New physics search via CP observables in $B_s^0 \to \phi\phi$ decays with left- and right-handed chromomagnetic operators

Tejhas Kapoor* and Emi Kou

Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

(Received 7 July 2023; accepted 21 September 2023; published 1 November 2023)

In this paper, we investigate the time-dependent angular analysis of $B_s^0 \to \phi\phi$ decay to search for new physics signals via CP-violating observables. We work with a new physics Hamiltonian containing both left- and right-handed chromomagnetic dipole operators. The hierarchy of the helicity amplitudes in this model gives us a new scheme of experimental search, which is different from the ones LHCb has used in its analysis. To illustrate this new scheme, we perform a sensitivity study using two pseudo datasets generated using LHCb's measured values. We find the sensitivity of CP-violating observables to be of the order of 5–7% with the current LHCb statistics. In addition, we present a revised version of the table of coefficients of time-dependent terms in the angular decay distribution with precisely defined quantities. Moreover, we show that Belle(II)'s $B_d^0 \to \phi K_s$ and LHCb's $B_s^0 \to \phi\phi$ measurements could be coupled within our model to obtain the chirality of the new physics.

DOI: 10.1103/PhysRevD.108.096002

I. INTRODUCTION

Currently, the only confirmed source of CP violation is the Kobayashi-Maskawa (KM) phase present in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1,2], which arises when we move the quarks from flavor to mass eigenstate in the Standard Model (SM). However, we expect to find more sources of CP violation owing to the observed matter-antimatter asymmetry in the Universe [3]. Thus, it is imperative to look for CP-violating observables, especially those which are very small or zero in the SM, because if they deviate even slightly from zero (which can be checked by a null test), it would not just be a discovery of a new source of CP violation, but also be a smoking-gun signal of new physics (NP).

In this article, we study the $B_s^0 \to \phi\phi$ decay [where $\phi(1020)$ is implied throughout this paper], which is a $B \to VV$-type pure penguin process. $B \to VV$ type processes have been extensively studied in the literature [4–18]. The presence of penguin quantum loop makes it an excellent probe to search for new heavy particles and being a purely penguin-type decay keeps it free from tree-penguin interference contamination, making it a clean observable to search for NP [16–18]. The object of interest is going to be the phase in the interference of the direct decay of B_s^0 mesons and decay via mixing of $B_s^0 - \bar{B}_s^0$ to CP eigenstates, which is a CP-violating parameter. This phase is expected to be very small in SM [$-2\beta_s \approx O(\lambda^2)$]. In this paper, we will be presenting a new scheme for the interference phases of different helicities within the framework of our chosen model of study, which is constructed by adding the chromomagnetic dipole operator (and its chirally flipped counterpart) to our Hamiltonian.

The objective of this article is threefold. The first is to show the power of angular decay distribution; it can help segregate the final state when it is a mixture of different helicities. Combining it with a $P \to VV$-type decay (P-pseudoscalar particle and V-vector particle) gives us access to three (helicity) amplitudes instead of one, meaning we can go beyond the assumption of helicity-independent phases to probe three CP-violating phases, and possibly three new indicators of NP.

Secondly, we present a new scheme for the interference phases, based on the hierarchy of helicity amplitudes arising in our model, which is different from the ones LHCb used in its fits [19]. We also note the fact that LHCb's objective is to do a null test of the interference phase, without any regard to its origin (decay or mixing). However, we specifically assume that the weak phase is coming from decay amplitude, not mixing amplitude. Consequently, we change the form of helicity/transversity amplitude to include a CP-violating decay phase. This modifies the coefficients of time-dependent part of amplitude, which we present in Table V. In addition, we investigate the $B_d^0 \to \phi K_s$ decay amplitude with our NP Hamiltonian. We show that the Belle(II)'s $B_d^0 \to \phi K_s$ decay

*tejhas.kapoor@ijclab.in2p3.fr

measurement along with the LHCb's $B_s^0 \to \phi\phi$ measurement can provide the chirality of NP in our model, as long as the signs of cosine of strong phases of these decays can be obtained from the theory.

Lastly, we perform a sensitivity study to illustrate the new scheme of experimental analysis we are proposing. We perform a fit with two pseudo datasets (based on two sets of result of LHCb) to calculate the sensitivities of the CP-violating parameters, which also act as null test parameters for new physics.

The organization of the article is as follows: In Sec. II, we describe the angular decay distribution of the $B_s^0 \to \phi(\to K^+K^-)\phi(\to K^+K^-)$. In Sec. III, we talk about the CP-violating parameters in SM and in the presence of a NP amplitude. In Sec. IV, we introduce our NP Hamiltonian and do a helicity/transversity analysis in order to pinpoint the effect of NP in the correct transversity amplitude, based on which we present our new phase scheme in Sec. V. Following this phase scheme, we do a sensitivity study on the CP-violating parameters with two pseudodatasets in Sec. VI. Finally, we show that under certain conditions, the results of $B_d^0 \to \phi K_s$ from Belle(II) can be used to complement the results of $B_s^0 \to \phi\phi$ to find the chirality of NP.

