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

$B^0 \rightarrow \eta' K_s$
$B^0 \rightarrow K_s K_s K_s$
$B^0 \rightarrow \Phi K_s$
$B^0 \rightarrow K_s \pi^0$
$B^0 \rightarrow K_s \pi^0 \gamma$
$B^0 \rightarrow J/\psi K_s$

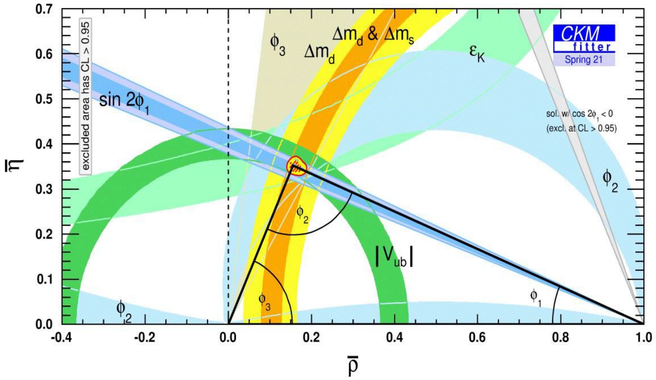
- Recent results from LHCb

$B^0 \rightarrow J/\psi K_s$
$B_s \rightarrow J/\psi \Phi$
$B_s \rightarrow \Phi\Phi$

- Summary and Outlook

Time-dependent CP violation

- 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 meson oscillation:

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

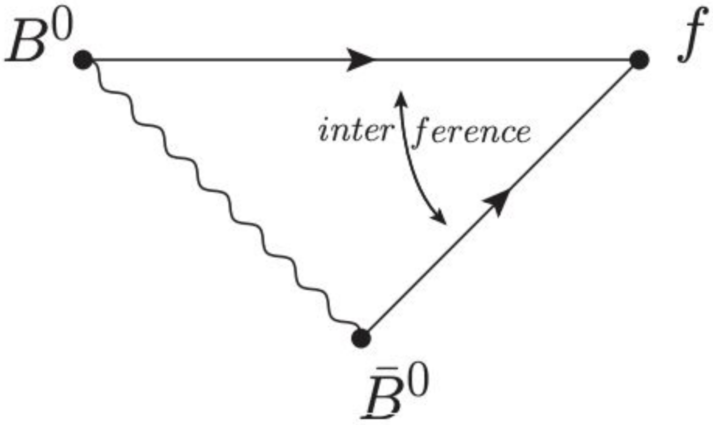
$$A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}}$$

