

Time-dependent CP asymmetries in $b \rightarrow sl^+l^-$ decays

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April 15, 2026



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Outline

- 1 Proving CP violation through mixing and decay interference in FCNC semileptonic decays
- 2 First measurement of time-dependent CP violation in the flavor-changing neutral-current decay $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ using Run 1 + 2 LHCb data
- 3 Prospects with Run 3 data, in $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ and $B_s \rightarrow f_0(980) \mu^+ \mu^-$
- 4 Interpretation of the first measurement of time-dependent CP violation in semileptonic decays
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Why CP violation in $b \rightarrow sl^+l^-$?

- $b \rightarrow sl^+l^-$ are **Flavour-Changing Neutral Currents**:
absent at tree level in the SM, CKM + loop suppressed \Rightarrow **high NP sensitivity**.
- New flavour structures (e.g. Z' , leptoquarks) not aligned with CKM
- Off-diagonal in flavour space \rightarrow couplings can be complex.
- They would induce **CP asymmetries**
- Not mimicked by hadronic effects
- Could be indirect evidence of a larger CPV sector beyond the SM

How can we measure CP violation in $b \rightarrow sl^+\ell^-$?

- Two complementary probes of **CP violation** in $B \rightarrow K\mu^+\mu^-$:

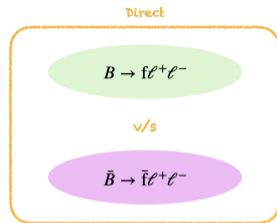
① **Direct CPV** ($\mathcal{A}_{CP}^{\text{dir}}$), $B^\pm \rightarrow K^\pm\mu^+\mu^-$ [Bečirević et al. 2008.09064]

⇒ Interference between weak & strong phase

⇒ Resonance enhancement

⇒ Probes only $\text{Im}(C_9^{\text{NP}})$

Limitation: Hadronic uncertainties / model dependence



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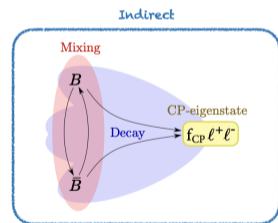
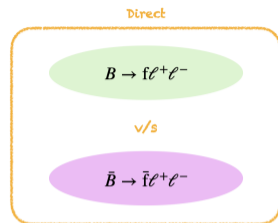
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⇒ Originates from mixing–decay interference

⇒ Clean access to $\text{Im}(\mathcal{C}_{9,10}^{\text{NP}})$

Limitation: Flavour tagging + time evolution



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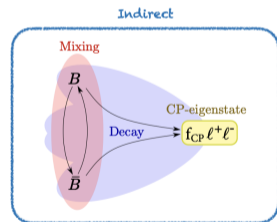
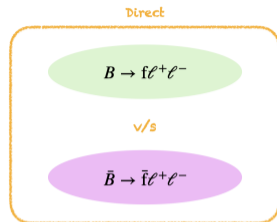
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- **Complementarity:** sensitivity (direct) vs cleanliness (mixing-induced)

- Similar picture in $B \rightarrow V\mu^+\mu^-$ (Here direct CPV also probes $\text{Im}(\mathcal{C}_{10}^{\text{NP}})$)

Indirect CPV: $B_d^0 - \bar{B}_d^0$ mixing

Mixing and time evolution

The **mass eigenstates** $B_{H,L}$ are $|B_{H,L}\rangle = p |B^0\rangle \mp q |\bar{B}^0\rangle$

Neutral $B_d - \bar{B}_d$ mesons mixing \Rightarrow a state produced as B^0 evolves as

$$|B^0(t)\rangle = g_+(t) |B^0\rangle + \frac{q}{p} g_-(t) |\bar{B}^0\rangle \quad g_{\pm}(t) = \frac{1}{2} e^{-imt - \frac{\Gamma}{2}t} \left(e^{\mp i \frac{\Delta m}{2}t} e^{\pm \frac{\Delta \Gamma}{4}t} \right)$$

$$\Delta \Gamma_d / \Gamma_d \simeq 0 \quad \Delta m_d / \Gamma_d \approx 0.77$$

For B_d mixing is dominated by top-quark box diagram

$$\frac{q}{p} \sim \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \quad \Rightarrow \quad \left| \frac{q}{p} \right| \approx 1 \quad \text{and} \quad \phi_d \equiv \arg\left(\frac{q}{p}\right) \simeq -2\beta$$

