Time-dependent CP violation measurements in radiative penguin decays of B mesons at Belle and Belle II

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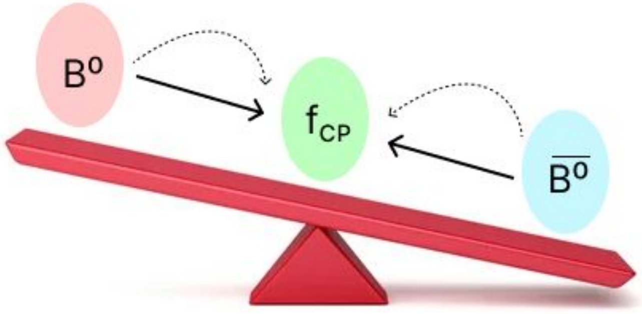
On behalf of Belle II Collaboration

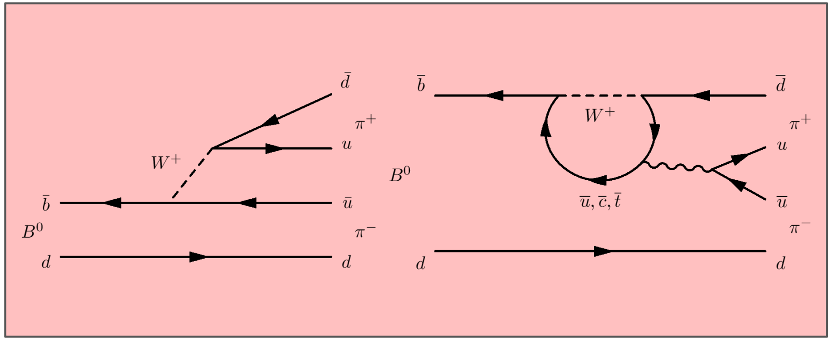
CP violation in B^0 decays



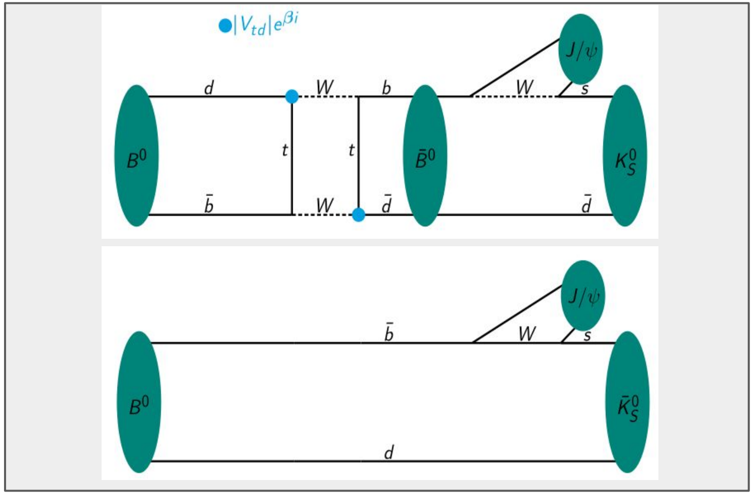
Interference between two paths (amplitudes).

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The CKM quark mixing matrix



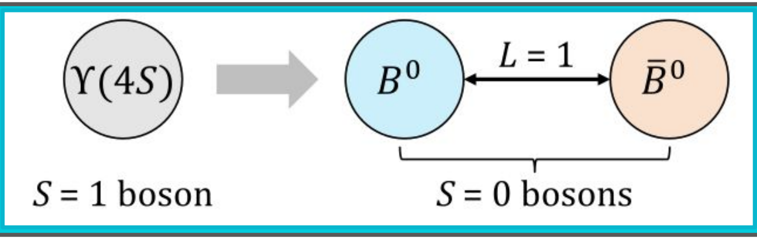
Direct CP Violation (C)