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

Mixing-induced CP asymmetry

Direct CP asymmetry

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

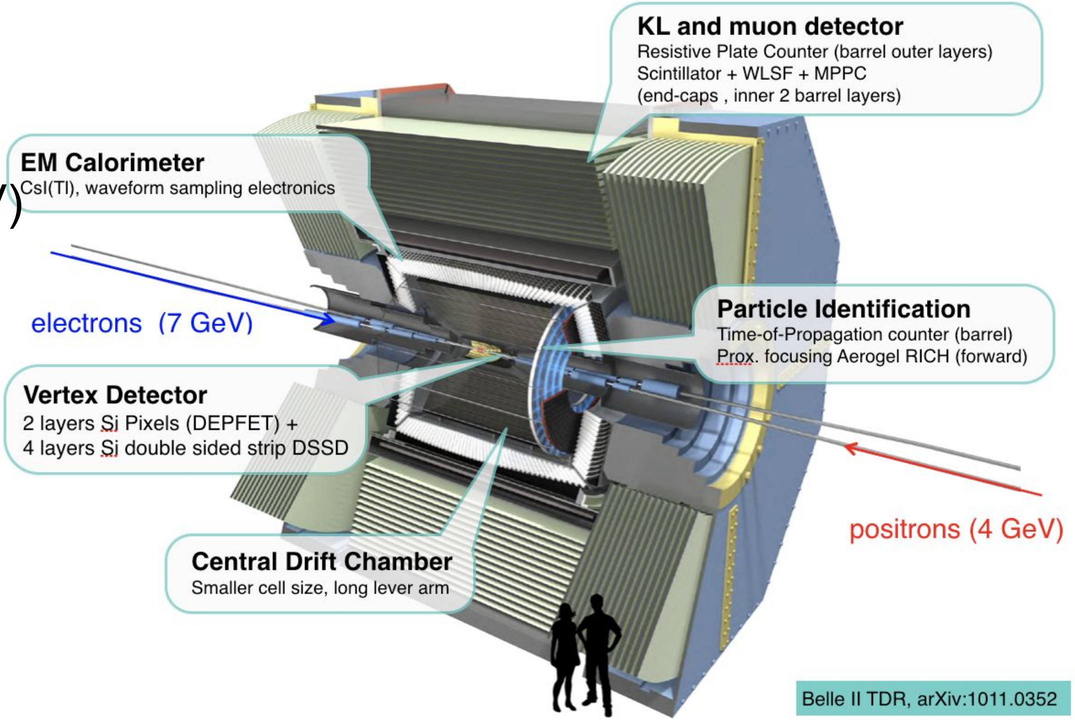


Time-dependent CPV

Belle and Belle II

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

Luminosity Frontier experiment

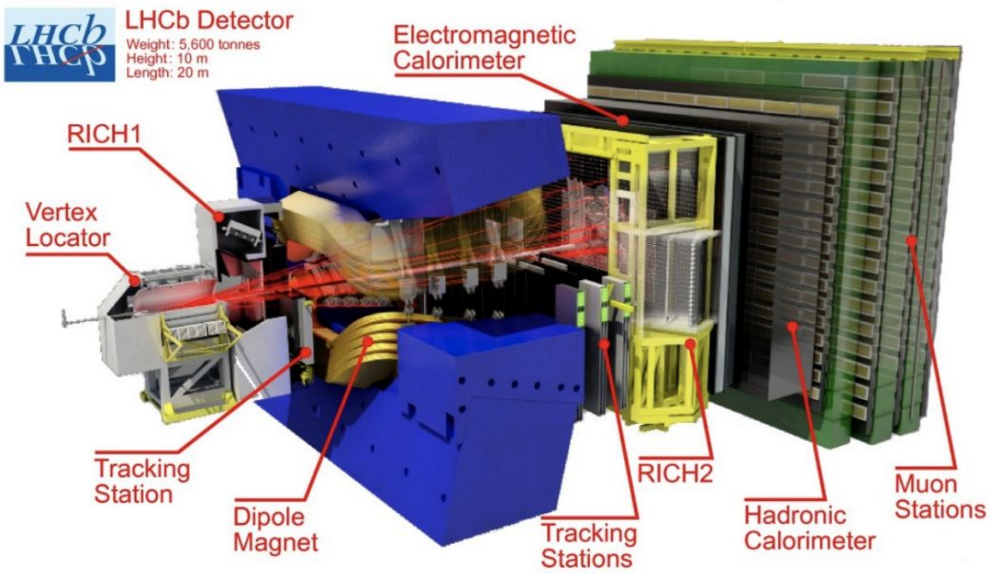


Belle II TDR, arXiv:1011.0352

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}

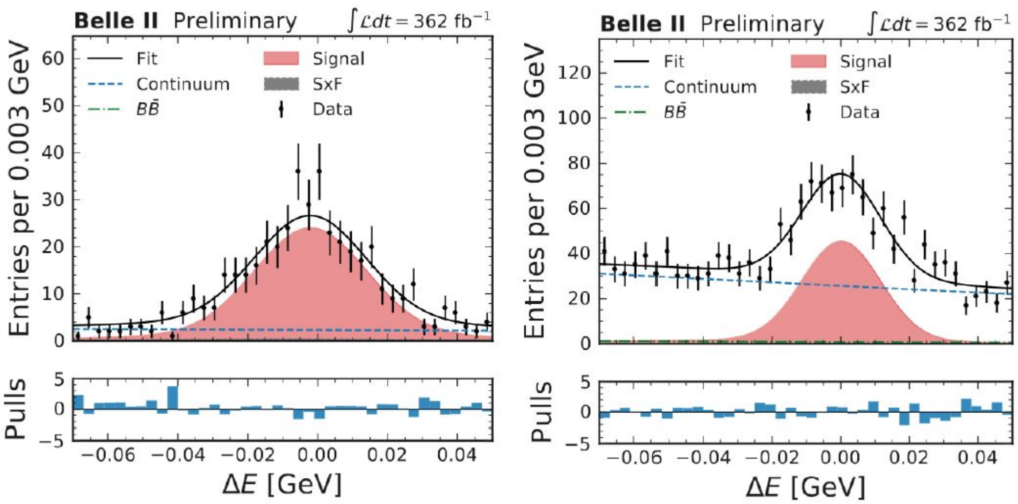


The LHCb Collaboration *et al* 2008 *JINST* 3 S08005

$B^0 \to \eta' K_s$

EPS-HEP 2023

- 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
- Background Δt shape controlled from sideband



$\eta' \to \eta\pi\pi$ $\eta' \to \rho\gamma$

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

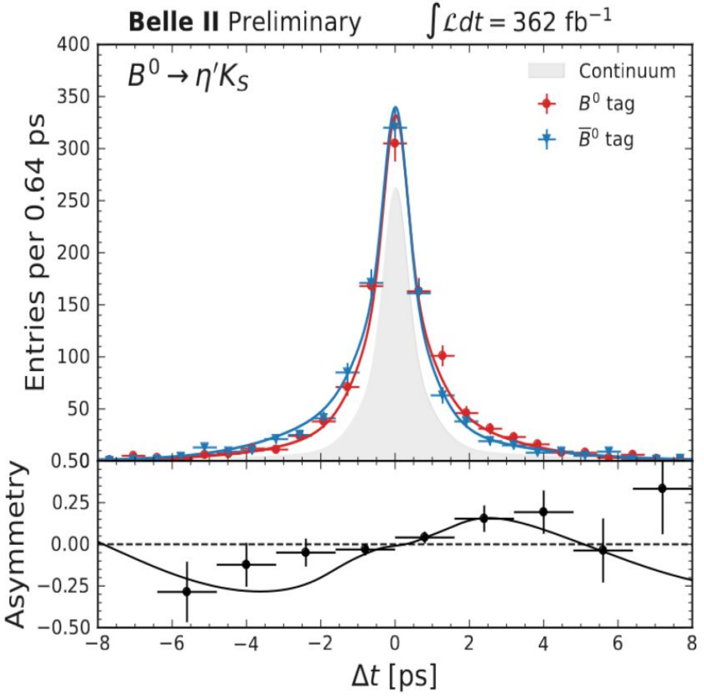
$B^0 \to \eta' K_S$

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

$$C_{CP} = 0.19 \pm 0.08 \pm 0.03$$
$$S_{CP} = 0.67 \pm 0.10 \pm 0.04$$

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

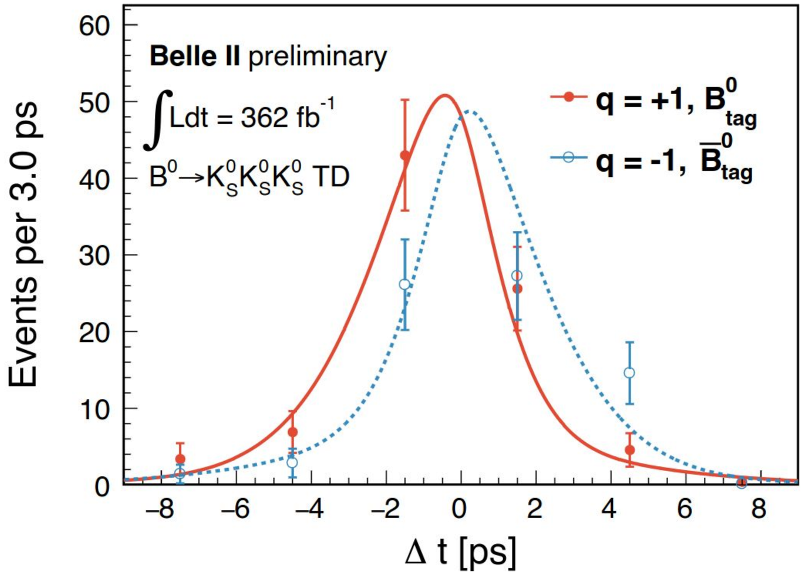
$$S_{CP} = 0.63 \pm 0.06$$



$B^0 \rightarrow K_s K_s K_s$

MORIOND 2023

- Unique at Belle II
- Major challenge: no prompt tracks→vertex reconstruction from K_S trajectories
- No contributions from opposite-CP backgrounds