Indirect CPV: $B^0 \rightarrow K_S^0 \mu^+ \mu^-$

- $K_S^0 \mu^+ \mu^-$ is a CP eigenstate: both B^0 and \bar{B}^0 decay to the *same* final state.
- We neglect kaon mixing (different time-scale)
- Time-dependent decay rates:

$$\Gamma(B^0(t) \rightarrow f) \propto e^{-\Gamma t} \left[\cosh\left(\frac{\Delta\Gamma_d t}{2}\right) - A_{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_d t}{2}\right) - \mathcal{C} \cos(\Delta m t) + \mathcal{S} \sin(\Delta m t) \right]$$
$$\Gamma(\bar{B}^0(t) \rightarrow f) \propto e^{-\Gamma t} \left[\cosh\left(\frac{\Delta\Gamma_d t}{2}\right) - A_{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \mathcal{C} \cos(\Delta m t) - \mathcal{S} \sin(\Delta m t) \right]$$

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- We neglect kaon mixing (different time-scale)
- Time-dependent decay rates:

$$\Gamma(B^0(t) \rightarrow f) \propto e^{-\Gamma t} \left[1 - \mathcal{C} \cos(\Delta m t) + \mathcal{S} \sin(\Delta m t) \right]$$

$$\Gamma(\bar{B}^0(t) \rightarrow f) \propto e^{-\Gamma t} \left[1 + \mathcal{C} \cos(\Delta m t) - \mathcal{S} \sin(\Delta m t) \right]$$

$\Delta\Gamma_{B_d} \approx 0 \Rightarrow \sinh$ term drops out

- The **CP asymmetries** \mathcal{C} and \mathcal{S} are:

$$\mathcal{C} = \frac{G_0 - \bar{G}_0}{G_0 + \bar{G}_0} = -\mathcal{A}_{\text{CP}}^{\text{dir}}(B^\pm \rightarrow K^\pm \ell \ell) \quad \mathcal{S} = \frac{-s_0}{G_0 + \bar{G}_0} = -\mathcal{A}_{\text{CP}}^{\text{mix}}$$

Indirect CPV: \mathcal{S} and s_0

- The mixing-induced CP-asymmetry is described (up to tensor/scalar NP and lepton mass) by

$$s_0 = \frac{8}{3} \text{Im} \left[e^{i\phi_d} (\bar{h}_V h_V^* + \bar{h}_A h_A^*) \right], \quad G_0 = \frac{4}{3} (|\bar{h}_V|^2 + |\bar{h}_A|^2)$$

$$\bar{h}_X \Rightarrow \text{Weak phases conjugated} \quad h_X^* \Rightarrow \text{All phases conjugated}$$

- The transversity amplitudes $h_{V,A}$ are proportional to

$$\bar{h}_V \sim \frac{2m_b}{m_B + m_K} (\mathcal{C}_7 + \mathcal{C}_{7'}) f_T + (\mathcal{C}_9^{\text{eff}} + \mathcal{C}_{9'}) f_+, \quad \bar{h}_A \sim (\mathcal{C}_{10} + \mathcal{C}_{10'}) f_+$$

$$\mathcal{S} \approx -\sin(\phi_d + \phi_{\text{decay}}) \quad \phi_{\text{decay}} \approx \arg(\bar{h}_V h_V^* + \bar{h}_A h_A^*)$$

Standard Model

- Wilson coefficients real $\Rightarrow h_{V,A} \approx \bar{h}_{V,A}$ up to tiny CKM phase

$$s_0 = 2 \sin \phi_d G_0 \quad \Rightarrow \quad \mathcal{S}^{\text{SM}} = -\sin \phi_d = \sin 2\beta = 0.7167 \pm_{0.007}^{0.010} \quad \mathcal{C}^{\text{SM}} = 0$$

independent of form factors / hadronic inputs!

