Time-dependent CP violation in B^0 decays

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Talk Outline

- Introduction
- Time-dependent CP violation
- Detectors: Belle II, LHCb
- Recent results from Belle II

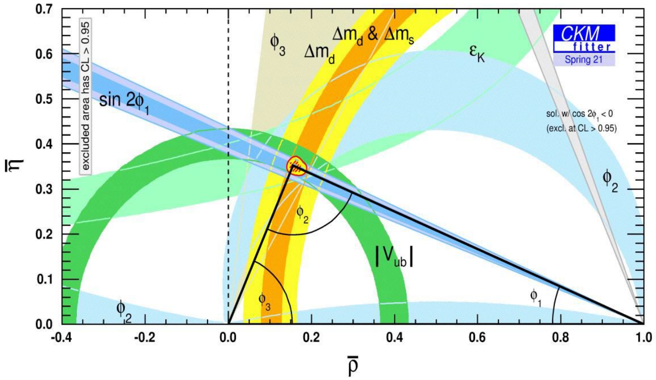
  $B^0 \to \eta' K_s$
  $B^0 \to K_s K_s K_s$
  $B^0 \to \phi K_s$
  $B^0 \to K_s \pi^0$
  $B^0 \to K_s \pi^0 \gamma$
  $B^0 \to J/\psi K_s$
- Recent results from LHCb

  $B^0 \to J/\psi K_s$

- Summary and Outlook

Introduction

- CP violation in Standard Model (SM) is manifested due to a complex phase in the CKM matrix.
- Unitarity of the CKM matrix leads to triangles in the complex (ρ, η) plane.
- Unitarity Triangles are closed in the SM. Any deviation would be a hint for New Physics.
- Precise measurements by Belle, Belle II, LHCb and others lead to improved precision in the measurement of the angles.



$$\Phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \cong \arg(V_{td})$$

$$\beta \equiv \phi_1 = (22.2 \pm 0.7)^\circ$$ (HFLAV 2021)

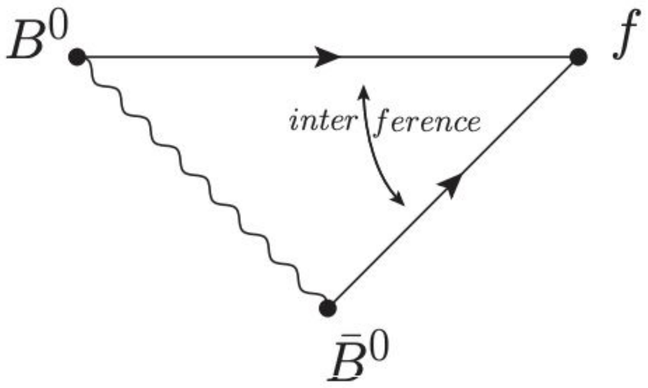
Time-dependent CP violation

CP violation in interference of decays with/without mixing (meson oscillation):

$$\Gamma(P^0_{(\rightsquigarrow \bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0_{(\rightsquigarrow P^0)} \to f)(t)$$

$$A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}}$$

$= \mathbf{S_{CP}} \sin(\Delta m_d t) - \mathbf{C_{CP}} \cos(\Delta m_d t)$



Time-dependent CPV

Mixing-induced CP asymmetry

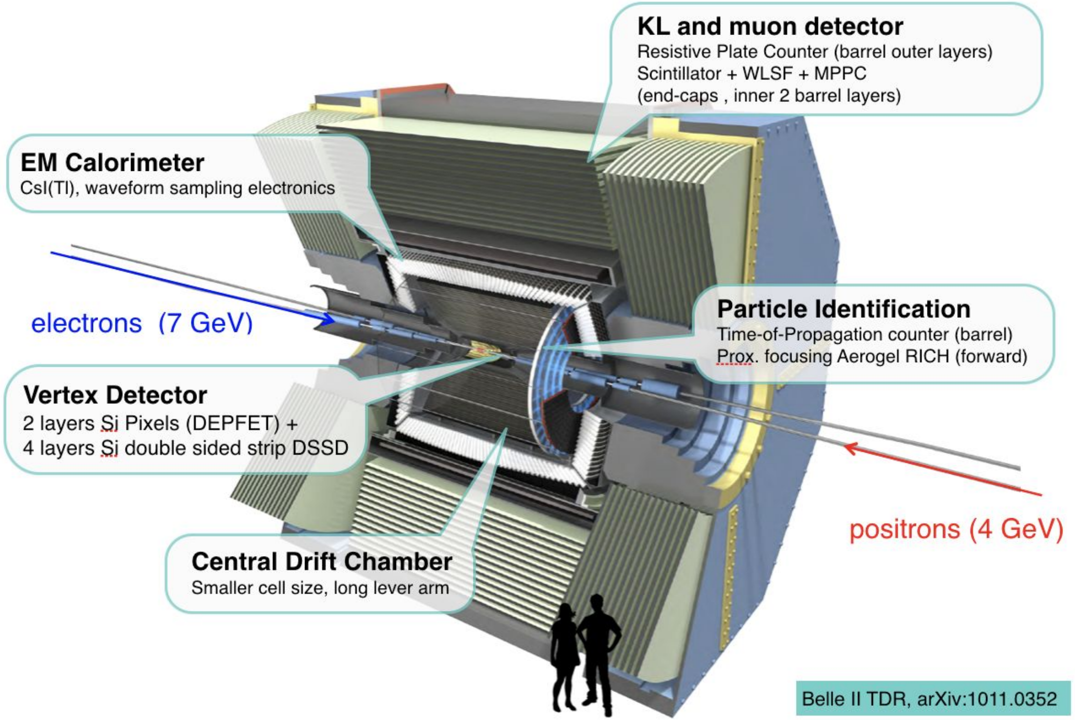
Direct CP asymmetry

In Standard Model, C= 0, S = $\sin 2\phi_1$

Belle and Belle II

- Asymmetric e^+-e^- colliders- B factories, also charm and τ factories
- Belle Belle II: e^+ (3.5 GeV) e^- (8 GeV) → e^+ (4 GeV) e^-(7 GeV)
- Improved vertex resolution allows lower boost
- 424 fb^{-1} (362 fb^{-1} at $\Upsilon(4S)$) collected at Belle II so far; Goal: 50 ab^{-1}

