[2] [D M Straub]

Mode	$\mathcal{B}$ $[10^{-6}]$ Ref. [2]	$\mathcal{B}$ $[10^{-6}]$ Ref. [1]
$B^+ \to K^+\nu\bar{\nu}$	$3.98 \pm 0.43 \pm 0.19$	4.68 ± 0.64
$B^0 \to K^0_S\nu\bar{\nu}$	$1.85 \pm 0.20 \pm 0.09$	2.17 ± 0.30
$B^+ \to K^{*+}\nu\bar{\nu}$	$9.91 \pm 0.93 \pm 0.54$	10.22 ± 1.19
$B^0 \to K^{*0}\nu\bar{\nu}$	$9.19 \pm 0.86 \pm 0.50$	9.48 ± 1.10

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



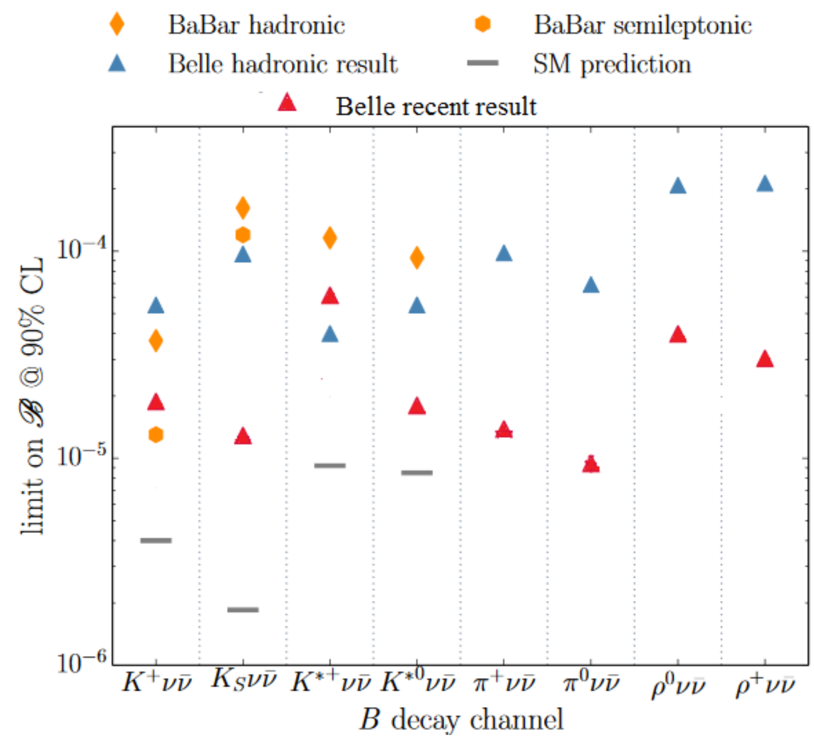


$b \to s\nu\bar{\nu}$: Belle II prospects

- Belle very recently updated $b \to (s,d)\ \nu\bar{\nu}$ measurement.

(See P.Goldenzweig's talk in this conference)

- Brighter prospects for Belle II to observe this decay.
- Belle II extrapolation based on previous Belle measurement (hadronic tag) **Phys.Rev.D87 111103 (2013**) [BELLE2-MEMO-2016-008].
- Assumes 100% more had. tag eff. and 30% more K_s reco. eff.



we are estimating the sensitivities

Mode	$\mathcal{B}$ $[10^{-6}]$	Efficiency Belle $[10^{-4}]$	$N_{\text{Backg.}}$ 711 fb^{-1} Belle	$N_{\text{Sig-exp.}}$ 711 fb^{-1} Belle	$N_{\text{Backg.}}$ 50 ab^{-1} Belle II	$N_{\text{Sig-exp.}}$ 50 ab^{-1} Belle II	Statistical error 50 ab^{-1}	Total Error
$B^+ \to K^+\nu\bar{\nu}$	4.68	5.68	21	3.5	2960	245	20%	22%
$B^0 \to K^0_S\nu\bar{\nu}$	2.17	0.84	4	0.24	560	22	94%	94%
$B^+ \to K^{*+}\nu\bar{\nu}$	10.22	1.47	7	2.2	985	158	21%	22%
$B^0 \to K^{*0}\nu\bar{\nu}$	9.48	1.44	5	2.0	704	143	20%	22%
$B \to K^*\nu\bar{\nu}$ combined							15%	17%

(We can include semileptonic tagging)

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 Nov 2017 (w/o vtx) $\rightarrow$ Phase 3 / Run 1: Fall 2018 (full det.).

- Detector is now mostly installed (CDC rolled in successfully in mid oct.). Gearing up for Phase II.

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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

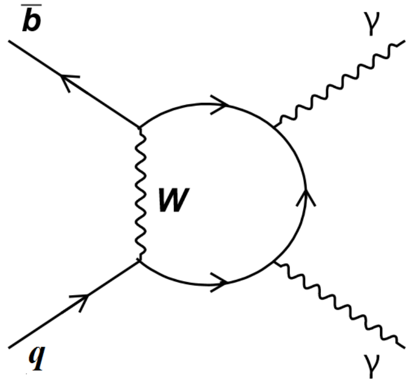
$Br(B_s \to \gamma\gamma)_{exp} < 3.1 \times 10^{-6}$

[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 → sensitive to BSM physics.