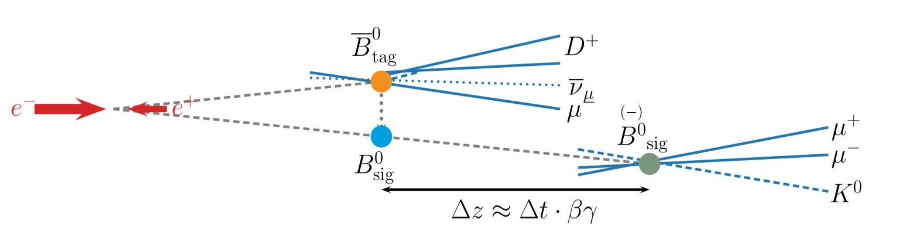
Mixing Induced CP Violation (S)

TDCPV analyses in B factories

Pair produced neutral BBbar mesons are in coherence until one of them decays.



Boosted B mesons in the lab frame: easier tag and signal side vertex resolution.



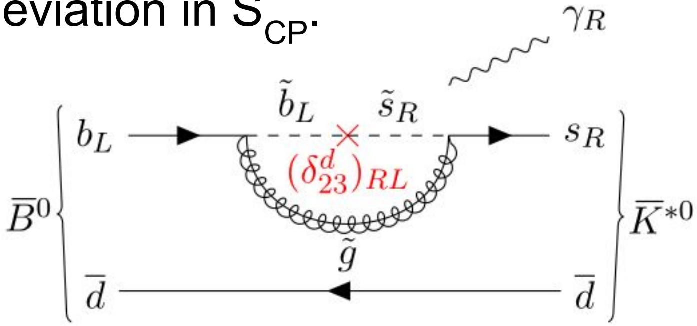
Decay time distribution encodes CP violation parameters.

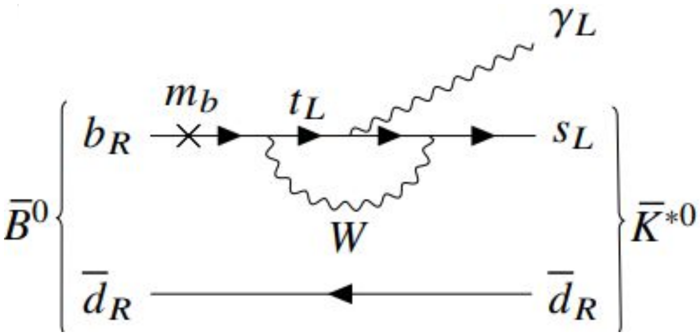
$$\mathcal{A}_{\text{CP}}(\Delta t) = \frac{N(B^0 \to f_{\text{CP}}) - N(\overline{B}^0 \to f_{\text{CP}})}{N(B^0 \to f_{\text{CP}}) + N(\overline{B}^0 \to f_{\text{CP}})}(\Delta t) = (S_{\text{CP}} \sin(\Delta m_d \Delta t) - C_{\text{CP}} \cos(\Delta m_d \Delta t))$$

Radiative Penguin Decays

- ➔ Proceeds via one-loop diagrams at the lowest order.
- ➔ Final state not a proper CP eigenstate due to photon polarisation.
- ➔ S_{CP} helicity suppressed as $b_L \rightarrow s_R \gamma_R$ is m_s/m_b suppressed compared to $b_R \rightarrow s_L \gamma_L$
- ➔ NP processes could contribute to a significant deviation in S_{CP}.

NP Eg: MSSM





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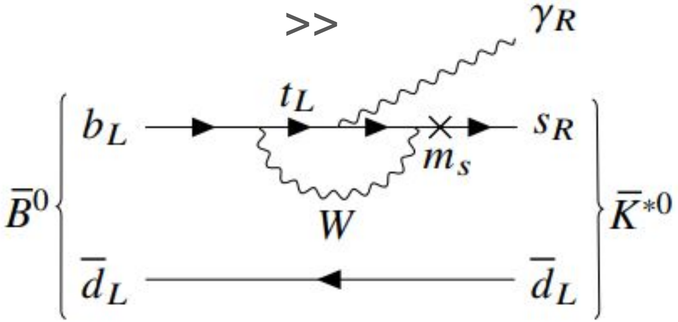
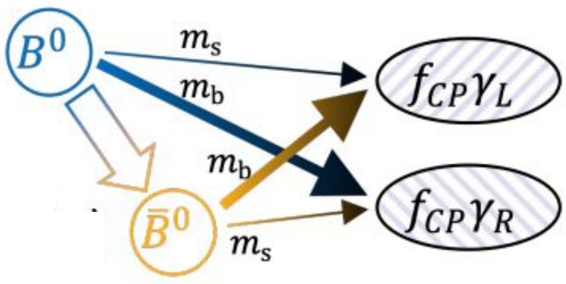