Luminosity Frontier experiment

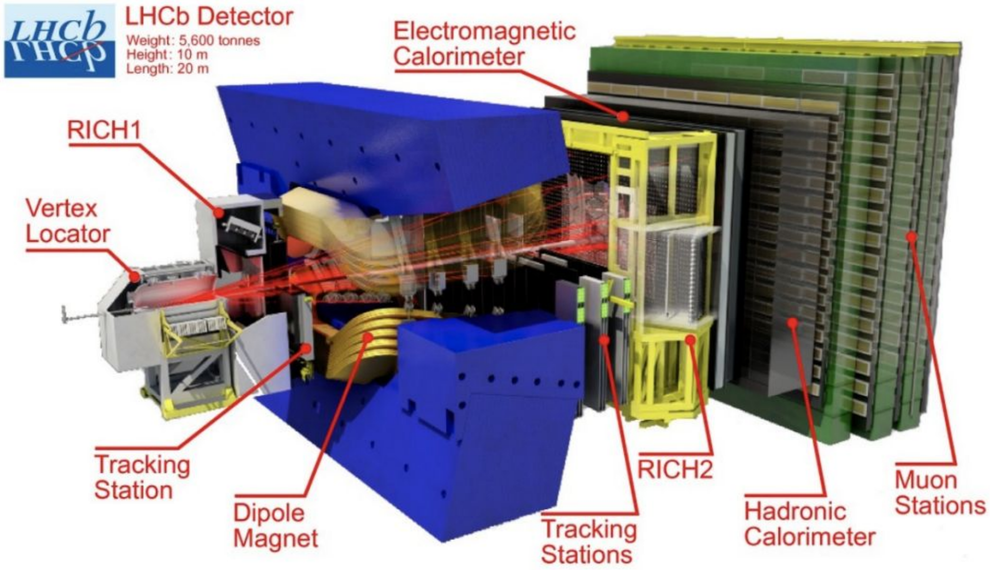


Belle II TDR, arXiv:1011.0352

LHCb

Energy Frontier experiment

- Huge b cross-section
- Excellent vertex resolution and particle identification
- Events with high multiplicity, reconstruction of neutrals is challenging
- 9 fb^{-1} accumulated during Run 1-2 (2010-2018)
- Run 3 started in 2022 with an upgraded LHCb detector, goal 50 fb^{-1}



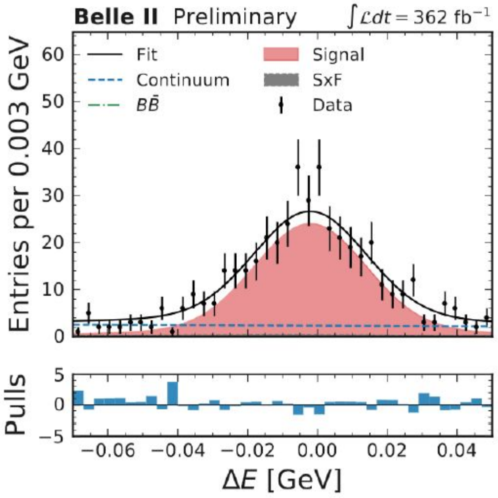
The LHCb Collaboration *et al* 2008 *JINST* 3 S08005

EPS-HEP 2023

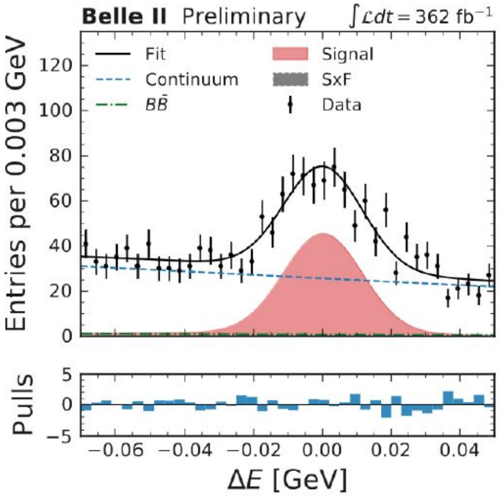
$B^0 \rightarrow \eta' K_s$

- Random combination of tracks from $q\bar{q}$ leads to high background
- Event-shape MVA used to suppress this combinatorial background
- Signal yield = 829 +/- 15 events; Fit Δt to extract S_{CP} and C_{CP}
- Background Δt shape controlled from sideband

