Time-dependent CP violation in **b → s γ** transitions at Belle II

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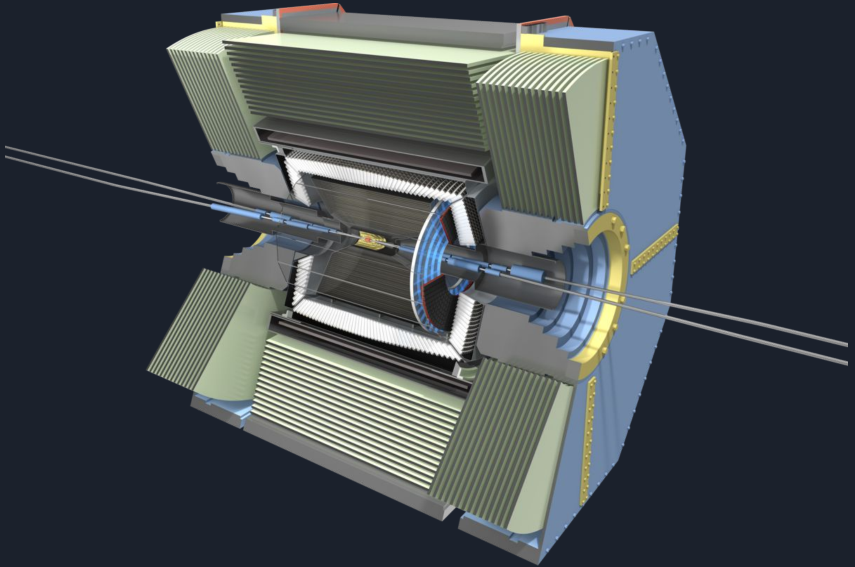
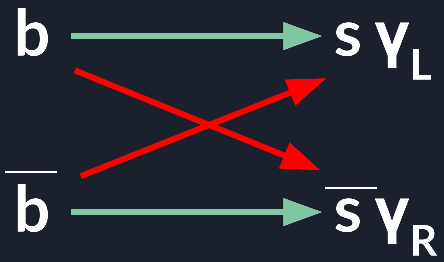


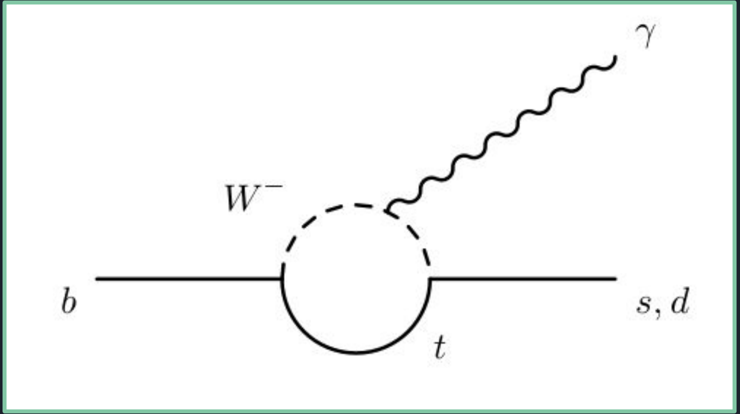
Motivation:

In Standard Model **b → s γ depend on b flavor**



❖ allowed

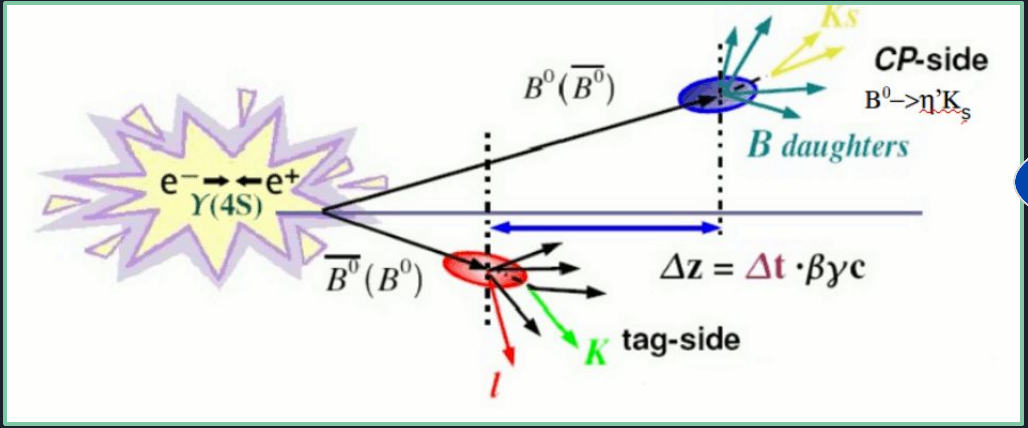
❖ suppressed by m_s/m_b



Presence of significant mixing-induced CP violation would indicate the presence of right handed currents and clear hint of new physics.

