



First measurement of time-dependent CP violation in $b \rightarrow s\ell^+\ell^-$ decays

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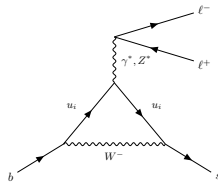
October 2026

FCNC as probe of NP

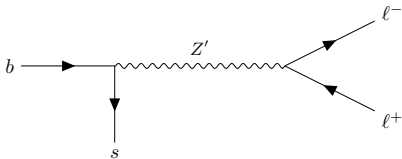
- ▶ **The FCNC decays:** Loop-suppressed in the SM, allowing heavy new particles to enter and strongly enhance NP effects.
- ▶ **The $b \rightarrow s \ell \ell$ semi-leptonic decay:**
 - ▶ **Clean signature:** The $\ell^+ \ell^-$ pair provides a clean experimental and theoretical signature.
 - ▶ **Tiny SM phase:** The SM weak phase is almost real. Any non-zero CP asymmetry is therefore a direct, highly sensitive probe of new phases.

⇒ **Excellent probe for NP!**

Standard Model — loop only



New physics — tree-level Z'



Wilson coefficients within the SM-EFT

$$\mathcal{H}_{\text{eff}} \supset -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i O_i + C'_i O'_i) + \text{h.c.}$$

$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$
Electromagnetic dipole $b \rightarrow s \gamma^*$	Vector lepton current $\bar{\ell} \gamma^\mu \ell$	Axial-vector lepton current $\bar{\ell} \gamma^\mu \gamma_5 \ell$

- ▶ Extended basis: scalar/pseudoscalar and tensor operators.
- ▶ New weak phases: $\text{Im } C_i^{(\prime)} \neq 0$.

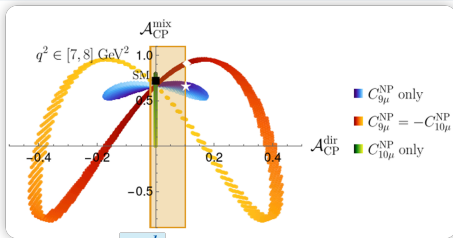
Motivation: time-dependent CP violation in $b \rightarrow s\ell\ell$

Probing new physics with CP asymmetries

- ▶ CP asymmetries in $b \rightarrow s\ell^+\ell^-$ constrain the phases of the relevant Wilson coefficients [JHEP 03 (2023) 113]: **direct CPV** is sensitive to C_9 or C_{10} , while **mixing-induced CPV** is sensitive to the phases of *all* Wilson coefficients.
- ▶ The $b \rightarrow s\ell^+\ell^-$ decay amplitude has tiny weak phase in the SM [PRD 104 (2021) 115004]:

$$[S \simeq \sin 2\beta, C \simeq 0]. \quad \text{at the leading order}$$

- ▶ A large weak phase in $B \rightarrow K^{(*)}\ell^+\ell^-$ is possible in NP models, e.g. the S_3 leptoquark with $m_{S_3} \sim$ a few TeV.



Time-dependent CPV parameters in $B^0 \rightarrow K_S^0 \mu^+ \mu^-$

- $K_S^0 \mu^+ \mu^-$ is not a purely CP eigenstate. A complete study requires a **time-dependent angular analysis**, using the μ^+ helicity angle θ_l .

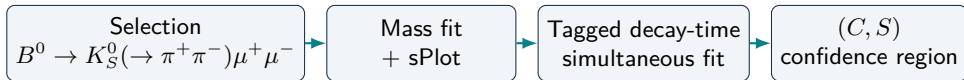
$$\frac{d\Gamma(\bar{B}^0/B^0(t) \rightarrow K_S l l)}{dt d \cos \theta_l} = e^{-\Gamma t} \sum_{i=0}^2 P_i(\cos \theta_l) \Gamma_i [1 \pm C_i \cos \Delta m_d t \mp S_i \sin \Delta m_d t]$$

Observable	Probed Wilson coefficients	SM predictions
S_0	$C_{9,10,S,P,T}$	$S_0^{SM} \approx \sin 2\beta, C_0^{SM} = 0$
S_1	$C_{9,S}$	$S_1^{SM} = 0, C_1^{SM} = 0$
S_2	$C_{9,10,T}$	$S_2^{SM} \approx \sin 2\beta, C_2^{SM} = 0$