$\eta' \rightarrow \eta\pi\pi$



$\eta' \rightarrow \rho\gamma$

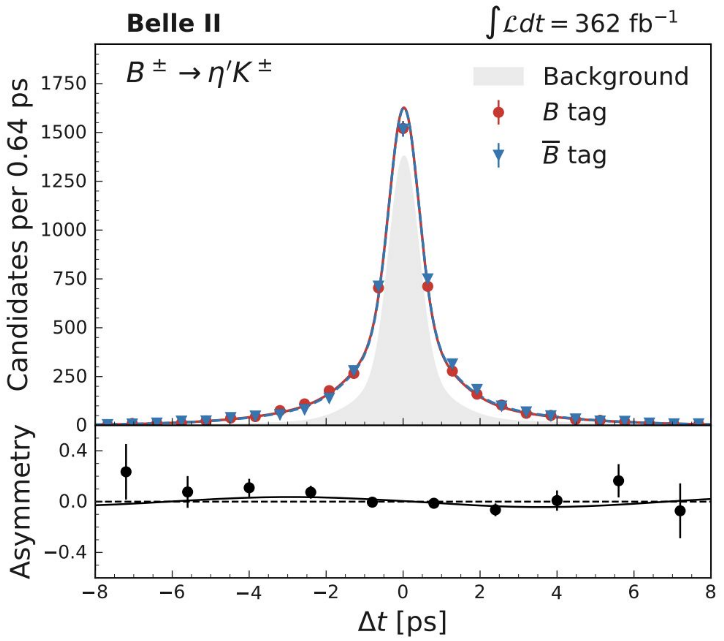


$$\Delta E = E_B^* - E_{\text{beam}}^*$$

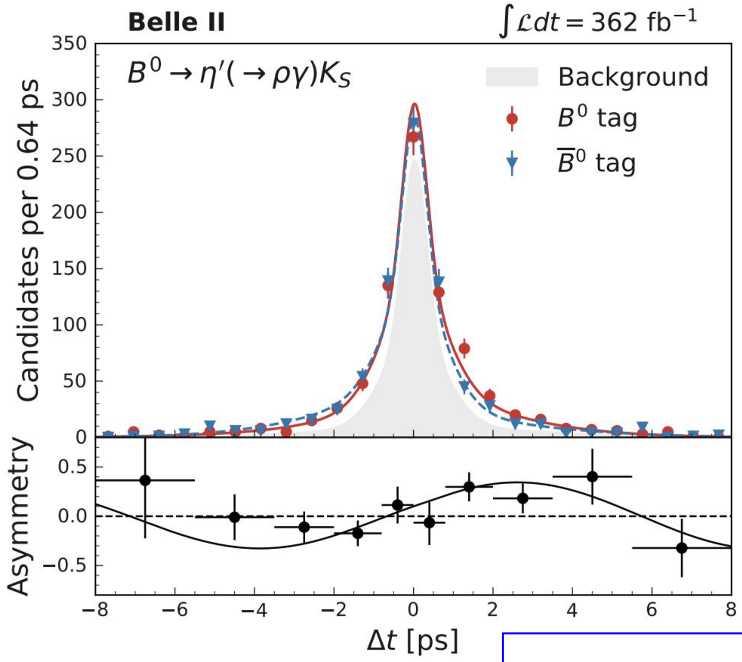
$B^0 \to \eta' K_s$

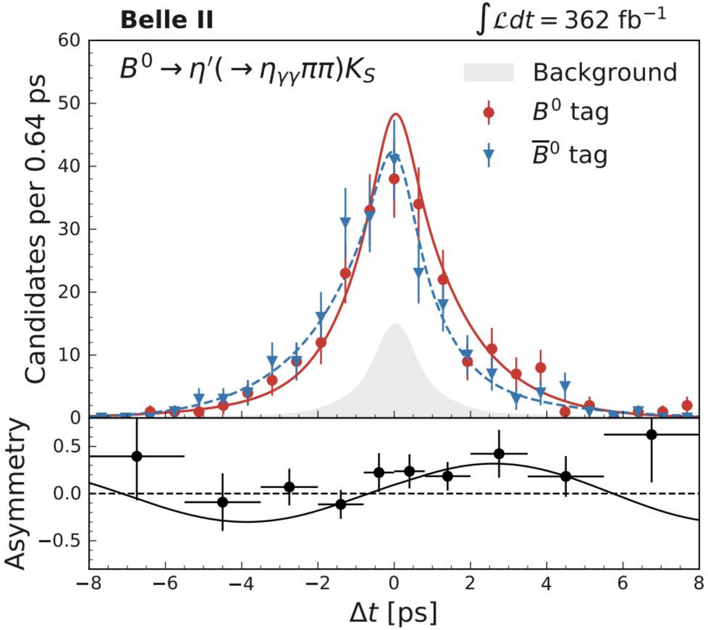
- S_{CP} and C_{CP} extracted from fit in signal region with background parameters fixed from first step
- Fit validated with $B^{\pm} \to \eta' K^{\pm}$

Channel	Signal yield	$C_{\eta' K_S^0}$	$S_{\eta' K_S^0}$
$\eta' \to \eta_{\gamma\gamma}\pi^+\pi^-$	358 ± 20	-0.10 ± 0.13	0.69 ± 0.14
$\eta' \to \rho\gamma$	471 ± 29	-0.24 ± 0.10	0.65 ± 0.13
$\eta' \to \eta_{3\pi}\pi^+\pi^-$	55 ± 8	0.11 ± 0.32	0.25 ± 0.50
Sim. fit	829 ± 35	-0.19 ± 0.08	0.67 ± 0.10



$B^0 \to \eta' K_s$





$$C_{\eta' K_S^0} = -0.19 \pm 0.08 \pm 0.03,$$
$$S_{\eta' K_S^0} = 0.67 \pm 0.10 \pm 0.04,$$