- This type of new physics does not require a new phase.

Time-dependant evolution at Belle II



$(\Delta z)_{Belle2} \sim 130\ \mu m$
$(\Delta t)_{Belle2} \sim 0.94\ ps$

$$a_{f_{CP}}(\Delta t) \equiv \frac{\Gamma[B(\Delta t)] - \Gamma[\bar{B}(\Delta t)]}{\Gamma[B(\Delta t)] + \Gamma[\bar{B}(\Delta t)]} = C\cos(\Delta M \Delta t) - S\sin(\Delta M \Delta t)$$

Direct CPV

mixing induced CPV

1. Fully reconstructed one of B mesons which decays to CP eigenstates
2. Tag-side determines its flavour (efficiency ≈ 30%)
3. Proper time (Δt) is measured from decay-vertex difference (Δz).

Inclusive analysis strategies for b → X_s γ

Fully inclusive:

- Exploit clean decay environment on Belle II
- Can be fully hadronic tag (have full event information)
- ...or semi-leptonic tag (don't have full event)

&

Sum-of-exclusives:

- Reconstruct, the 'X' from many exclusive decays: $X_s \rightarrow Kn\pi$, $3Km\pi$, $K\eta m\pi$ $(n>1, m\geqslant1)$
- Know flavor of B
- Know isospin

reco. method	tagging	effi.	S/B	q	p_B	A_{CP}	Δ_{0+}	ΔA_{CP}
sum-of-exclusive	none	high	moderate	s or d	yes	yes	yes	yes
fully-inclusive	had. B	very low	very good	s and d	yes	yes	yes	yes
	SL B	very low	very good	s and d	no	yes	yes	yes
	L	moderate	good	s and d	no	yes	no	no
	none	very high	very bad	s and d	no	no	no	no

Electroweak FCNCs

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu)\, O_i(\mu)$$

Wilson coefficients

(calculated perturbatively; encode short-distance physics)

Products of field operators

(non-perturbative hadronic matrix elements; Heavy quark expansion in inverse powers of m_b)

We can write the amplitude including RH contribution as:

$$\mathcal{M}(b \to s\gamma) \simeq -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left[\underbrace{(C_{7\gamma}^{\text{SM}} + C_{7\gamma}^{\text{NP}})\langle \mathcal{O}_{7\gamma}\rangle}_{\propto \mathcal{M}_L} + \underbrace{C_{7\gamma}^{\prime\text{NP}} \langle \mathcal{O}_{7\gamma}^{\prime}\rangle}_{\propto \mathcal{M}_R} \right]$$

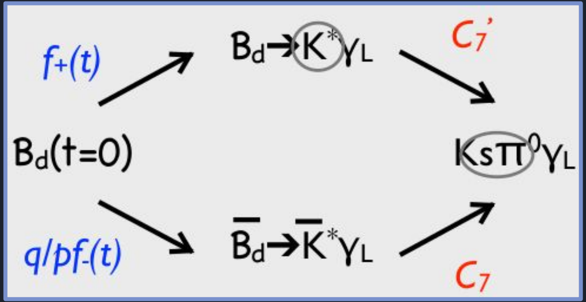
We have a constraint from inclusive branching ratio measurement:

$$Br(B \to X_S \gamma) \propto |C_{7\gamma}^{\text{SM}} + C_{7\gamma}^{\text{NP}}|^2 + |C_{7\gamma}^{\prime\text{NP}}|^2$$

The polarization measurement carries information on

$$\frac{\mathcal{M}_R}{\mathcal{M}_L} \simeq \frac{C_{7\gamma}^{\prime\text{NP}}}{C_{7\gamma}^{\text{SM}} + C_{7\gamma}^{\text{NP}}}$$

Time dependent CP violation analysis of $B^0 \to K_S^0 \pi^0 \gamma$

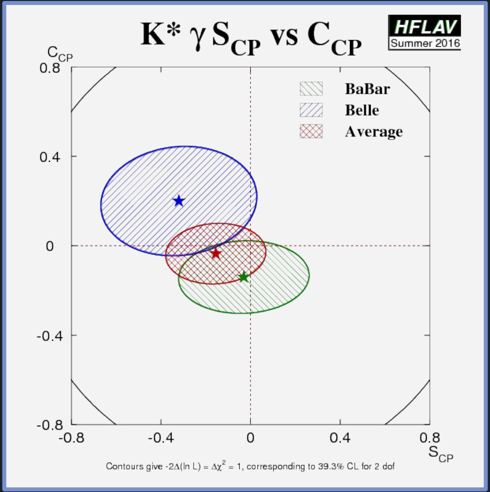


Prediction:

$$S^{SM}_{K^0_S\pi^0\gamma} \sim -2\frac{m_s}{m_b}\sin 2\phi_1 = -(2.3 \pm 1.6)\%$$