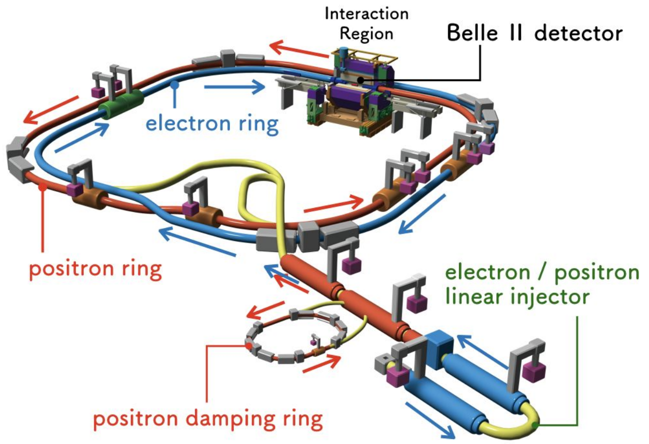
SuperKEKB and Belle II

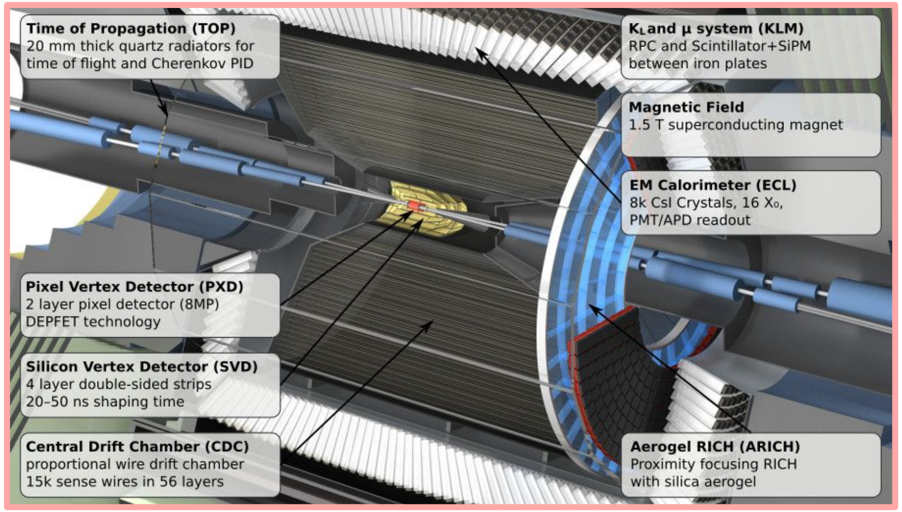
SuperKEKB: an asymmetric e^+e^- collider with electron (positron) beam energies at 7 (4) GeVs.

- ➔ World record for the highest instantaneous luminosity!
- ➔ Total $\Upsilon(4s)$ Run 1 data: 365 fb^{-1}

Belle II: detector built around the interaction point of the two beams.

- ➔ ~2x impact parameter resolution as compared to Belle.
- ➔ Better reconstruction efficiency of neutrals eg K_s, π^0 etc.