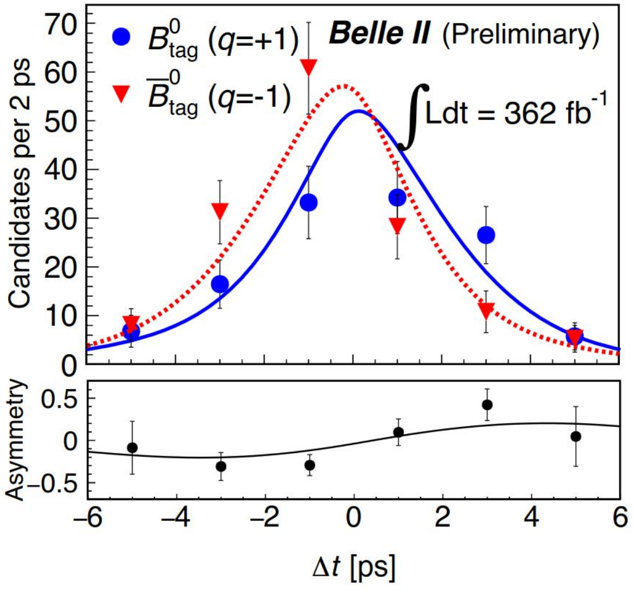
$$C_{CP} = -0.07 \pm 0.20 \pm 0.05$$
$$S_{CP} = -1.37^{+0.35}_{-0.45} \pm 0.03$$

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

$B^0 \to \Phi K_s$

arXiv:2307.02802

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



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

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

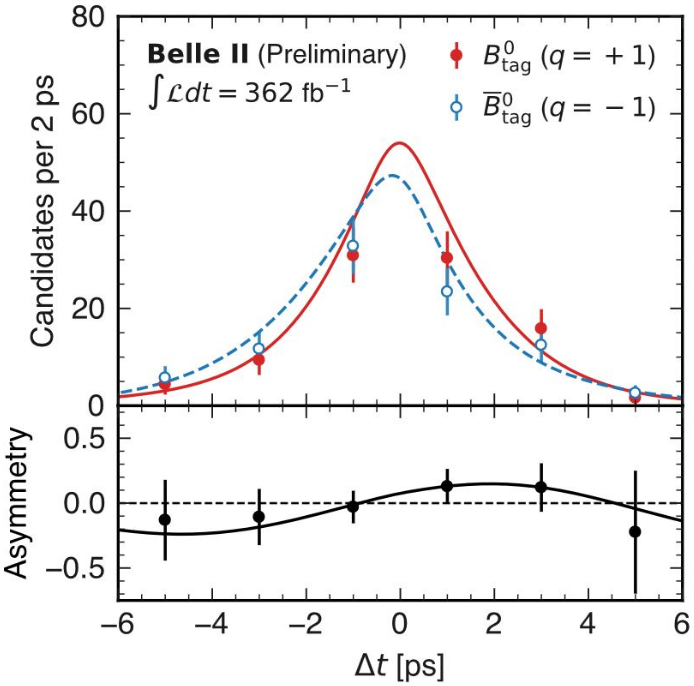
$B^0 \rightarrow K_s \pi^0$

PRL 131, 111803 (2023)

arXiv:2305.07555

- 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 of 415 signal events

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



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

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

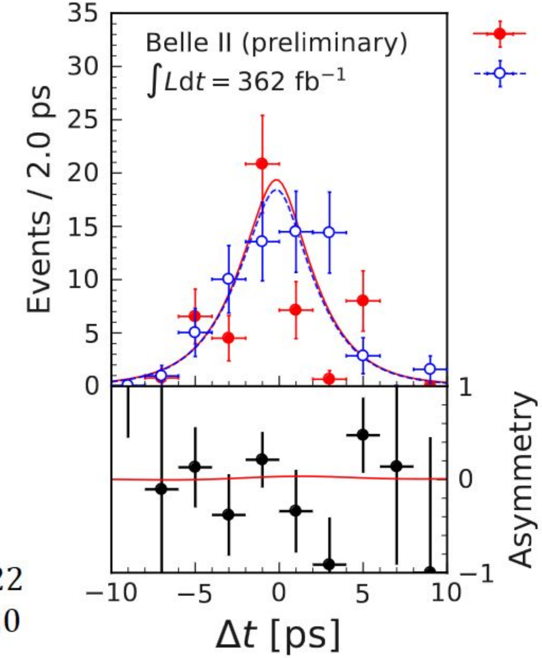
EPS-HEP 2023

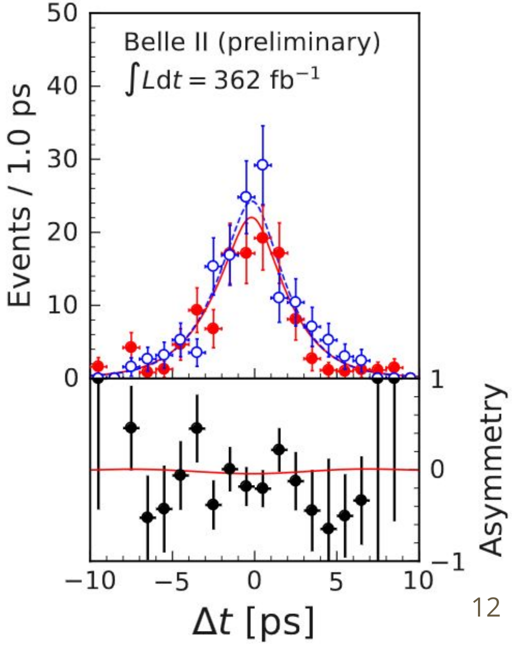
- Consider exclusive decay to $K^{*0}(\rightarrow K_S\pi^0)\gamma$ and inclusive decay to $K_S\pi^0\gamma$ separately
- Polarization of photon strongly constrains flavor
- SM: S_{CP} helicity suppressed NP processes could contribute to a significant mixing-induced CPV

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

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

Most precise result till date





HFLAV:

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

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

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

EPS-HEP 2023

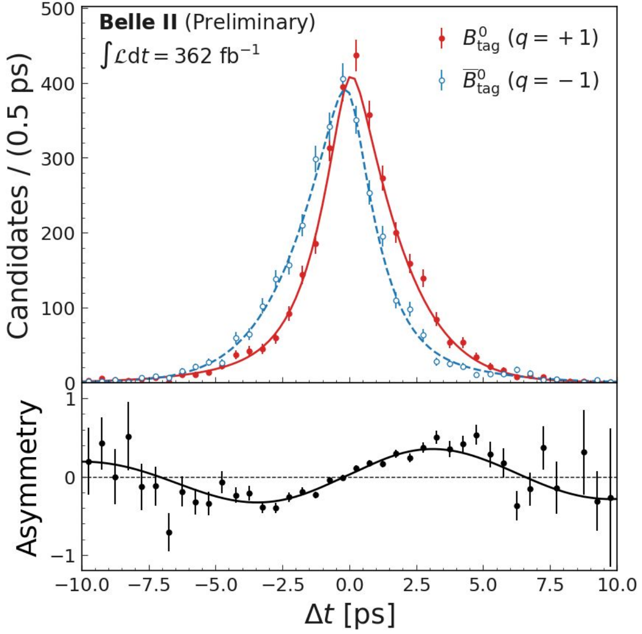
arXiv:2302.12898 (190 fb^{-1})

- 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

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

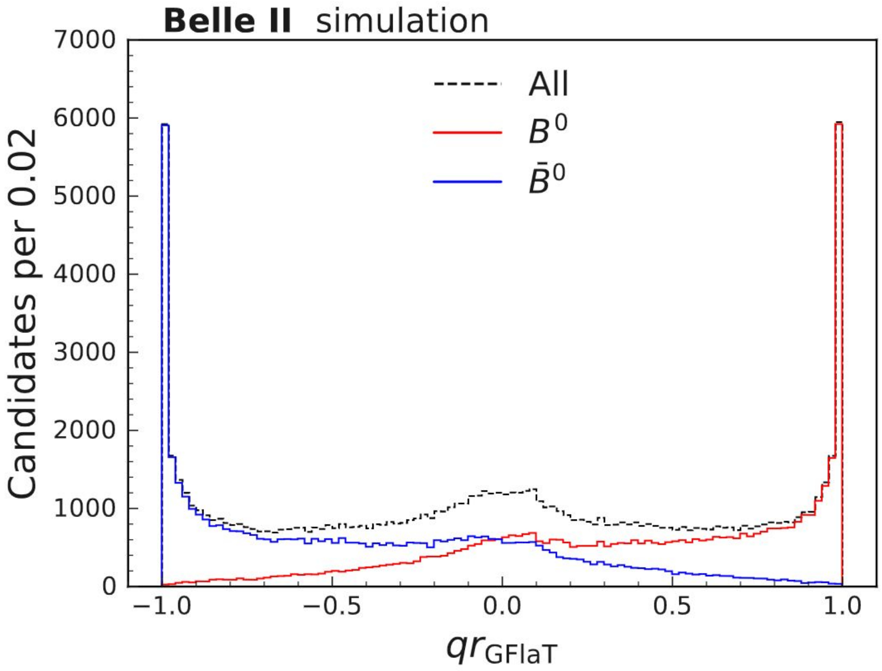


HFLAV: $C_{CP} = 0.000 \pm 0.020$ $S_{CP} = 0.695 \pm 0.019$

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

- 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!



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

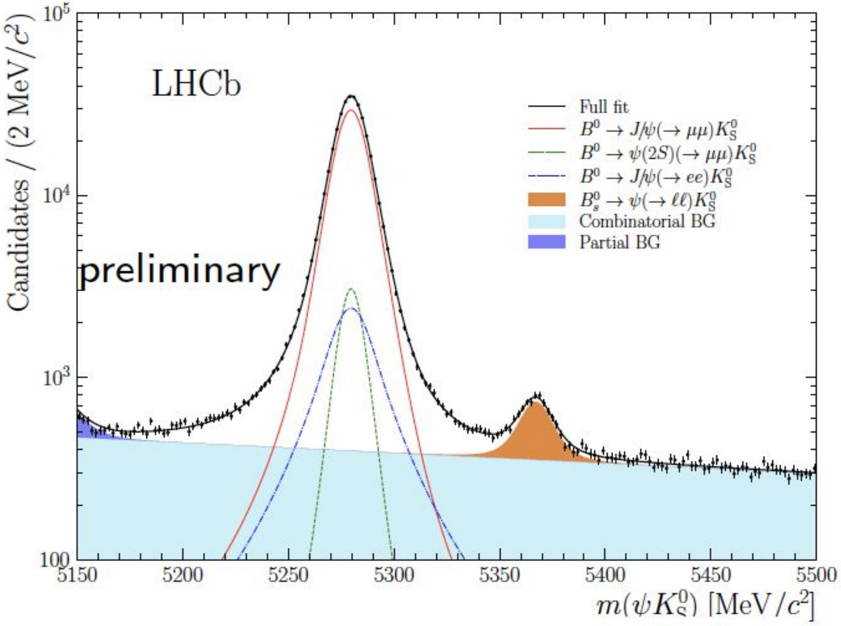
2309.09728 [hep-ex]

(Submitted to PRL)

LHCB-PAPER-2023-013

- New LHCb Run 2 (6 fb^{-1}) results using $B_d \rightarrow J/\psi\, K_s$ (both muons and electrons) and $B_d \rightarrow \psi' K_s$ Tagged time dependent analysis to determine sin2β
- Using Run 1 (3 fb^{-1}) + Run 2 data:

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

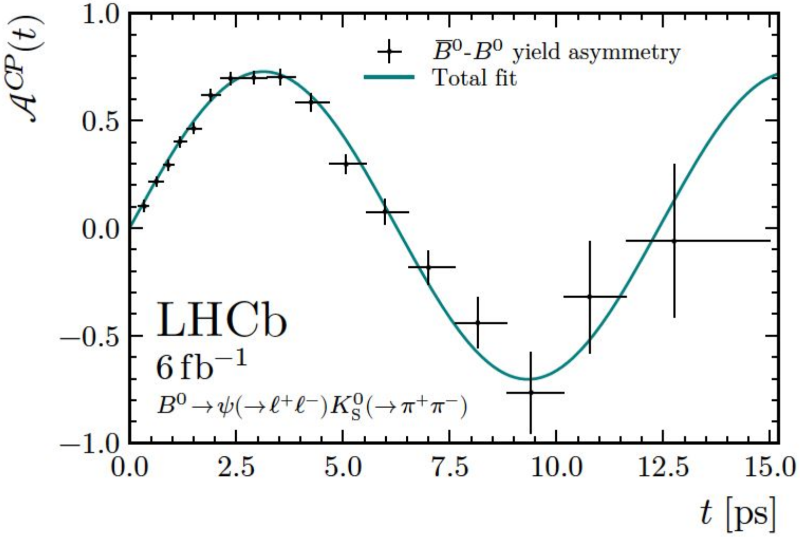


(Simultaneous fit of 3 decay modes, $B^0 \rightarrow J/\psi\, (l^+l^-)\, K_s$ and $B^0 \rightarrow \psi(2S)\, (\mu^+\mu^-)\, K_s$, where l = e or μ