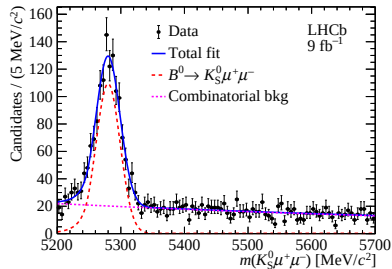
- This analysis integrates over the angle θ_l and measures S_0 and C_0 .
- $\Rightarrow B^0 \rightarrow K_S^0 \mu^+ \mu^-$ **behaves like** $B^0 \rightarrow J/\psi K_S^0$ **in the SM, with** $C = 0, S = \sin 2\beta$.

$$\frac{d\Gamma(\bar{B}^0/B^0(t) \rightarrow K_S l l)}{dt} = e^{-\Gamma t} \Gamma_0 [1 \pm C_0 \cos \Delta m_d t \mp S_0 \sin \Delta m_d t]$$

Experimental method to extract (C, S)



- ▶ Exclude J/ψ and $\psi(2S)$ dimuon regions.
- ▶ Use both long and downstream tracking to collect K_S^0 categories.
- ▶ 943 ± 55 signals collected using full Run 1+2 data



Detector effects

The observed decay-time distribution is distorted by the detector.

To extract the true CP observables, three experimental effects must be accurately modelled:

$$\frac{d\Gamma}{dt'} \propto \varepsilon(t') e^{-t'/\tau_{B^0}} [1 \mp D_{\text{tag}} C \cos(\Delta m_d t') \pm D_{\text{tag}} S \sin(\Delta m_d t')] \otimes R(t' - t).$$

Flavour tagging

$$D_{\text{tag}} = 1 - 2\omega$$

$\sim 5\%$ effective statistical power.

Time acceptance

$$\varepsilon(t)$$

Trigger and selection efficiency versus decay time; spline floated in fit.

Time resolution

$$R(t' - t)$$

Effective resolution ~ 60 fs.

First result of time-dependent CPV in $b \rightarrow sl^+\ell^-$

Dataset

Run 1 + Run 2
 9 fb^{-1}

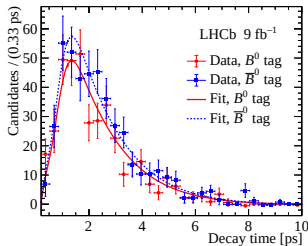
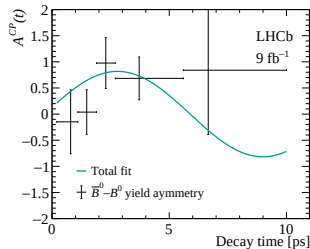
Statistics-dominated; systematic
 ≈ 0.05 .

$S \neq 0$ at 2.8σ

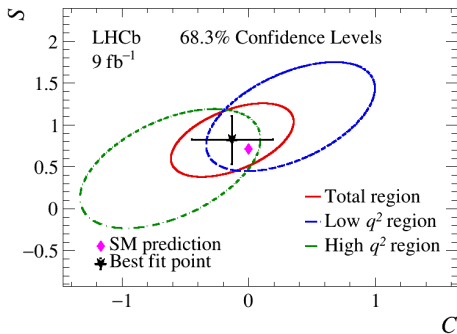
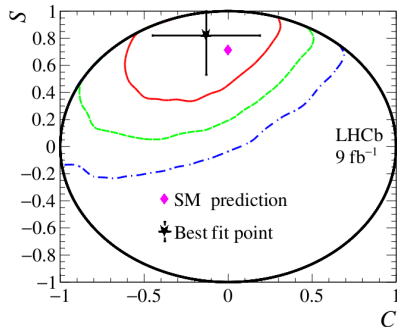
consistent with
 $\sin 2\beta = 0.699 \pm 0.017$

$$C = -0.13 \pm 0.32 (\text{stat}) \pm 0.04 (\text{syst})$$

$$S = +0.82 \pm 0.29 (\text{stat}) \pm 0.05 (\text{syst})$$



The parameter confidence region



Best fit $(S, C) = (0.82, -0.13)$;