[CKMFitter]

\mathcal{C} and \mathcal{S} : NP benchmark

- Predictions in the SM and NP benchmark point $\mathcal{C}_9^{\text{NP}} = -1 + i$ based on a resonance model fitted to data

[LHCb 2603.12477]

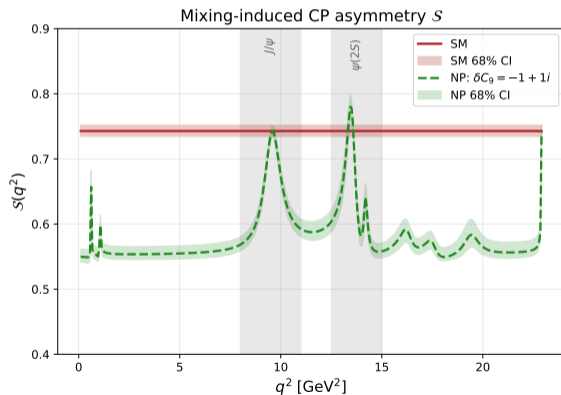
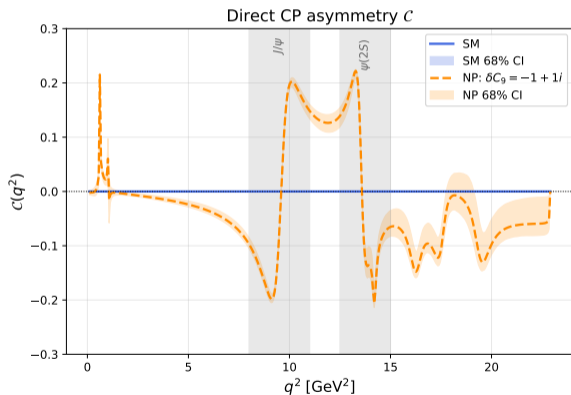
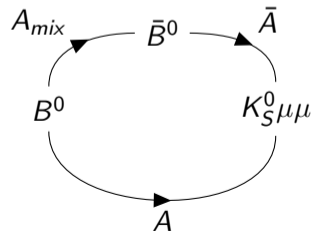


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- **First measurement of time-dependent CP violation in $b \rightarrow s \ell^+ \ell^-$ decays**, with $B^0 \rightarrow K_S^0 \mu^+ \mu^-$, $K_S^0 \rightarrow \pi^+ \pi^-$, provides model-independent constraints on CP violating NP, using Run1+Run2 data.
- $K_S \mu \mu$ is a CP eigenstate, such that $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ decays are mediated through two different paths:

- ▶ B going to $K_S^0 \mu \mu$ directly with amplitude A .
- ▶ B mixing to \bar{B} with amplitude A_{mix} and then going to $K_S^0 \mu \mu$ (\bar{A}).



- After some calculation

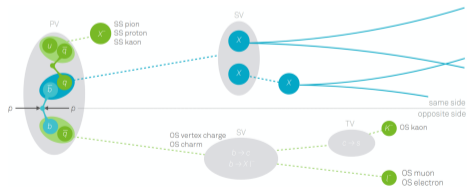
$$\Gamma(t) = e^{-\Gamma t} \left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) - A_{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma t}{2}\right) - C \cos(\Delta m t) + S \sin(\Delta m t) \right] \quad (1)$$

$$\bar{\Gamma}(t) = e^{-\Gamma t} \left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) - A_{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma t}{2}\right) + C \cos(\Delta m t) - S \sin(\Delta m t) \right] \quad (2)$$

where Γ is the average decay width, $\Delta\Gamma$ and Δm the width and mass differences between the heavy and light B states.

- In $B \rightarrow K_S \mu \mu$: $\Delta\Gamma \approx 0$, so we only fit for S and C .
- Separating Γ and $\bar{\Gamma}$ is necessary to retain sensitivity to S and C : we need **two tagged samples**, that we fit simultaneously.