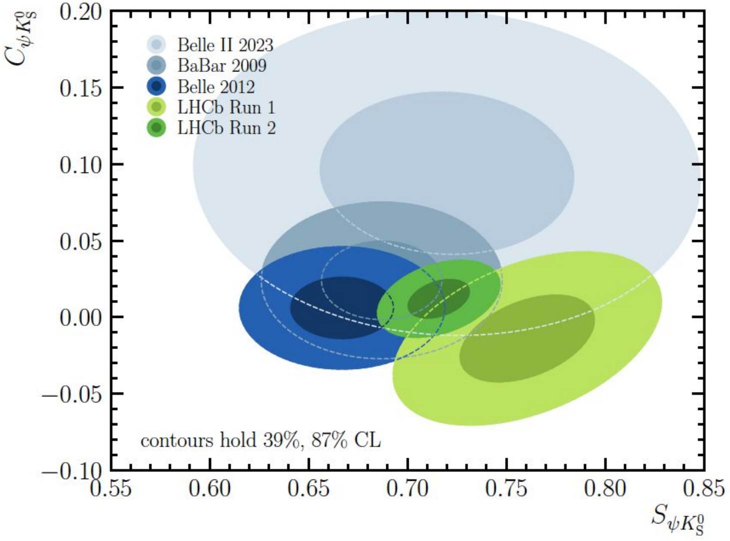
$B^0 \to J/\psi\, K_s$

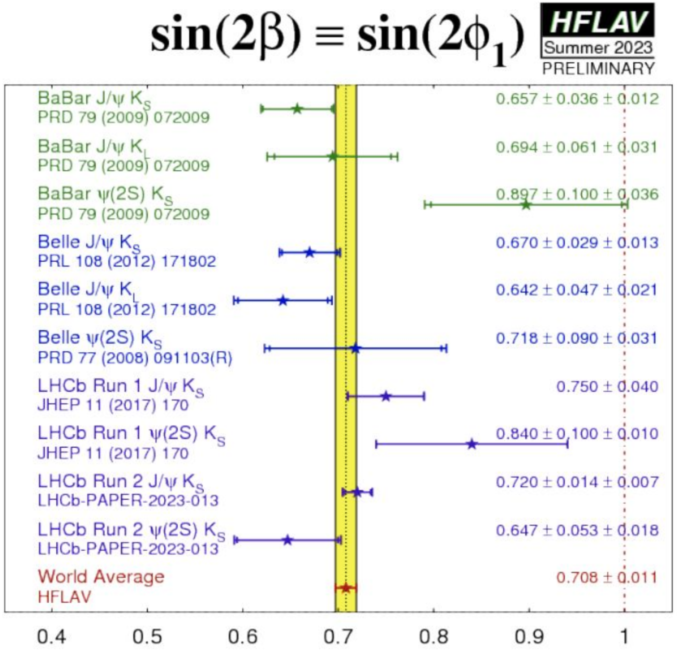
- Small CP violation asymmetry observed
- Consistent with SM predictions
- Using Run 1 (3 fb^{-1}) + Run 2 data, using combination of measurements:

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



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





LHCb Run 2 result most precise to date

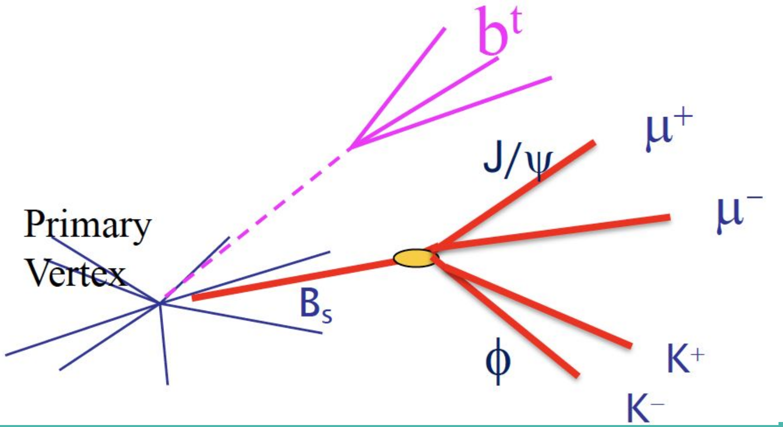
$B_s \to J/\psi\,\phi$

- Golden mode used by all LHC experiments, excluding ALICE

- Since $B_s \to J/\psi\,\phi$ is not a CP eigenstate time-dependent angular analysis needed to determine ϕ_s

$$\langle M^0|H|\overline{M^0}\rangle = M_{12} - \frac{i}{2}\Gamma_{12}$$
$$\langle \overline{M^0}|H|M^0\rangle = M_{12}^* - \frac{i}{2}\Gamma_{12}^*$$

H is the 2 × 2 effective Hamiltonian governing neutral meson mixing.