Current world average:

$$S^{exp}_{K^0_S\pi^0\gamma} = -0.16 \pm 0.22$$



- $b \to s\gamma_R$ is helicity suppressed (m_s/m_b) wrt $b \to s\gamma_L$
- $B^0 \to f_{CP}\, \gamma_R$ interferes with $B^0 \to B^0$-bar $\to f_{CP}\, \gamma_R$ only for helicity suppressed $b \to s\gamma_R$ decay

- TDCPV analysis is sensitive to the decay rate of b into “wrongly” polarized γ .

- New physics can enhance the $b \to s\gamma_R$ decay rate

BaBar (N_{BB} = 467 * 10^6)[PRD 78 (2008) 071102]

Belle (N_{BB} = 535 · 10^6)[PRD 74 (2006) 111104(R)]

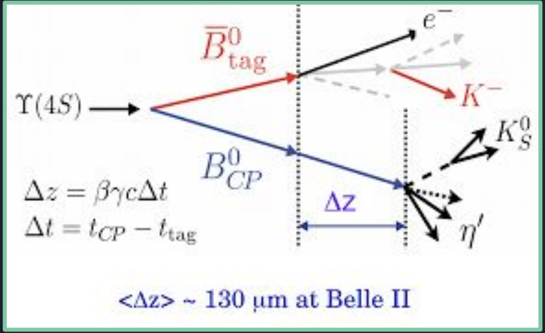
K_S^0 reconstruction

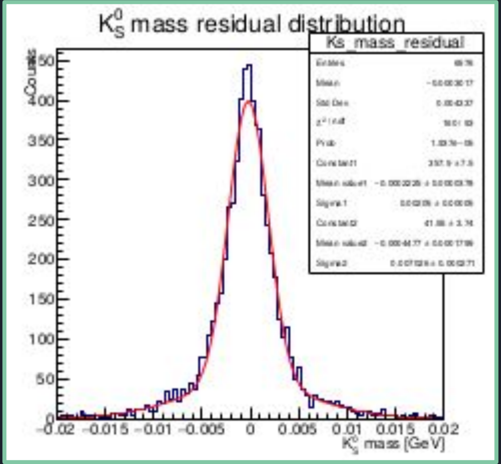
- The reconstruction of K_S^0 is the only source of information to determine the vertex position of B_{sig}^0.

- The channel of K_S^0 reconstruction is $K_S^0 \rightarrow \pi^+ \pi^-$

- The K_S^0 flight direction is extrapolated backwards and matched to the estimated region in which the $e^+ e^-$ collisions take place.

	K_S^0	π^0	γ	B^0
ε^{reco}	58.6 %	53.7 %	83.4 %	26.2 %

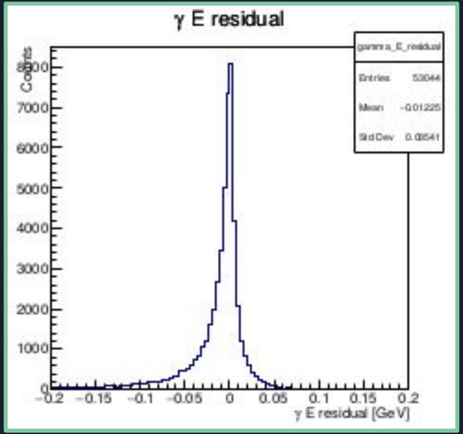


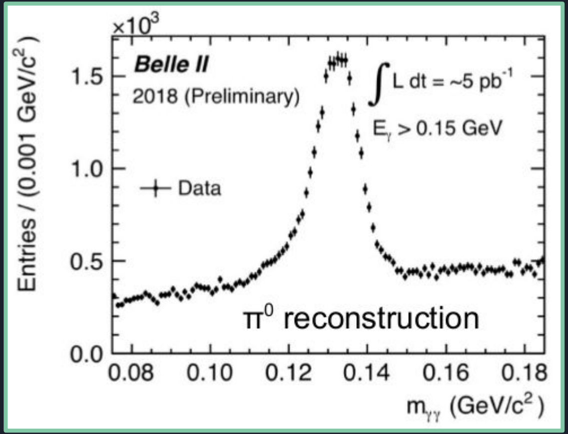


Photon polarization

Indirect probe of photon polarization by measuring:

$$\mathcal{A}_{CP}(t) \equiv \frac{\Gamma(\bar{B}(t) \to f_{CP}\gamma) - \Gamma(B(t) \to f_{CP}\gamma)}{\Gamma(\bar{B}(t) \to f_{CP}\gamma) + \Gamma(B(t) \to f_{CP}\gamma)} \simeq -2\left(\frac{m_s}{m_b}\right)\sin(2\beta)\sin(\Delta m \cdot t)$$