$K_s\pi^0\gamma$: Introduction

- ➔ b $\rightarrow s\gamma$ decay, proceeds via one loop FCNC process at the leading order.
- ➔ S_{CP} suppressed by (m_s/m_b).
- ➔ Largest branching fraction ($K^*\gamma$) amongst radiative penguin modes and hence highest potential for NP search.
- ➔ Theoretical uncertainty of a few % due to charm loop effect.
  - ◆ $S^{SM} = -(2.3 \pm 1.6)\%$[1]

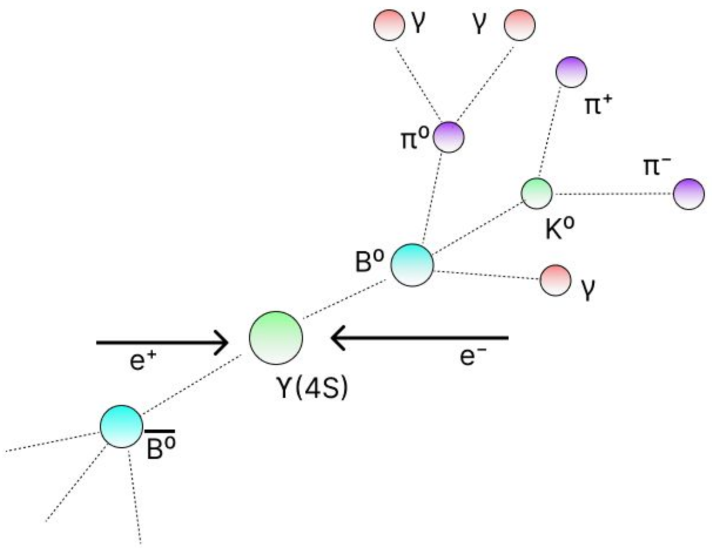
[1] P. Ball, G. W. Jones, and R. Zwicky, Phys. Rev., D75, 054004 (2007)

$K_s\pi^0\gamma$: Event Selection

K_s selection:
- Use two charged tracks with pion mass hypothesis to reconstruct a Ks.
- Use BDT classifiers for removal of fake candidates.

π^0 selection:
- Use two photon clusters from ECL to form the π^0 candidate.
- Use BDT classifier for removal of fake candidates.

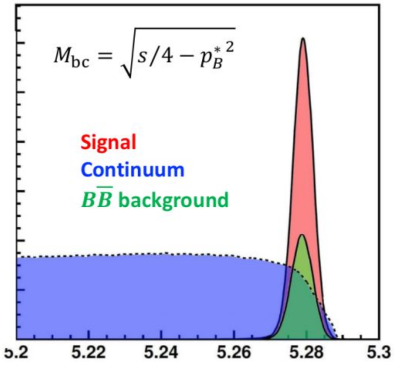
Prompt γ selection:
- Use the highest energy photon cluster from ECL.
- Use BDT based classifier for removal of photons from π^0/η.



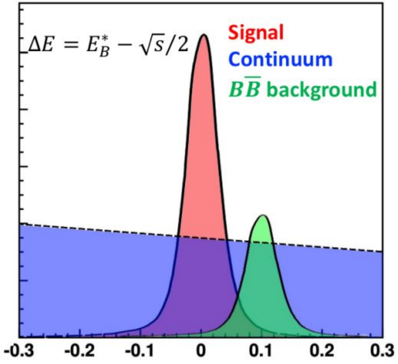
Event selection:
- BDT classifier to suppress continuum background.
- Divide events into two regions:
  - MR1 (K*gamma) $M_{Ks\pi 0} \in [0.8,1]$ GeV/c^2
  - MR2 (Ksπ0γ) $M_{Ks\pi 0} \in [0.6,0.8], [1,1.8]$GeV/c^2