- ▶ the SM benchmark $(0.70, 0)$ lies inside the contours.
- ▶ the left region: No constraint on C and S . the right region: $C^2 + S^2 \leq 1$

Complementary CPV measurements from $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

The four-dimensional angular distribution connects experimental observables to the underlying helicity amplitudes and Wilson coefficients:

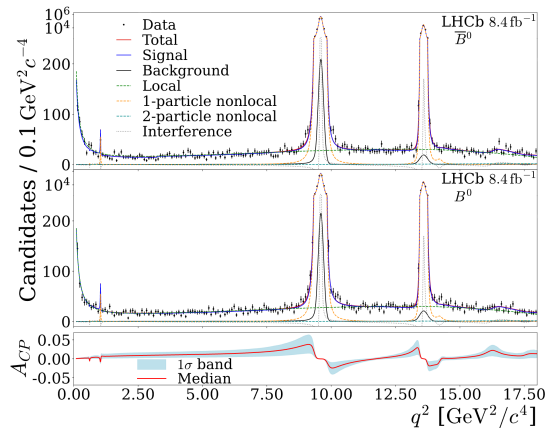
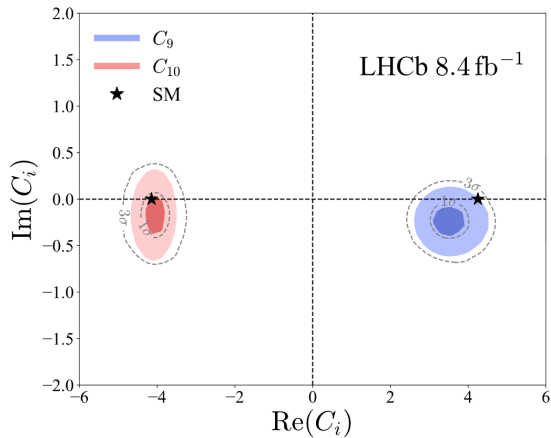
$$\underbrace{\frac{d^4\Gamma}{dq^2 d\cos\theta_K d\cos\theta_l d\phi}}_{\text{Experiment: 4D angular distribution}} = \underbrace{\sum_i \left[\frac{I_i(q^2) + \bar{I}_i(q^2)}{2} + \frac{I_i(q^2) - \bar{I}_i(q^2)}{2} \cdot C_i \right] f_i(\theta_K, \theta_l, \phi)}_{\text{Angular expansion (CP-averaged + CP-violating terms)}}$$

where the angular coefficients are built from helicity amplitudes:

$$I_i(q^2) \propto \underbrace{\sum_{\lambda, \lambda'} \text{Re} \left[A_{\lambda}^{L,R*}(q^2) A_{\lambda'}^{L,R}(q^2) \right]}_{\text{Interference of amplitudes}}$$

$$A_{\lambda}^{L,R} = \underbrace{\mathcal{N}_{\lambda} \left[(C_9 + \Delta C_9^{\text{non-local}}(q^2)) \mp C_{10} \right] F_{\lambda}(q^2) + k_{\lambda} (C_7 + \Delta C_7) T_{\lambda}(q^2)}_{\text{Short-distance Wilson coefficients + long-distance non-local effects}}$$

Run 2 full-amplitude results in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

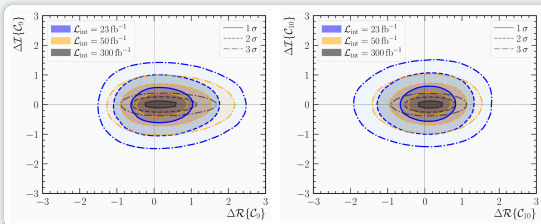


Future prospects: precision constraints from $B_s^0 \rightarrow \phi \mu^+ \mu^-$

Why $B_s^0 \rightarrow \phi \mu^+ \mu^-$?

- ▶ A rich $P \rightarrow V(\rightarrow K^+ K^-) \ell^+ \ell^-$ decay. The three-dimensional angular distribution provides multiple helicity-interference observables.
- ▶ Highly sensitive to chirality-flipped operators (C_7', C_9', C_{10}') and the imaginary parts of the Wilson coefficients.
- ▶ The rapid $B_s - \bar{B}_s$ mixing ($\Delta m_s \gg \Delta m_d$) makes it a powerful laboratory for mixing-induced CP violation.