HFLAV: $C_{CP} = -0.05 \pm 0.04$
$S_{CP} = 0.63 \pm 0.06$

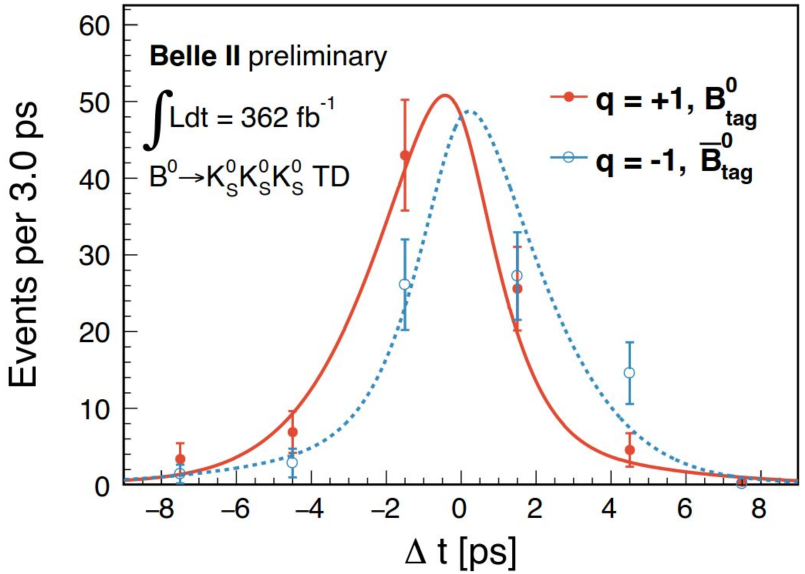
$B^0 \to K_S K_S K_S$

MORIOND 2023

- Major challenge: no prompt tracks→vertex reconstruction from K_S trajectories

- No contributions from opposite-CP backgrounds

$$C_{CP} = -0.07 \pm 0.20 \pm 0.05$$
$$S_{CP} = -1.37^{+0.35}_{-0.45} \pm 0.03$$

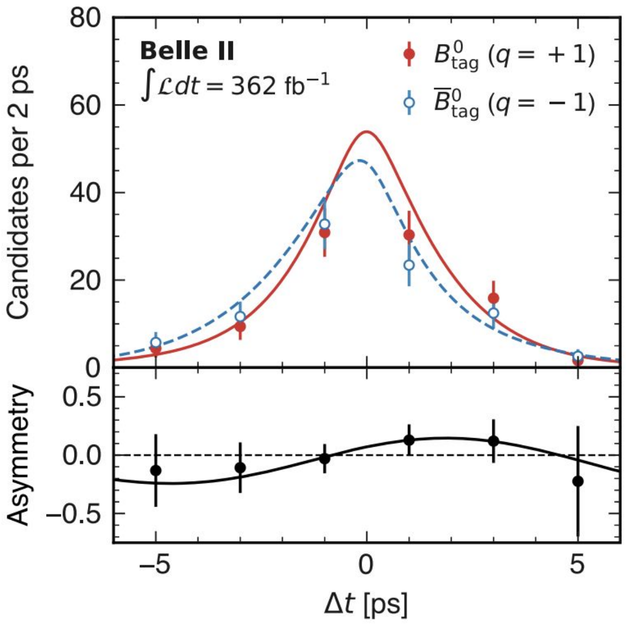


HFLAV: $C_{CP} = -0.15 \pm 0.12$ $S_{CP} = -0.83 \pm 0.17$

$B^0 \rightarrow \Phi K_s$

Phys. Rev. D 108, 072012 (2023)

- Results competitive with best measurements
- Two prompt tracks from $\Phi \rightarrow K^+K^-$: Clean signature
- Major challenge: non-resonant backgrounds with opposite-CP



$$C_{CP} = -0.31 \pm 0.20 \pm 0.05$$
$$S_{CP} = 0.54 \pm 0.26^{+0.06}_{-0.08}$$

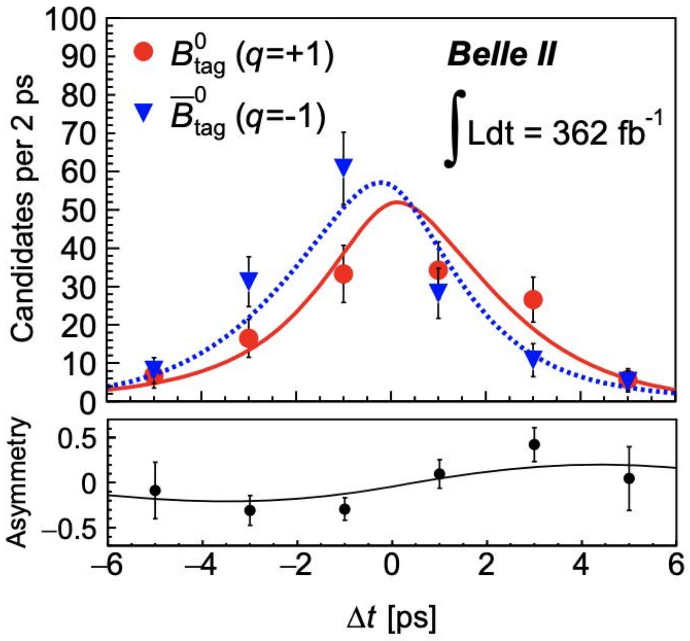
HFLAV: $C_{CP} = 0.01 \pm 0.14$ $S_{CP} = 0.74^{+0.11}_{-0.13}$

$B^0 \to K_s \pi^0$

PRL 131, 111803 (2023)