$K_s\pi^0\gamma$: Signal Extraction

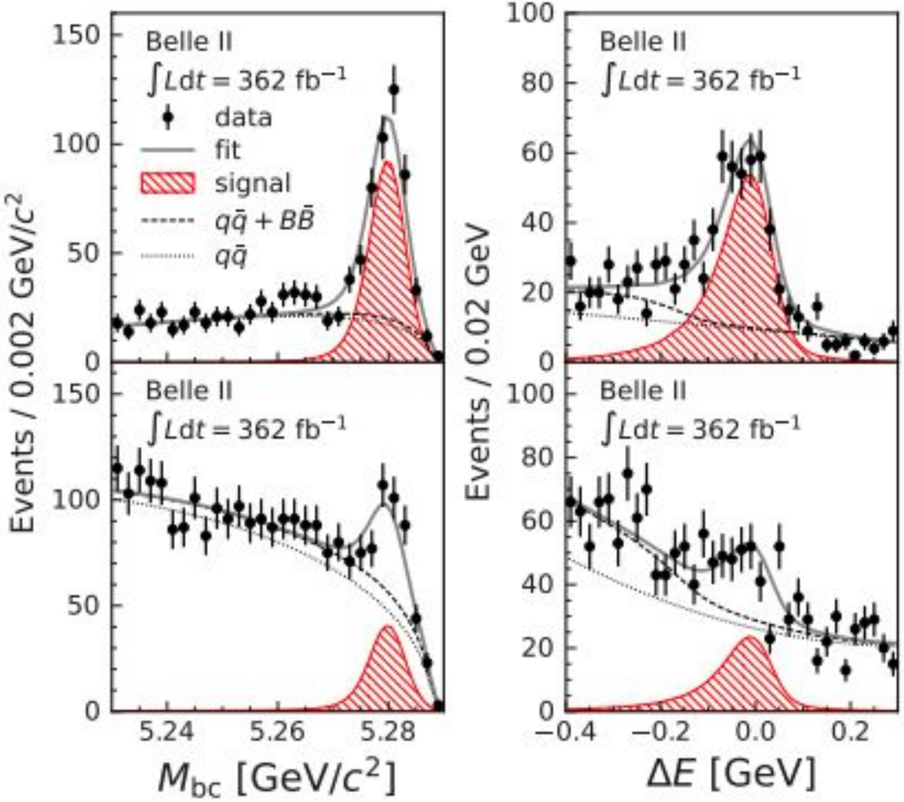
- 2-D fit to M_{bc} - ΔE
- 3 components:
  - signal,
  - qqbar background,
  - BBbar background



Beam-constrained mass [GeV/c2]



Energy difference [GeV]



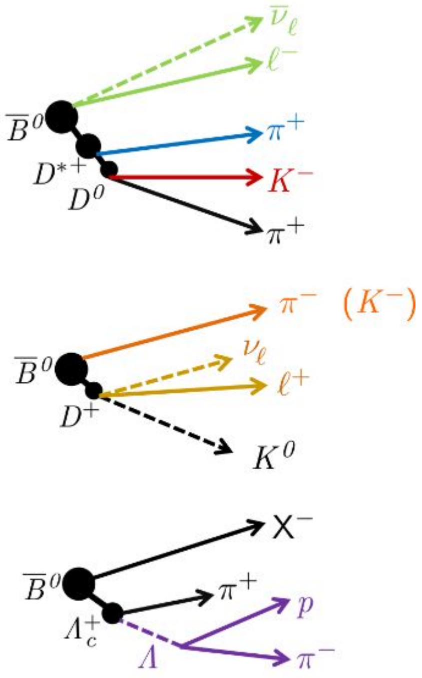
Sample	Signal yield	$B\bar{B}$ bkg yield	S/N
$B^0 \to K_S^0\pi^0\gamma$ in MR1	385 ± 24	20 ± 8	2.36
$B^0 \to K_S^0\pi^0\gamma$ in non-MR1	171 ± 23	69 ± 19	0.34

https://arxiv.org/abs/2407.09139

Detour: Flavor Tagging at Belle II

- ➔ Determine the flavor of tag side B (the other B) at the time of decay.
- ➔ Accomplished using multivariate methods:
  - ◆ Different categories for different signatures of flavor-specific decays.
  - ◆ Returns the tag flavor q and the dilution factor r.
- ➔ Most efficient B flavor-tagger: 33% tagging efficiency (to be superseded by a newly developed GNN based flavor tagger[2])

Categories	Targets
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
KinLepton	e^-
Intermediate KinLepton	ℓ^+
Kaon	K^-
KaonPion	K^-, π^+
SlowPion	π^+
FastHadron	π^-, K^-
MaximumP	ℓ^-, π^-
FSC	ℓ^-, π^+
Lambda	Λ
Total= 13	