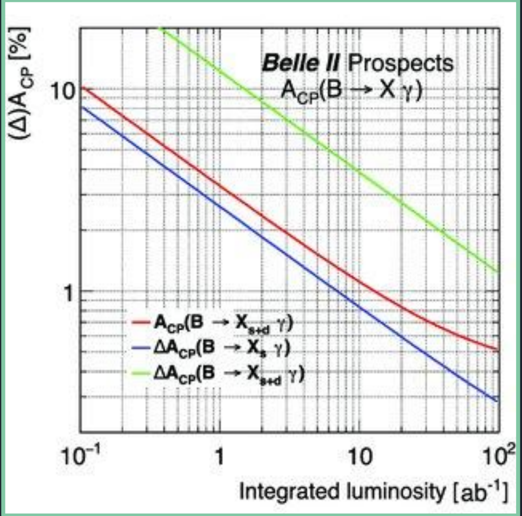
Photon polarization
Standard Model makes definite prediction of photon helicity (D. Atwood et al., Phys. Rev. Lea. 79, 185 (1997)):

- $B^0 \to X_s\, \gamma_R$
- $\bar{B}^0 \to X_s\, \gamma_L$

If a helicity flip occurs, the photon will also flip its helicity, producing
$B^0 \to X_s\, \gamma_L$.
No common final state for B^0 and B^0-bar

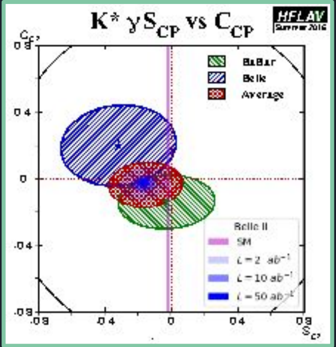
- Suppression of asymmetry S due to interference between B^0 mixing and decay diagrams
- TD CP asymmetry measurements give an indirect measurement of photon polarization.

Predictions for Belle II



Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B \to X_s\gamma)^{\text{lep-tag}}_{\text{inc}}$	5.3%	3.9%	3.2%
$Br(B \to X_s\gamma)^{\text{had-tag}}_{\text{inc}}$	13%	7.0%	4.2%
$Br(B \to X_s\gamma)_{\text{sum-of-ex}}$	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%

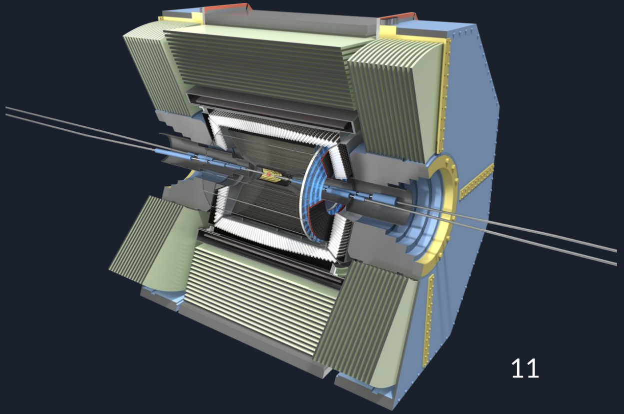
	WA (2017)		5 ab^{-1}		50 ab^{-1}	
Channel	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$
$J/\psi K^0$	0.022	0.021	0.012	0.011	0.0052	0.0090
ϕK^0	0.12	0.14	0.048	0.035	0.020	0.011
$\eta' K^0$	0.06	0.04	0.032	0.020	0.015	0.008
ωK_S^0	0.21	0.14	0.08	0.06	0.024	0.020
$K_S^0\pi^0\gamma$	0.20	0.12	0.10	0.07	0.031	0.021
$K_S^0\pi^0$	0.17	0.10	0.09	0.06	0.028	0.018