- First Belle II measurement of CP asymmetries in the decay
- Results competitive with previous measurements
- Fitting to the proper decay-time distribution of a sample 415^{+26}_{-25} signal events

$$C_{CP} = -0.04 \pm 0.15 \pm 0.05$$
$$S_{CP} = 0.75^{+0.20}_{-0.23} \pm 0.04$$



HFLAV: $C_{CP} = 0.01 \pm 0.10$ $S_{CP} = 0.57 \pm 0.17$

$B^0 \to K_s \pi^0 \gamma$

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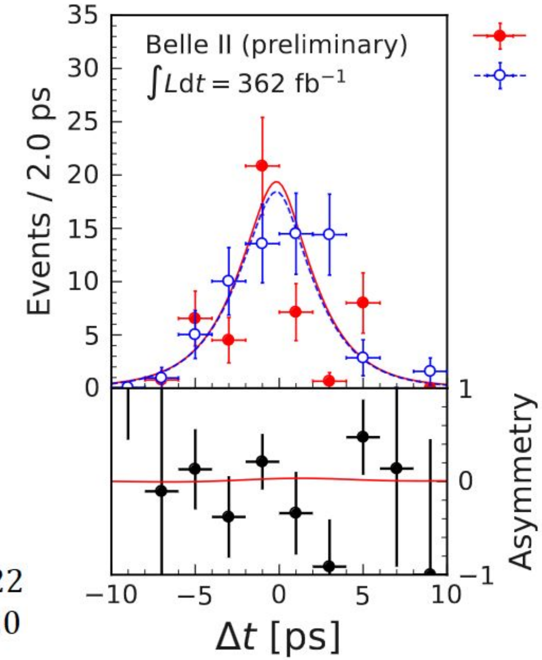
Belle II

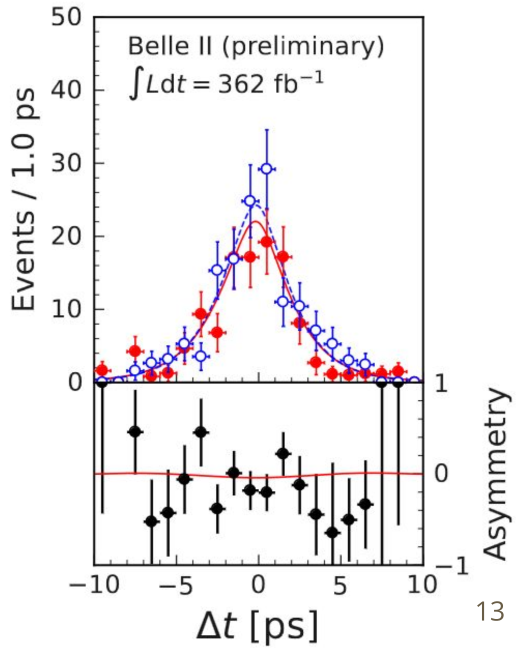
- Consider exclusive decay to $K^{*0}(\to K_S\pi^0)\gamma$ and inclusive decay to $K_S\pi^0\gamma$ separately
- Polarization of photon strongly constrains flavor
- SM: S_{CP} helicity suppressed NP processes could contribute to a significant mixing-induced CPV

$$C_{CP} = 0.10 \pm 0.13 \pm 0.03$$
$$S_{CP} = 0.00^{+0.27+0.03}_{-0.26-0.04}$$

$$C_{CP} = -0.06 \pm 0.25 \pm 0.07$$
$$S_{CP} = 0.04^{+0.45}_{-0.44} \pm 0.10$$

Most precise result till date





HFLAV:

$K^{*0}\gamma$: $C_{CP} = -0.04 \pm 0.14$ $S_{CP} = -0.16 \pm 0.22$

$K_S\pi^0\gamma$: $C_{CP} = -0.07 \pm 0.12$ $S_{CP} = -0.15 \pm 0.20$

$B^0 \to K_s \pi^0 \gamma$

- No prompt tracks - challenge
- Reconstruct vertex only from K_s using beam-spot constraint
- To measure C_{CP} in a time integrated manner, candidates with poor vertex reconstruction are used
- Fake beam background π^0 are suppressed using MVA method to select one candidate

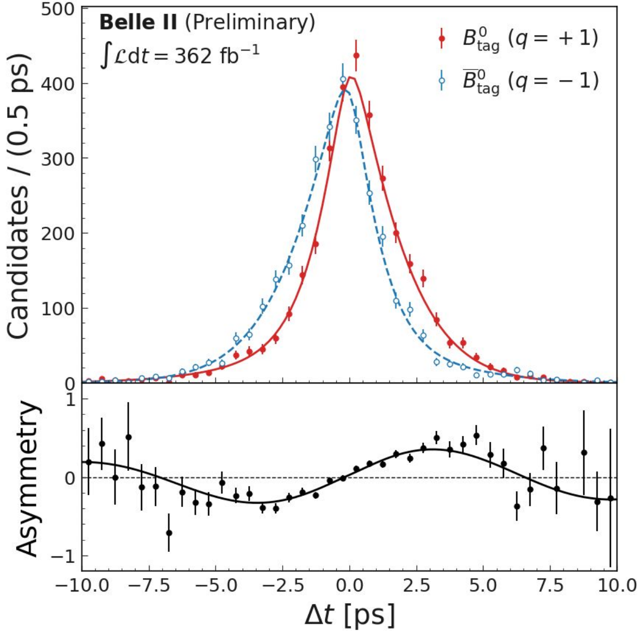
$B^0 \to J/\psi K_s$

EPS-HEP 2023

- SM measurement with large BF and experimentally clean signature
- Validate Flavor Tagger (FT) performance

- New flavor tagger (GFlaT) based on graph neural network (GNN), which uses inter-relational information between particles, developed in Belle II