[2]. Adachi et al. (Belle II Collaboration), Phys. Rev. D 110, 012001

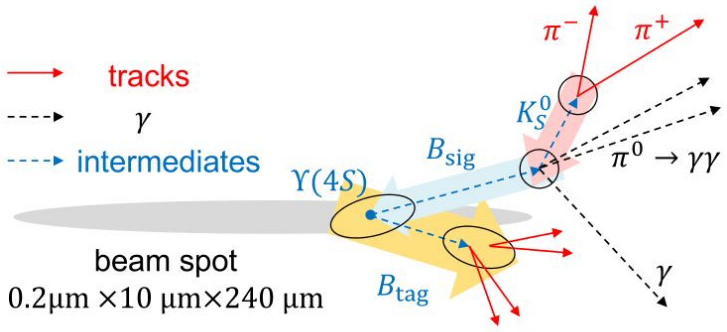
Detour: Vertexing at Belle II

Signal B:

- Uses TreeFitter[3] algorithm to simultaneously fit an entire decay chain.
- Vertexed by using only track information from K_s pions.
- Nano-beam scheme helps in precise determination of beam spot used to further constrain the vertex.
- Events with poor vertex quality reserved for time-integrated fit.

Tag B:

- Uses KFit[4] algorithm to fit the vertex using tracks in the rest of the event.



[3]. Krohn, J.-F. et al. Nucl.Instrum.Meth.A 976 (2020) 164269
[4] J. Tanaka, Belle Note 194.

$K_s\pi^0\gamma$: CPV parameter extraction

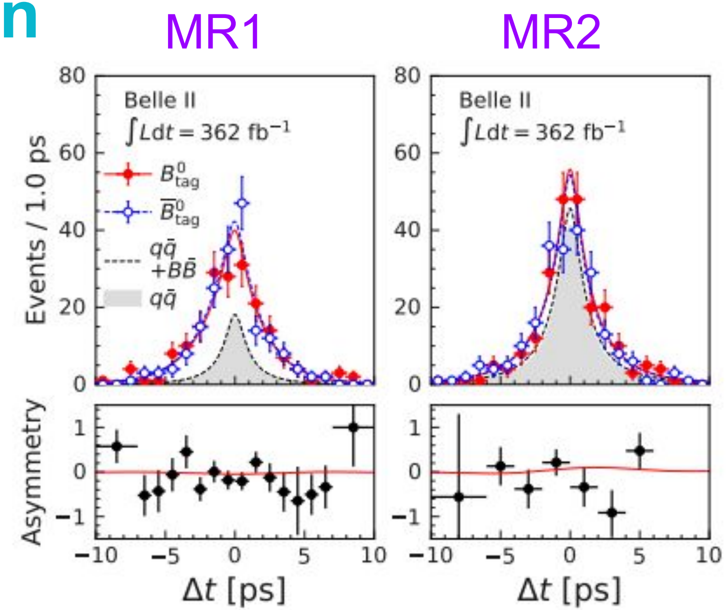
- Fit Δt distribution in seven bins of r values.

Param	Belle II	HFalv
S	$0.00^{+0.27}_{-0.26} \pm 0.03$	−0.16 ± 0.22
C	-0.06 ± 0.25 ± 0.09	−0.04 ± 0.14

CPV in $K^*\gamma$

Param	Belle II	HFalv (*incl $K^*\gamma$)
S	$0.04^{+0.45}_{-0.44} \pm 0.10$	−0.15 ± 0.20
C	0.10 ± 0.13 ± 0.03	−0.07 ± 0.12

CPV in $K_s\pi^0\gamma$



$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 + q \cdot [S \cdot \sin(\Delta m \Delta t) - C \cdot \cos(\Delta m \Delta t)]\}$$

Most precise S_{CP} result till date!