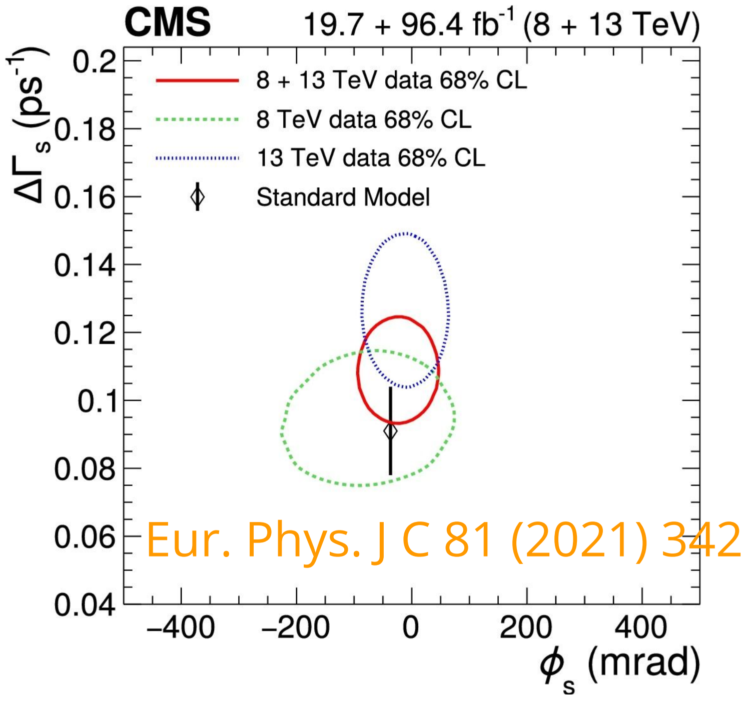


$$\phi_s = arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

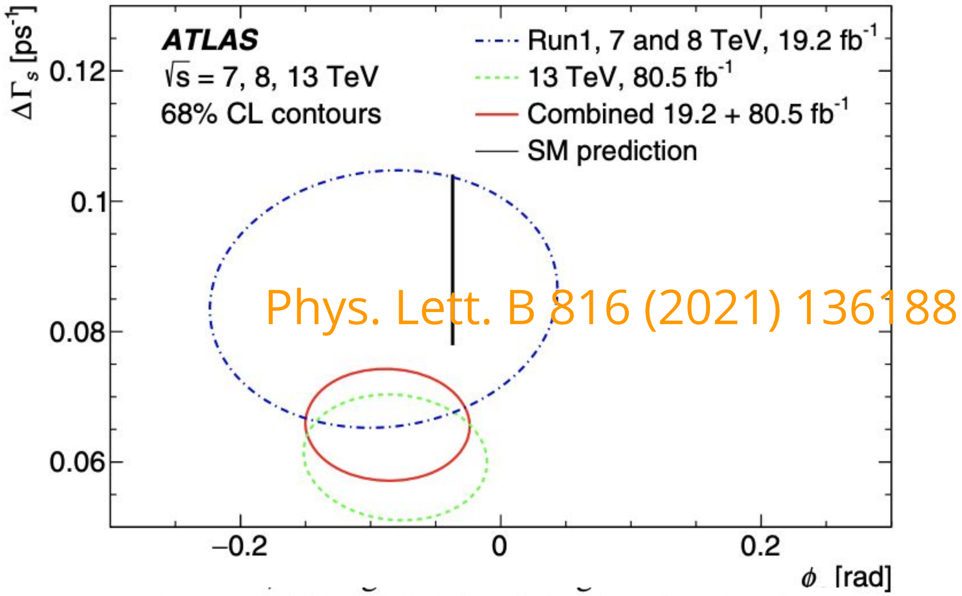
$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$

$$\Delta m_s = M_H - M_L$$

$B_s \rightarrow J/\psi\ \phi$



$$\phi_s = -21 \pm 44\,(\text{stat}) \pm 10\,(\text{syst})\,\text{mrad},$$
$$\Delta\Gamma_s = 0.1032 \pm 0.0095\,(\text{stat}) \pm 0.0048\,(\text{syst})\,\text{ps}^{-1}$$



$$\phi_s = -0.087 \pm 0.036\ (\text{stat.}) \pm 0.021\ (\text{syst.})\ \text{rad}$$
$$\Delta\Gamma_s = 0.0657 \pm 0.0043\ (\text{stat.}) \pm 0.0037\ (\text{syst.})\ \text{ps}^{-1}$$
$$\Gamma_s = 0.6703 \pm 0.0014\ (\text{stat.}) \pm 0.0018\ (\text{syst.})\ \text{ps}^{-1}$$

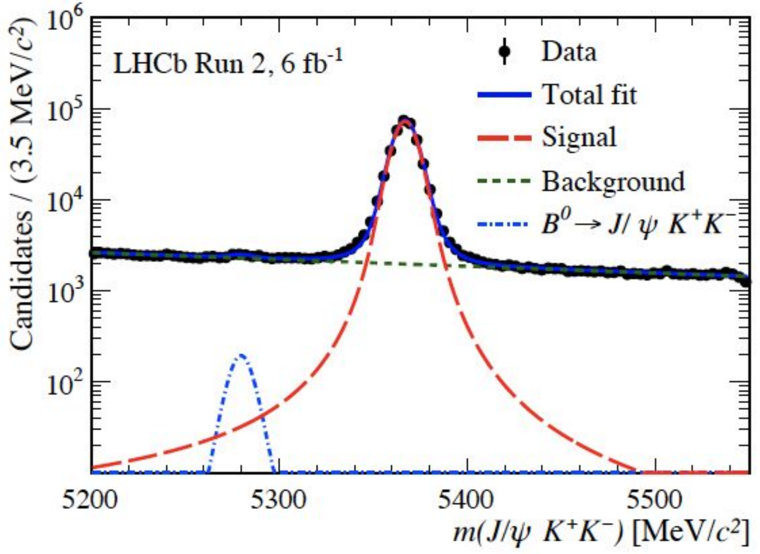
$B_s \to J/\psi\ \phi$

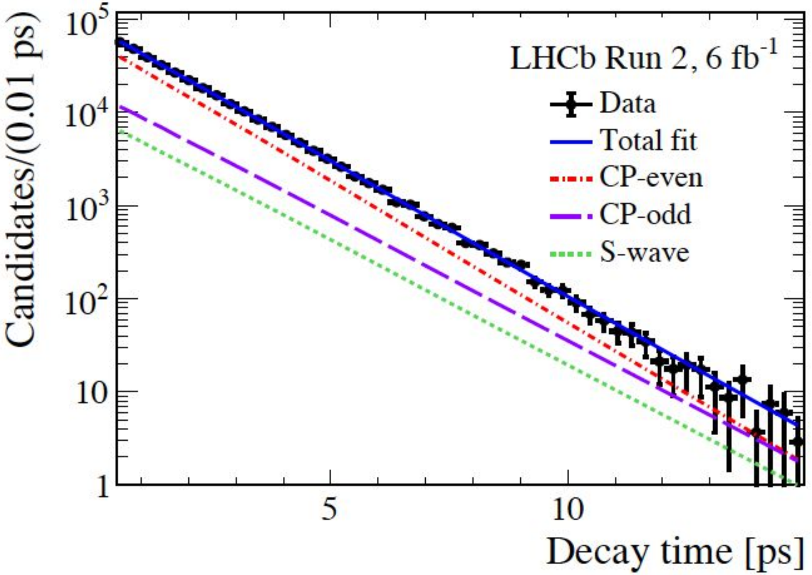
2308.01468 [hep-ex]