Summary

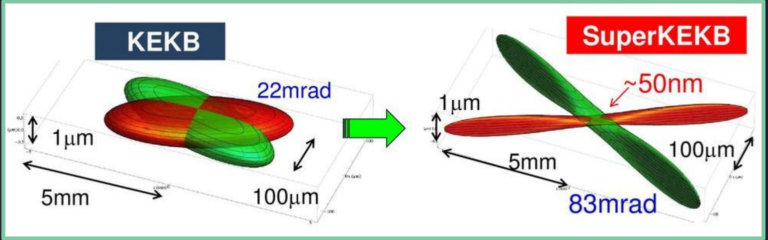
1. Belle II provides a large dataset + improved detector and physics software (Flavor tagging and Vertex reconstruction).
2. Unique possibilities for modes with final state with neutral particles (π^0, γ)
3. For $b \rightarrow s \gamma$ transitions we can safely assume that all the channels will be dominated by the statistical uncertainties.
4. For most of the penguin dominated modes Belle II is projected to reduce the WA errors by a factor of:

- 2 to 3 already with 5 ab^{-1}
- 8 with 50 ab^{-1}



Backup

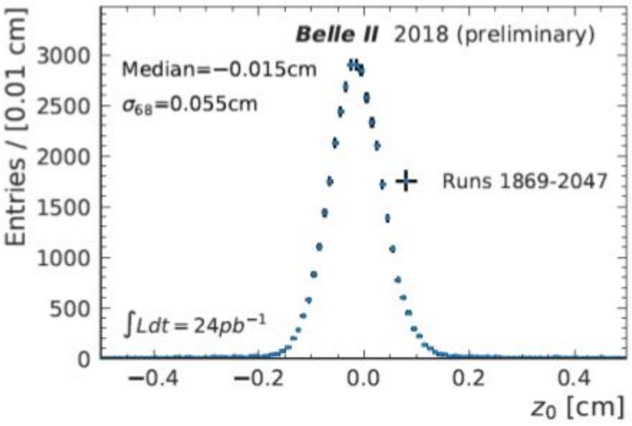
Belle II Nano-Beam

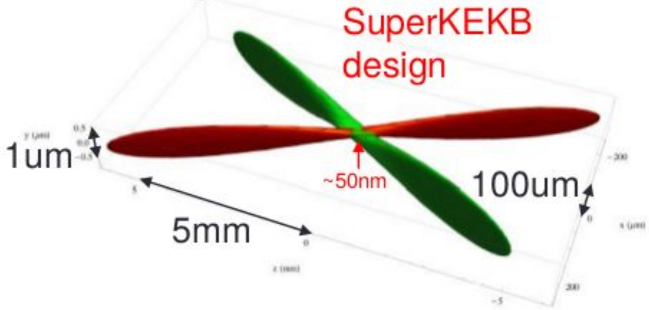


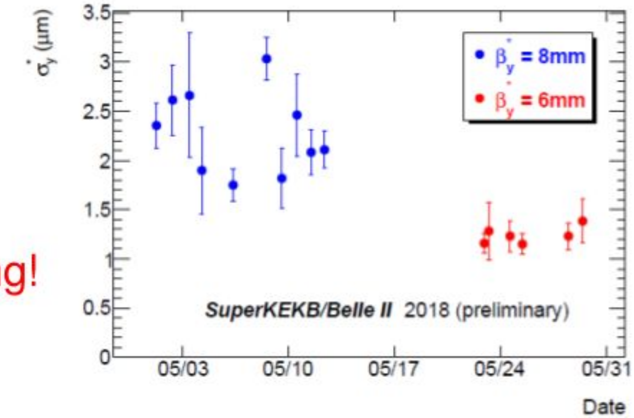
	KEKB Achieved LER	KEKB Achieved HER	SuperKEKB LER	SuperKEKB HER
RF frequency f [MHz]	508.9			
# of Bunches N	1584		2500	
Horizontal emittance εx [nm]	18	24	3.2	4.6
Beta at IP $\beta x^*/\beta y^*$ [mm]	1200/5.9		32/0.27	25/0.30
beam-beam param. ξy	0.129	0.090	0.088	0.081
Bunch Length Sz [mm]	6.0	6.0	6.0	5.0
Horizontal Beam Size sx^* [μm]	150	150	10	11
Vertical Beam Size sy^* [nm]	0.94		48	62
Half crossing angle φ [mrad]	11		41.5	
Beam energy Eb [GeV]	3.5	8	4	7.007
Beam currents Ib [A]	1.64	1.19	3.6	2.6
Lifetime t [min]	133	200	6	6
Luminosity L [$cm^{-2}s^{-1}$]	2.1×10^{34}		8×10^{35}	

Interaction vertex

- Distribution of the longitudinal component of the interaction vertex is much smaller than the bunch length







- The nano beam scheme is working!