More potential modes at Belle II

$K_S \eta \gamma$	BaBar N(BB)=465M	$-0.18\ ^{+0.49}_{-0.46} \pm 0.12$	$-0.32\ ^{+0.40}_{-0.39} \pm 0.07$
	Belle N(BB)=772M	$-1.32 \pm 0.77 \pm 0.36$	$0.48 \pm 0.41 \pm 0.07$
	Average	-0.49 ± 0.42	0.06 ± 0.29
$K_S \rho^0 \gamma$	BaBar N(BB)=471M	$-0.18 \pm 0.32\ ^{+0.06}_{-0.05}$	$-0.39 \pm 0.20\ ^{+0.03}_{-0.02}$
	Belle N(BB)=657M	$0.11 \pm 0.33\ ^{+0.05}_{-0.09}$	$-0.05 \pm 0.18 \pm 0.06$
	Average	-0.06 ± 0.23	-0.22 ± 0.14
$K_S \varphi \gamma$	Belle N(BB)=772M	$0.74\ ^{+0.72}_{-1.05}\ ^{+0.10}_{-0.24}$	$-0.35 \pm 0.58\ ^{+0.10}_{-0.23}$

Conclusion and Outlook

- ★ Time-dependent study of radiative penguin modes provide a rich ground for search for New Physics.
- ★ Belle II is the most promising experiment for study of these modes due to a clean environment and good neutrals reconstruction.
- ★ We present the most precise results to date for time-dependent study of $K_s\pi^0\gamma$ decays of B mesons, by Belle II.
- ★ The results agree with SM within uncertainty.

Thank You

Backup

$K_s\pi^0\gamma$: Resolution Function Modelling

- Need to model the detector and other effects on decay time difference to get the true deltat distribution.

1. Kinematic approximation: corrects the bias from small B^0 momentum in the CM frame.
2. Sig B decay vertex resolution: accounts for the smearing of the decay vertex position by the finite detector resolution,
3. Tag B decay vertex resolution: consists of the detector resolution and the bias from non-primary decay vertices.

Purpose	Name	Component	Configuration	Readout channels	θ coverage
Beam pipe	Beryllium		Cylindrical, inner radius 10 mm, 10 μm Au, 0.6 mm Be, 1 mm paraffin, 0.4 mm Be		
Tracking	PXD	Silicon Pixel (DEPFET)	Sensor size: 15×(L1 136, L2 170) mm^2, Pixel size: 50×(L1a 50, L1b 60, L2a 75, L2b 85) μm^2; two layers at radii: 14, 22 mm	10M	[17°;150°]
	SVD	Silicon Strip	Rectangular and trapezoidal, strip pitch: 50(p)/160(n) - 75(p)/240(n) μm, with one floating intermediate strip; four layers at radii: 38, 80, 115, 140 mm	245k	[17°;150°]
	CDC	Drift Chamber with He-C_2H_6 gas	14336 wires in 56 layers, inner radius of 160mm outer radius of 1130 mm	14k	[17°;150°]
Particle ID	TOP	RICH with quartz radiator	16 segments in ϕ at $r \sim 120$ cm, 275 cm long, 2cm thick quartz bars with 4×4 channel MCP PMTs	8k	[31°;128°]
	ARICH	RICH with aerogel radiator	2×2 cm thick focusing radiators with different n, HAPD photodetectors	78k	[14°;30°]
Calorimetry	ECL	CsI(Tl)	Barrel: $r = 125 - 162$cm, end-cap: $z = -102 - +196$cm	6624 (Barrel), 1152 (FWD), 960 (BWD)	[12.4°;31.4°], [32.2°;12 [130.7°;155.1°]
Muon ID	KLM	barrel:RPCs and scintillator strips	2 layers with scintillator strips and 12 layers with 2 RPCs	θ 16k, ϕ 16k	[40°;129°]
	KLM	end-cap: scintillator strips	12 layers of (7-10)×40 mm^2 strips	17k	[25°;40°], [129°;155°]