- Two types of algorithms to determine the initial production flavour of a decaying B/\bar{B} , Same Side (SS) and Opposite Side (OS) tagging.
- Outputs of this algorithm: a tagging efficiency ϵ_{TAG} and a per-event mis-tag probability ω , with the worst case being $\omega = 0.5$.



Tagger	$\epsilon_{\text{TAG}}(\%)$	$\omega(\%)$	$\epsilon(1 - 2\omega)^2$
SS	83	42	1.8
OS	~ 80	40	2.7

- We recall the expression for the decay time:

$$\Gamma/\bar{\Gamma}(t) = e^{-\Gamma t} \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - A_{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right. \\ \left. \mp C \cos(\Delta m_s t) \pm S \sin(\Delta m_s t) \right] \quad (3)$$

where t is the *true* decay time.

- This mis-tag probability ω dilutes the decay rate by a factor $(1 - 2\omega)$, such that

$$\Gamma/\bar{\Gamma}(t) = e^{-\Gamma t} \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - A_{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right. \\ \left. \mp (1 - 2\omega) C \cos(\Delta m_s t) \pm (1 - 2\omega) S \sin(\Delta m_s t) \right] \quad (4)$$

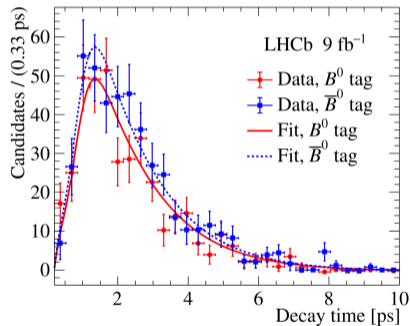
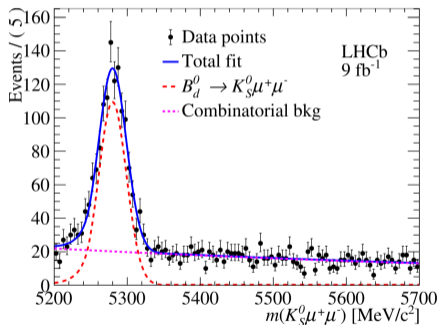
- Decay-time resolution smears the true decay time $t \rightarrow t'$.
- Decay-time dependent selections modifies the decay-time distribution.
- The decay rate expressions with efficiency and resolution become

$$\text{PDF}(t') = [\Gamma(t) \otimes R(t, t')] \times \epsilon(t') \quad (5)$$

with $R(t, t')$ the resolution and $\epsilon(t)$ the efficiency.

- Effective resolution: **60 fs**.
- Non-flat efficiency is left free in the fit

- Invariant mass fit to extract the signal
- Unbinned fit to the background-subtracted decay-time distribution.



- Consistent with the SM: **no sign of NP at the current level of precision.**
- No q^2 dependence within uncertainties.

q^2 range [GeV ² /c ⁴]	C	S
Total	-0.13 ± 0.32	$+0.82 \pm 0.29$
Low: $q^2 < 8.0$	$+0.33 \pm 0.44$	$+1.10 \pm 0.43$
High: $11.0 < q^2 < 15.0$ or $q^2 > 17.5$	-0.62 ± 0.47	$+0.48 \pm 0.47$

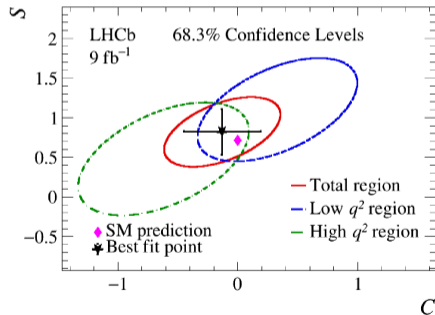


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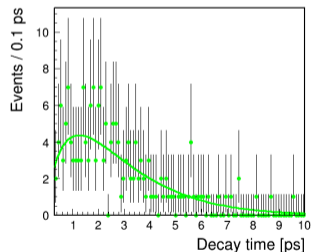
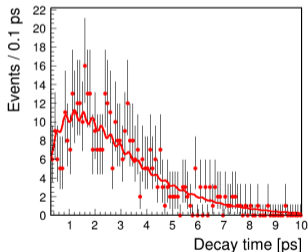
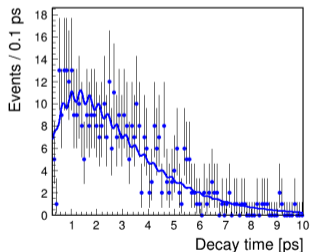
Toy studies