- ~8% reduction in statistical uncertainty due to a GFlaT

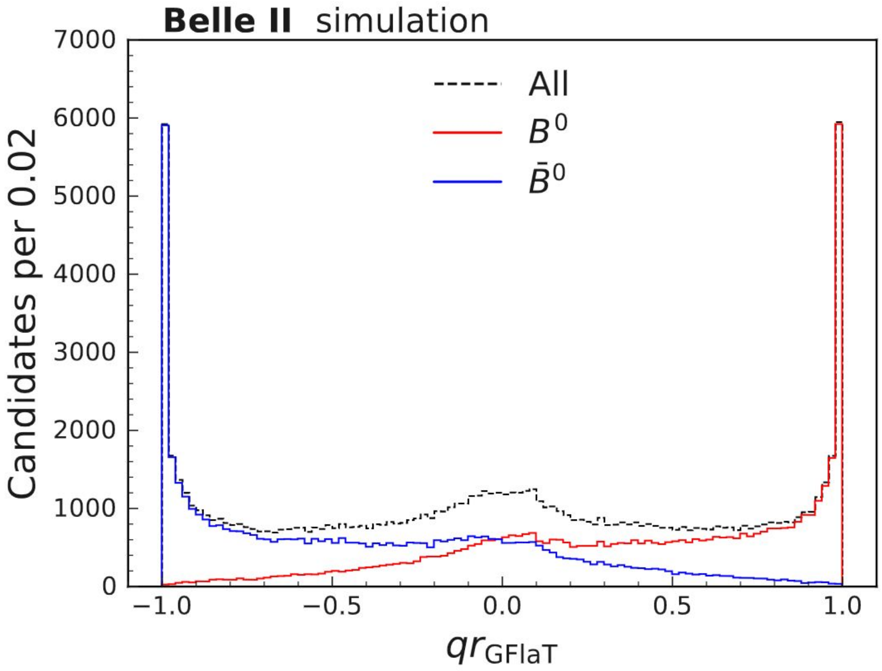


$$C_{CP} = -0.035 \pm 0.026 \pm 0.012$$
$$S_{CP} = 0.724 \pm 0.035 \pm 0.014$$

HFLAV: $C_{CP} = 0.000 \pm 0.020$ $S_{CP} = 0.695 \pm 0.019$

$B^0 \to J/\psi\, K_s$

- Conventional FT:
  ϵ_{tag} = 31.68 ± 0.45 ± 0.41%
- GFlaT:
  ϵ_{tag} = 37.40 ± 0.43 ± 0.34%
- ~18% more effective data due to increase in tagging efficiency compared to conventional flavor tagger!



$B^0 \to J/\psi\, K_s$

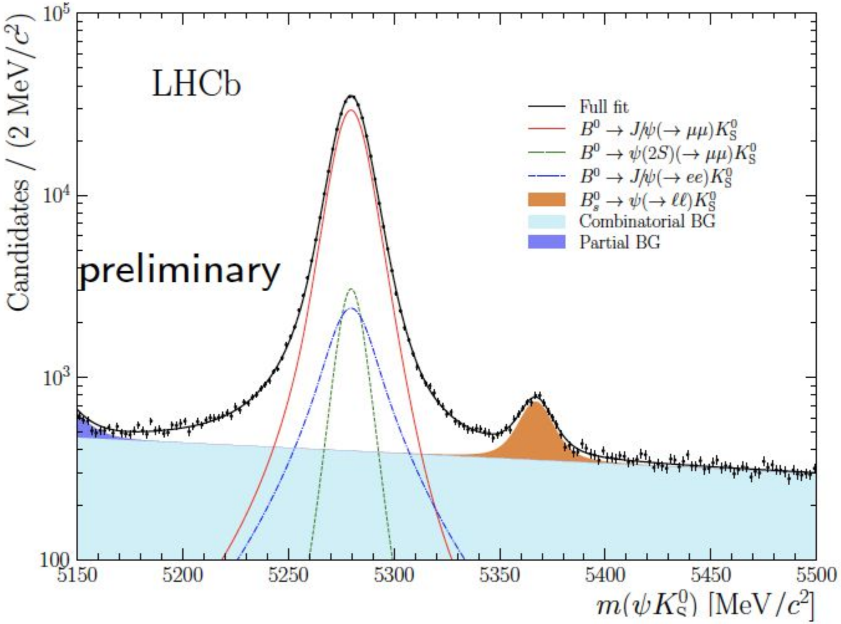
2309.09728 [hep-ex]

(Submitted to PRL)

LHCB-PAPER-2023-013

- New LHCb Run 2 (6 fb^{-1}) results using $B_d \to J/\psi\, K_s$ (both muons and electrons) and $B_d \to \psi(2S)\, K_s$ tagged time dependent analysis to determine sin 2β (= sin 2Φ_1)
- Using Run 1 (3 fb^{-1}) + Run 2 data:

$$S_{\psi K^0_S} = 0.717 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst})$$
$$C_{\psi K^0_S} = 0.008 \pm 0.012\,(\text{stat}) \pm 0.003\,(\text{syst})$$

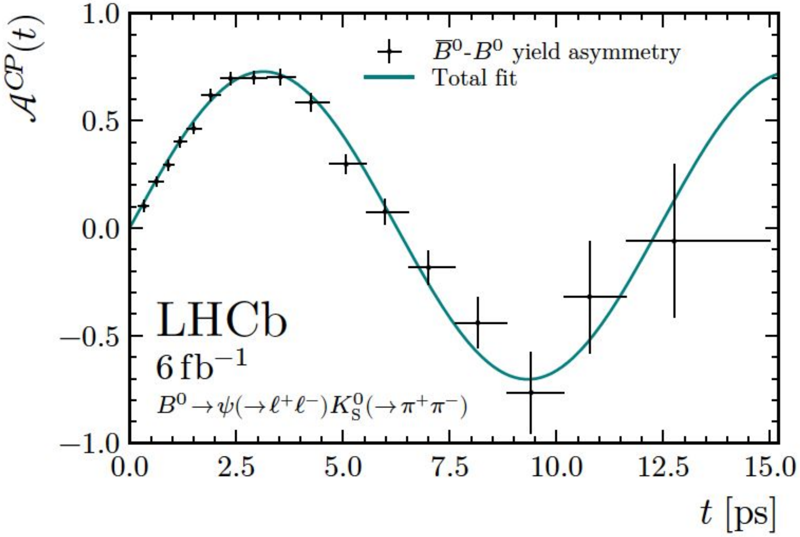


(Simultaneous fit of 3 decay modes, $B^0 \to J/\psi\, (l^+l^-)\, K_s$ and $B^0 \to \psi(2S)\, (\mu^+\mu^-)\, K_s$, where l = e or μ)