(Submitted to PRL)

LHCB-PAPER-2023-016

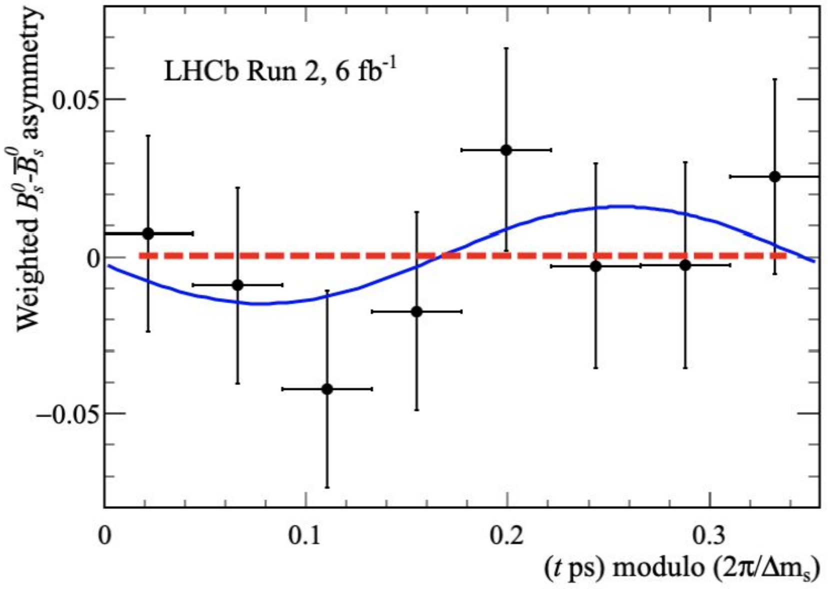
Full Run 2 dataset used

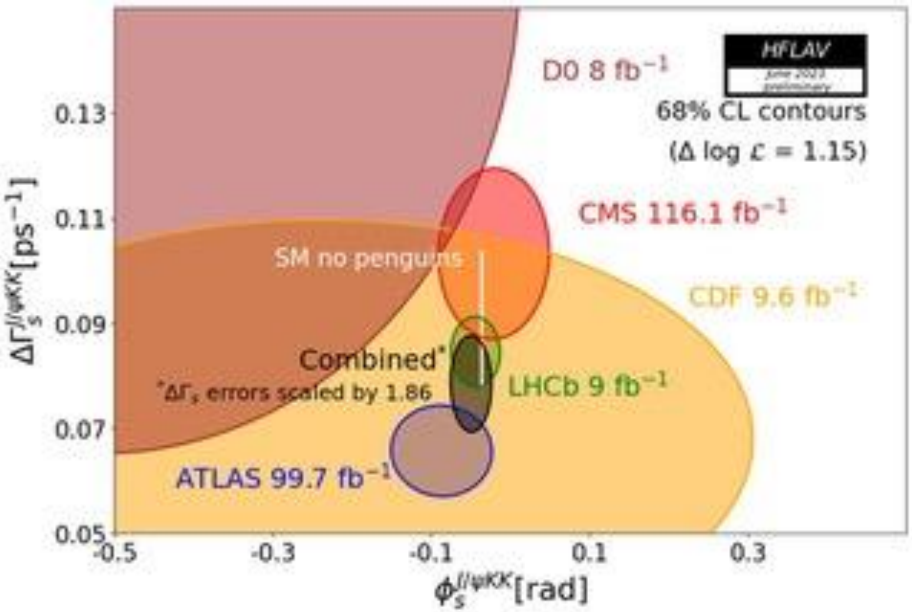




Current world average: $B_s \to J/\psi\ \phi$

Preliminary HFLAV 2023





Parameter	Values
ϕ_s [rad]	$-0.039 \pm 0.022 \pm 0.006$

Consistent with SM predictions

Tensions in experimental data

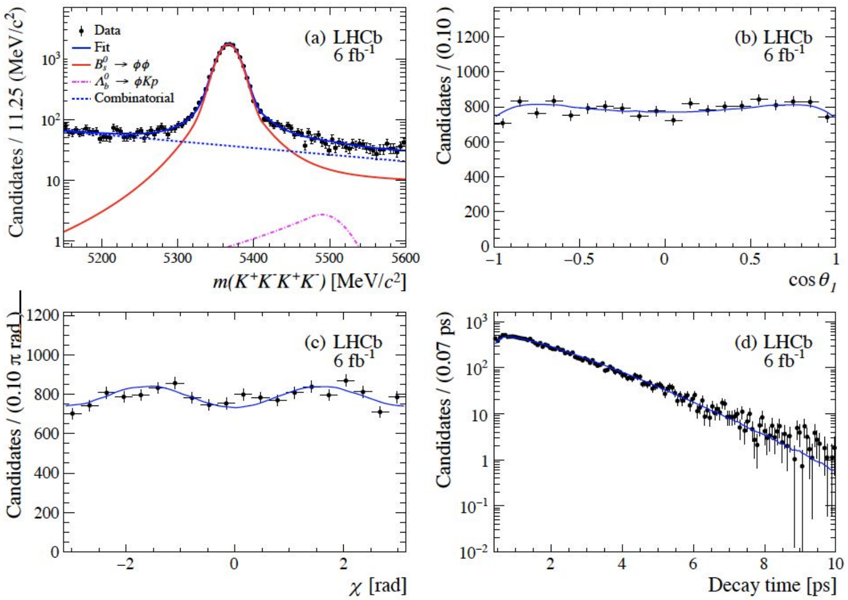
$B_s \to \Phi\Phi$

PRL 131, 171802 (2023)

arXiv: 2304.06198

- CP violation in B_s mixing in loop diagrams
- CP violation in SM predicted to be small, $\phi_s = -36.96\,^{+0.72}_{-0.84}\,\mathrm{mrad}$
  [Phys. Rev. D, 84 (2011), Article 033005]
- Tagged time dependent angular analysis to determine $\boldsymbol{\phi_s}$
- Using Run 1 + 2 data (6 fb^{-1}), LHCb measured:

$$\phi_s^{s\bar{s}s} = -0.074 \pm 0.069\,\mathrm{rad}$$

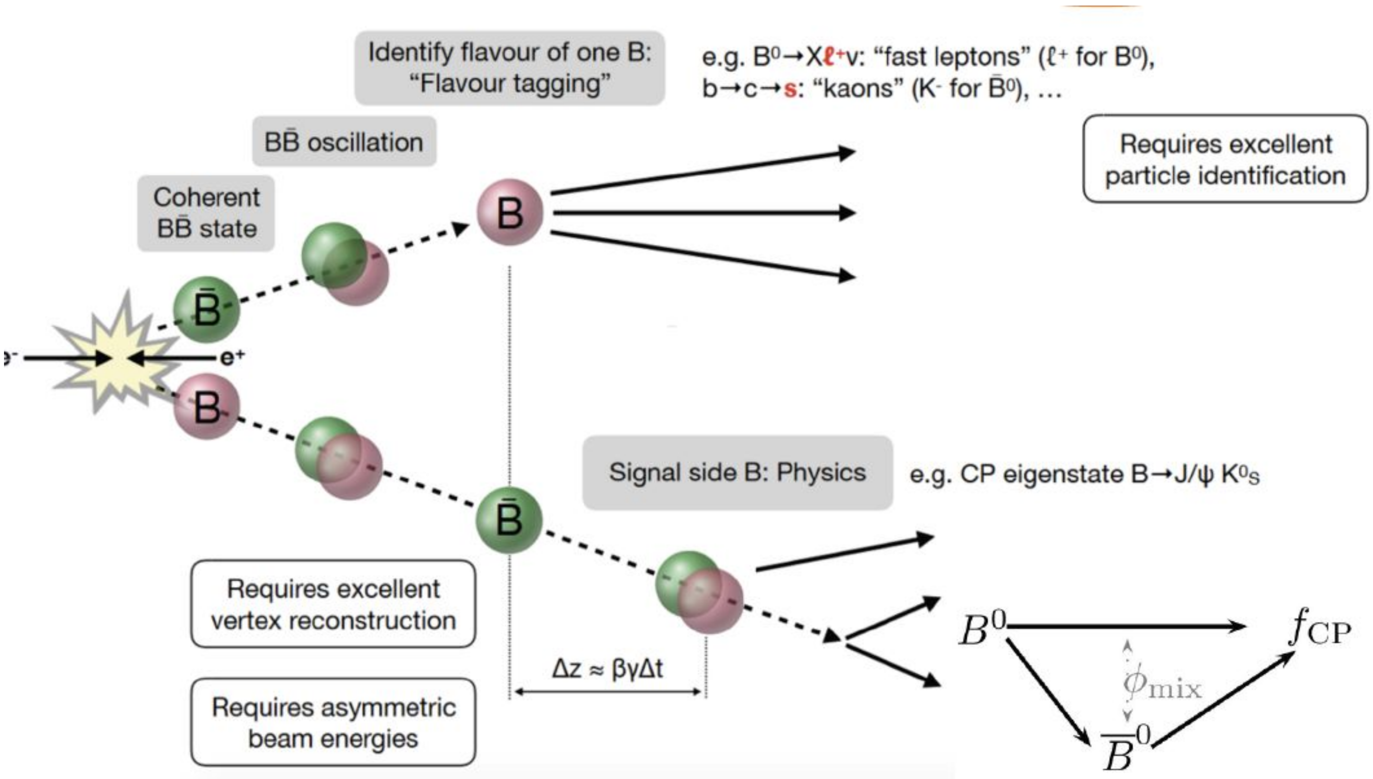


Most precise measurement of TDCPV in $B_s \to \Phi\Phi$

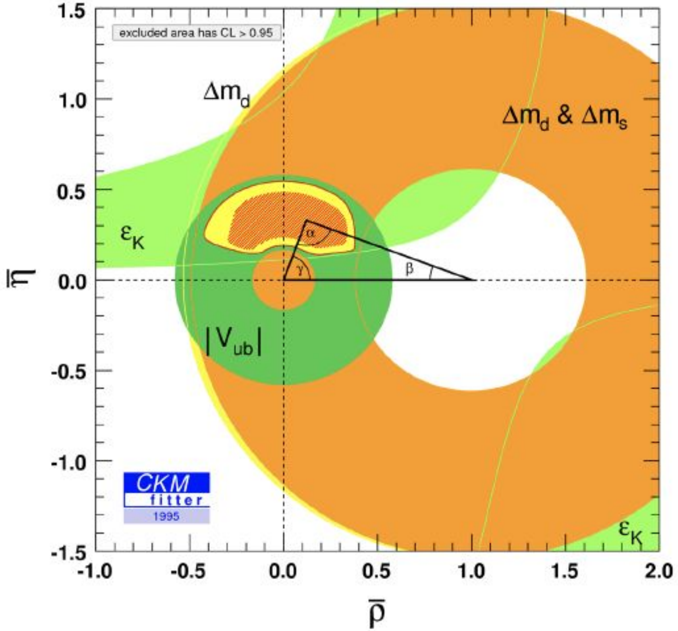
Summary and Outlook

- 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 CPV physics so far.
- Large datasets will allow precision measurements.

Time-Dependent CP violation



Unitarity Triangle - Timeline



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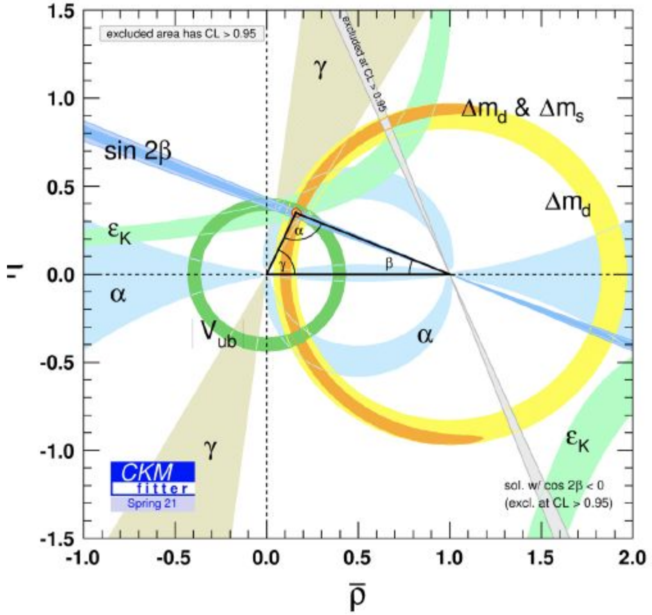

2021

Preliminary HLAV 2023 update