- We estimate the number of events for our toy studies by scaling the number of events from previous analyses.
- For $B_s \rightarrow f_0 \mu \mu$ $N_1 = 55$ [[LHCb collaboration, Physics Letters B 743 \(April 2015\) 46–55](#)], times luminosity and the production cross-section

Run	Luminosity	$\sigma/\sigma(\text{Run1})$	N
I	3.2	1	55
II	5.9	2	201
III	22.56	2	768
Total	–	–	1024

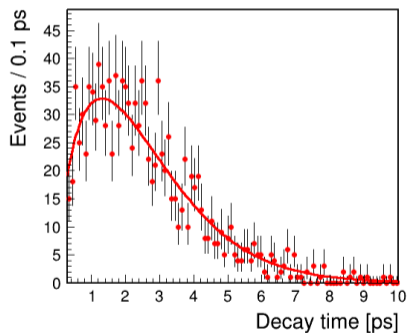
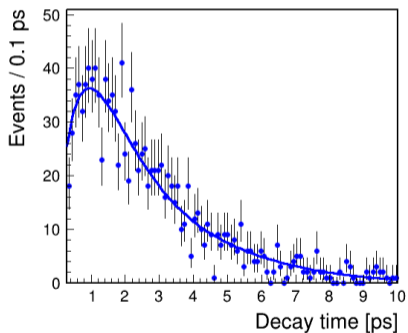
$B_s \rightarrow f_0 \mu \mu$ - results

- In the $B_s \rightarrow f_0 \mu \mu$ channel, **additional sensitivity to $A_{\Delta\Gamma}$** .
- Oscillations are much faster, so the loss due to imperfect flavour tagging is more pronounced.



$B \rightarrow K_S \mu \mu$ - results

- For $B \rightarrow K_S \mu \mu$ channel, there are no oscillations, no sensitivity to $A_{\Delta\Gamma}$.



- Summary of uncertainties

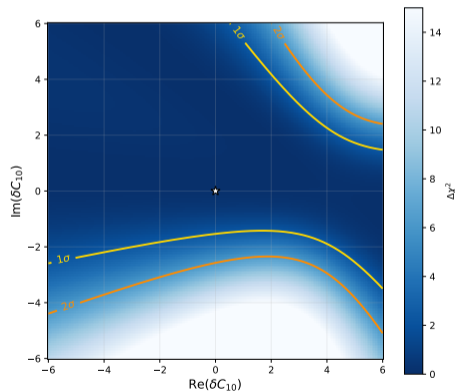
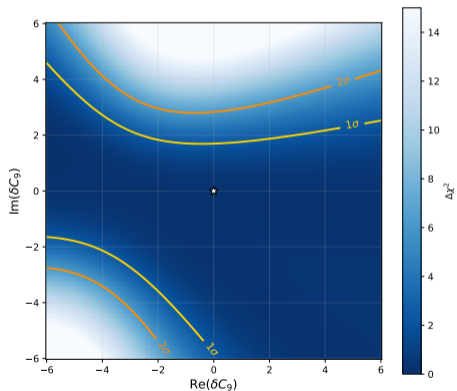
	$A_{\Delta\Gamma}$	S	C
$B \rightarrow K_S^0 \mu\mu$	–	0.72 ± 0.20	0.0 ± 0.14
$B \rightarrow f_0 \mu\mu$	$– \pm 0.45$	$– \pm 0.52$	$– \pm 0.52$