Projected sensitivity

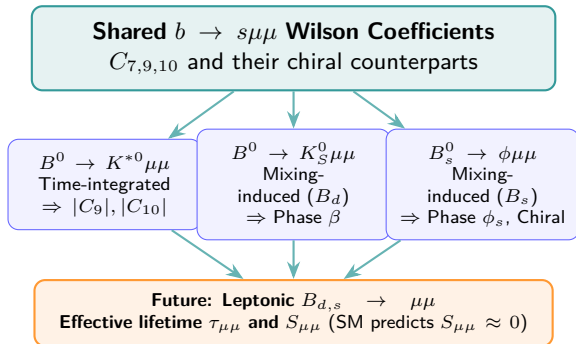


Projected confidence intervals for $\delta C_i = C_i - C_i^{\text{SM}}$ at different integrated luminosities.

Outlook: LHCb Run 3 and beyond

- ▶ Substantial Run 3 statistics $\Rightarrow$ preliminary results soon.
- ▶ Optimized angular CPV observables $\Rightarrow$ stringent SM test and phase extraction.

Unified Roadmap: Probing NP Phases in $b \rightarrow s\mu\mu$

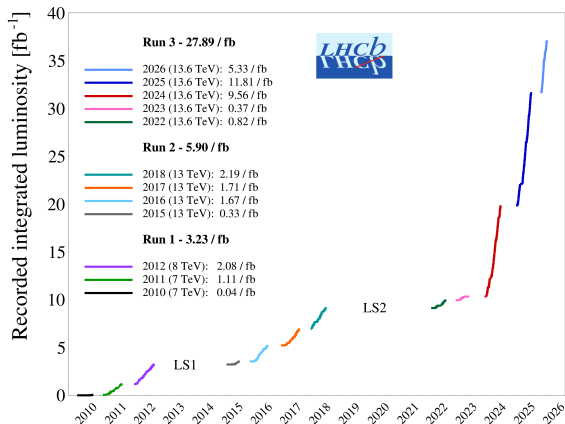


Why this network?

- **Complementary probes:** $K_S^0 \mu\mu$ provides a clean SM null test ($S \approx \sin 2\beta$), while $\phi\mu\mu$ cross-checks this via the B_s phase ϕ_s and its helicity structure.
- **Strict null tests:** Leptonic $B_s \rightarrow \mu\mu$ has $S_{\mu\mu} = 0$ in the SM, making any non-zero value a smoking gun for new scalar phases.
- **Global Synergy:** Reaching sensitivity to $S_{\mu\mu}$ and $\tau_{\mu\mu}$ —especially for the extremely rare $B_{d,s} \rightarrow \mu\mu$ —mandates a joint combination of LHCb and other experiments.

Run 3 outlook

Total recorded luminosity – pp – 37.0 fb^{-1}



Integrated luminosity in LHCb Run 3.

- ▶ **More data:** Run 3 will provide a substantial increase in integrated luminosity.
- ▶ **Better K_S^0 efficiency:** The upgraded detector and reconstruction algorithms significantly improve the K_S^0 detection efficiency.
- ▶ **Higher yield.** The Run 3 analysis is currently underway, with new results expected soon..

Summary and outlook

- ① **First measurement:** We report the first time-dependent CP measurement in $b \rightarrow s\ell^+\ell^-$, extracting $S = +0.82 \pm 0.29 \pm 0.05$ and $C = -0.13 \pm 0.32 \pm 0.04$ from 9fb^{-1} of $B^0 \rightarrow K_S^0\mu^+\mu^-$ data.
- ② **SM compatibility:** The parameter S deviates from zero at 2.8σ , and the result is consistent with the SM benchmark $\sin 2\beta = 0.699 \pm 0.017$.
- ③ **Outlook:** The substantial increase in statistics from LHCb Run 3 and future upgrades will drastically reduce uncertainties. Combined with angular CPV observables and B_s modes, this will enable the most stringent constraints on New Physics in $b \rightarrow s\ell^+\ell^-$ transitions.

Thank you!