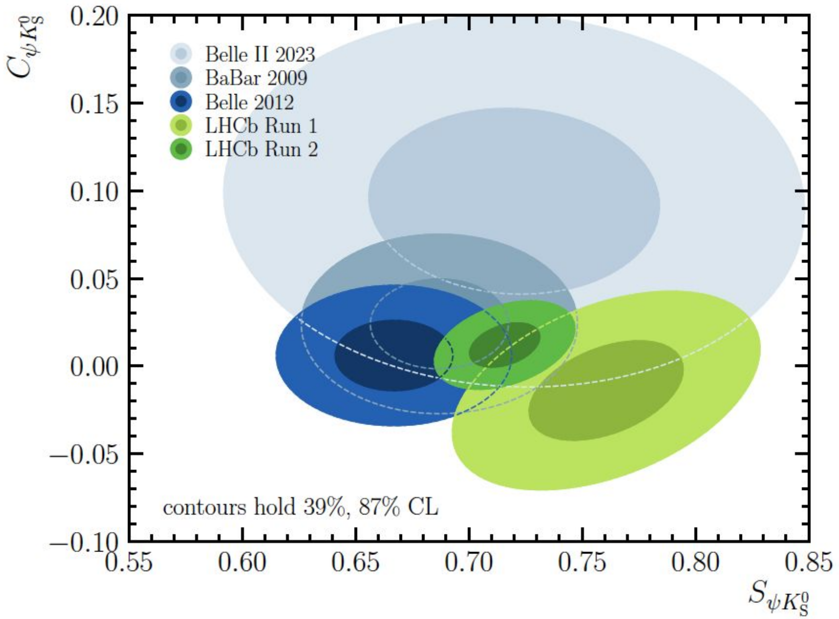
$B^0 \to J/\psi\, K_s$

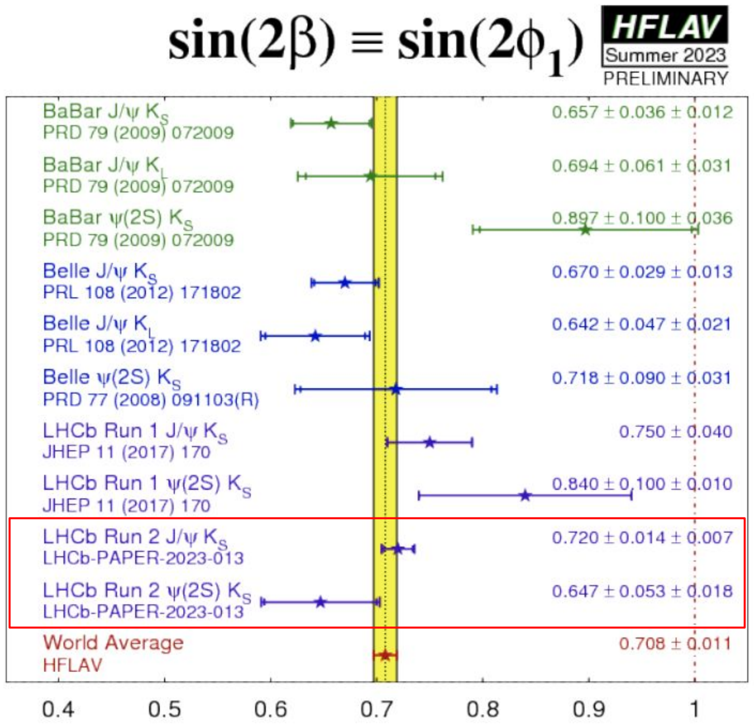
- Small CP violation asymmetry observed
- Consistent with SM predictions
- Using Run 1 (3 fb^{-1}) + Run 2 data, using combination of measurements:

$$S_{\psi K^0_S}^{\text{Run 1\&2}} = 0.724 \pm 0.014\,(\text{stat+syst})$$
$$C_{\psi K^0_S}^{\text{Run 1\&2}} = 0.004 \pm 0.012\,(\text{stat+syst})$$