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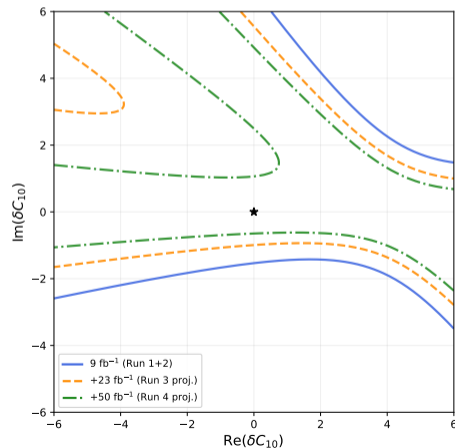
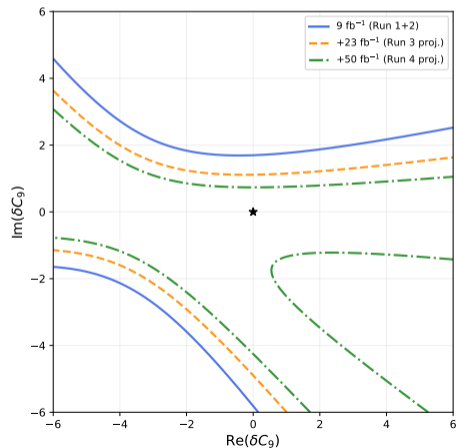
Simplified fit to \mathcal{C}_9 and \mathcal{C}_{10} from indirect CP asymmetries

- We fit \mathcal{C}_9 and \mathcal{C}_{10} over the complex plane neglecting theoretical uncertainties (experimentally dominated)



Projections for Run 3 and Run 4

- We scale the sensitivity with luminosity (Run 3 and Run 4)
 - ⇒ Statistically dominated measurement
 - ⇒ No improvement in flavour tagging



Comparison to model-dependent constraints from Direct CP-asymmetries

- We can compare to the constraints on $\text{Im}C_{9(10)}$ from $B \rightarrow K^*$ direct CP-asymmetries :
Resonance model LHCb [LHCb 2405.17347] v/s Fit to linear model [Altmannshofer et al. 2603.27753]

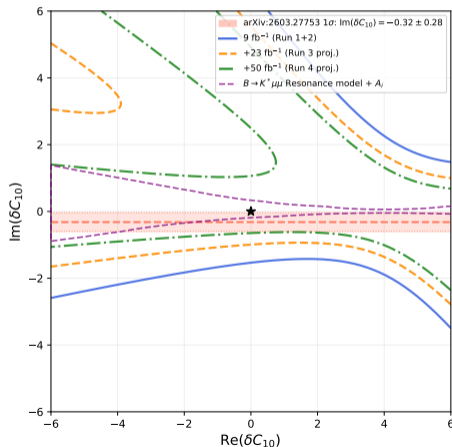
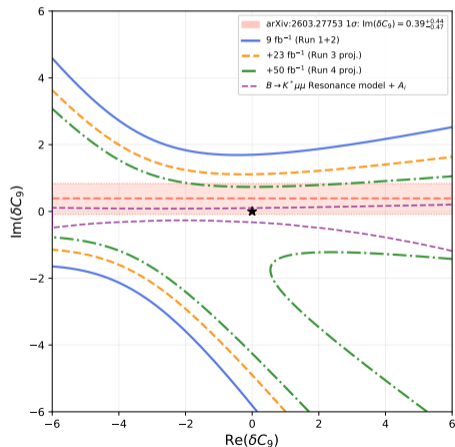


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Conclusion

- Rare $b \rightarrow s\ell^+\ell^-$ decays provide a theoretically clean probe of CP-violating NP, sensitive to $\text{Im}(C_{9(\ell)}^{\text{NP}}, C_{10(\ell)}^{\text{NP}})$.
- First time-dependent CPV measurement in $B^0 \rightarrow K_S^0\mu^+\mu^-$ was obtained (Run 1+2), consistent with the SM.
- Current constraints are significantly weaker than direct CP asymmetries, due to limited flavour-tagging power and mistag dilution.
- Even with Run 3–4 statistics, sensitivity remains limited, hence not yet competitive with direct CPV constraints.
- Improving flavour tagging is essential for this method to become competitive.

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