Mode	Experiment	S_{CP} (b → sγ)	C_{CP} (b → sγ)	Correlation	Reference
K*(892)γ	BaBar N(BB)=467M	$-0.03 \pm 0.29 \pm 0.03$	$-0.14 \pm 0.16 \pm 0.03$	0.05 (stat)	PRD 78 (2008) 071102
	Belle N(BB)=535M	$-0.32\ ^{+0.36}_{-0.33} \pm 0.05$	$0.20 \pm 0.24 \pm 0.05$	0.08 (stat)	PRD 74 (2006) 111104
	Average	-0.16 ± 0.22	-0.04 ± 0.14	0.06	HFLAV correlated average χ^2 = 1.9/2 dof (CL=0.40 ⇒ 0.9σ)
$K_S\pi^0\gamma$ (incl. K*γ)	BaBar N(BB)=467M	$-0.17 \pm 0.26 \pm 0.03$	$-0.19 \pm 0.14 \pm 0.03$	0.04 (stat)	PRD 78 (2008) 071102
	Belle N(BB)=535M	$-0.10 \pm 0.31 \pm 0.07$	$0.20 \pm 0.20 \pm 0.06$	0.08 (stat)	PRD 74 (2006) 111104(R)
	Average	-0.15 ± 0.20	-0.07 ± 0.12	0.05	HFLAV correlated average χ^2 = 2.4/2 dof (CL=0.30 ⇒ 1.0σ)
$K_S\,\eta\,\gamma$	BaBar N(BB)=465M	$-0.18\ ^{+0.49}_{-0.46} \pm 0.12$	$-0.32\ ^{+0.40}_{-0.39} \pm 0.07$	−0.17 (stat)	PRD 79 (2009) 011102
	Belle N(BB)=772M	$-1.32 \pm 0.77 \pm 0.36$	$0.48 \pm 0.41 \pm 0.07$	−0.15 (stat)	PR D97 (2018) 092003
	Average	-0.49 ± 0.42	0.06 ± 0.29	−0.15	HFLAV correlated average χ^2 = 2.9/2 dof (CL=0.24 ⇒ 1.2σ)
$K_S\,\rho^0\,\gamma$ (*)	BaBar N(BB)=471M	$-0.18 \pm 0.32\ ^{+0.06}_{-0.05}$	$-0.39 \pm 0.20\ ^{+0.03}_{-0.02}$	−0.09 (stat)	PRD 93 (2016) 052013
	Belle N(BB)=657M	$0.11 \pm 0.33\ ^{+0.05}_{-0.09}$	$-0.05 \pm 0.18 \pm 0.06$	0.04 (stat)	PRL 101 (2008) 251601
	Average(*)	-0.06 ± 0.23	-0.22 ± 0.14	−0.02	HFLAV correlated average χ^2 = 1.9/2 dof (CL=0.38 ⇒ 0.9σ)
$K_S\,\varphi\,\gamma$	Belle N(BB)=772M	$0.74\ ^{+0.72}_{-1.05}\ ^{+0.10}_{-0.24}$	$-0.35 \pm 0.58\ ^{+0.10}_{-0.23}$	-	PRD 84 (2011) 071101

$$
\begin{aligned}
P(\Delta t, q; A, S) = f_{\mathrm{sig}} &\int \mathrm{d}\Delta\tau P_{\mathrm{sig}}(\Delta t, q; A, S, \tau_B) R_{\mathrm{sig}}(\Delta t - \Delta\tau) \\
&+ (1 - f_{\mathrm{sig}}) f_{B\overline{B}} \int \mathrm{d}\Delta\tau P_{\mathrm{sig}}(\Delta t, q; 0, 0, \tau_{B\overline{B}}) R_{B\overline{B}}(\Delta t - \Delta\tau) \\
&+ (1 - f_{\mathrm{sig}})(1 - f_{B\overline{B}}) \frac{1}{2} P_{q\overline{q}}(\Delta t),
\end{aligned} \tag{32}
$$

$$
P_{\mathrm{sig}}(\Delta t, q; A, S, \tau) = \frac{1}{4\tau} e^{-\frac{|\Delta t|}{\tau}} [1 - q\Delta w + q(1 - 2w)(A \cos \Delta m_d \Delta t + S \sin \Delta m_d \Delta t)]. \tag{33}
$$