$B^0 \rightarrow J/\psi\, K_s$





LHCb Run 2 result most precise to date

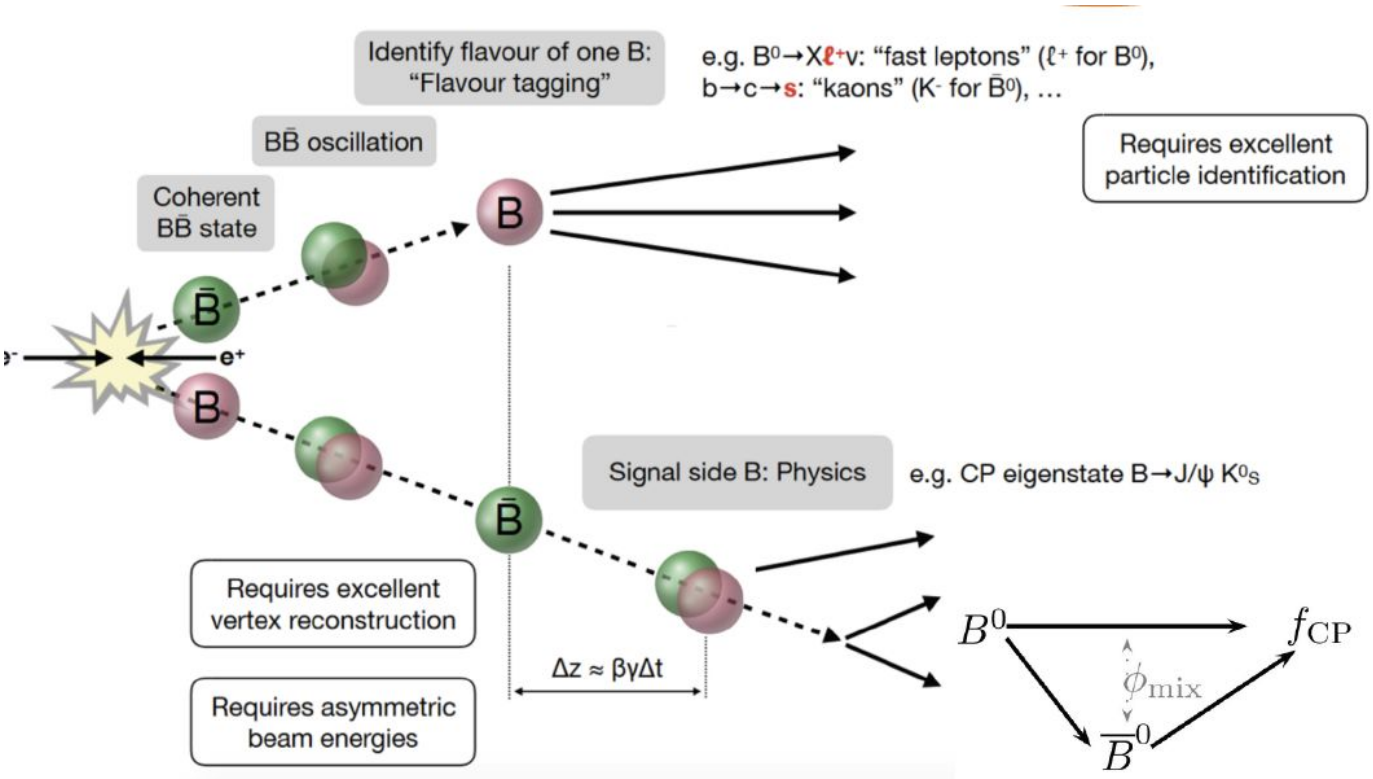
Summary and Outlook

• CP violation is being tested at several experiments, such as Belle II/ LHCb/BESIII. Exciting results to follow in future.
• Current focus is search for new physics corrections to SM CP violation.
• No evidence for new CP violation so far.
• Large datasets will allow precision measurements.

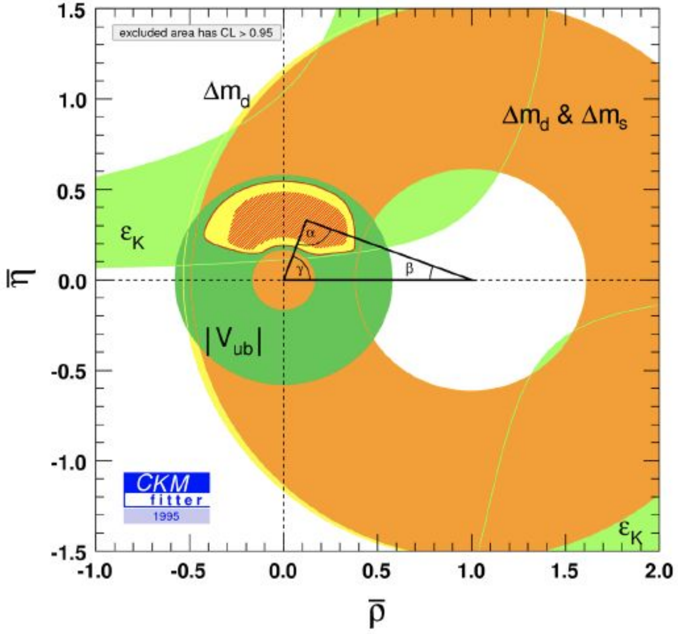
Time-dependent CP violation in B_s decays -> Bhagyashree's talk

BACK-UP SLIDES

Time-Dependent CP violation



Unitarity Triangle - Timeline



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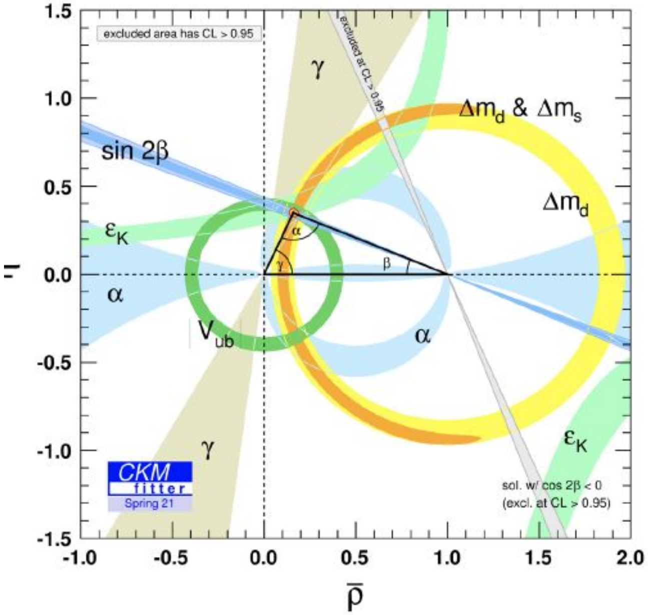

2021