II. ANGULAR DECAY DISTRIBUTION

The angular decay distribution for $B_s^0 \to \phi(\to K^+K^-)\times \phi(\to K^+K^-)$ decay can be described by the help of three angles as shown in Fig. 1. A random choice is made for which ϕ meson is used to determine θ_1 and θ_2. The power of angular analysis is that it can disentangle the final states of $B_s^0 \to \phi\phi$ decay (which is a mixture of CP eigenstates) and we get access to three (helicity/transversity) amplitudes instead of one, meaning we can probe three CP-violating phases, and possibly three new indicators of NP. We will neglect the contribution of scalar $f_0(980)$ resonance, as it can be removed by appropriate experimental cuts [19,20]. The amplitude then for this process is given by

$$\mathcal{A}(t,\theta_1,\theta_2,\Phi) = A_0(t)\cos\theta_1\cos\theta_2 + \frac{A_\parallel(t)}{\sqrt{2}}\sin\theta_1\sin\theta_2\cos\Phi + i\frac{A_\perp(t)}{\sqrt{2}}\sin\theta_1\sin\theta_2\sin\Phi, \quad (1)$$

where A_0 is the longitudinal CP-even, $A_\parallel$ is the transverse-parallel CP-even, and $A_\perp$ is the transverse-perpendicular CP-odd transversity amplitude. The resulting angular decay distribution is proportional to square of the amplitude in Eq. (1) and has six terms [21],

$$\frac{d^4\Gamma}{dt\,d\cos\theta_1\,d\cos\theta_2\,d\Phi} \propto |\mathcal{A}(t,\theta_1,\theta_2,\Phi)|^2 = \frac{1}{4}\sum_{i=1}^{6} K_i(t) f_i(\theta_1,\theta_2,\Phi). \quad (2)$$

The angular dependence contained in $f_i(\theta_1,\theta_2,\Phi)$ is as follows:

$$|\mathcal{A}(t,\theta_1,\theta_2,\Phi)|^2 = \frac{1}{4}\big[4K_1(t)\cos^2\theta_1\cos^2\theta_2 + K_2(t)\sin^2\theta_1\sin^2\theta_2(1+\cos2\Phi) + K_3(t)\sin^2\theta_1\sin^2\theta_2(1-\cos2\Phi) - 2K_4(t)\sin^2\theta_1\sin^2\theta_2\sin2\Phi + \sqrt{2}K_5(t)\sin2\theta_1\sin2\theta_2\cos\Phi - \sqrt{2}K_6(t)\sin2\theta_1\sin2\theta_2\sin\Phi\big]. \quad (3)$$

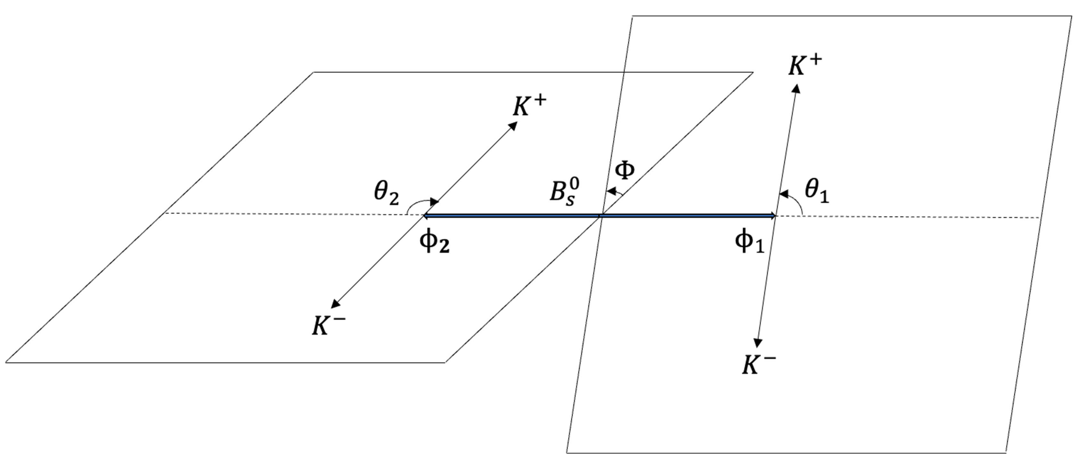

FIG. 1. Decay angles for the $B_s^0 \to \phi(\to K^+K^-)\phi(\to K^+K^-)$ decay, where $\theta_{1(2)}$ is the angle between the K^+ momentum in the $\phi_{1(2)}$ meson rest frame and the $\phi_{1(2)}$ momentum in the B_s^0 rest frame. Φ is the angle between the two ϕ meson decay planes. The angular conventions used are defined in detail in Appendix A.

The time dependence is contained in $K_i(t)$ which is defined as

$$K_i(t) = N_i e^{-\Gamma_s t}\left[a_i \cosh\left(\frac{1}{2}\Delta\Gamma_s t\right) + b_i \sinh\left(\frac{1}{2}\Delta\Gamma_s t\right) + c_i \cos(\Delta m_s t) + d_i \sin(\Delta m_s t)\right]. \quad (4)$$

The coefficients a_i, b_i, c_i and d_i are the LHCb experimental observables given in Table V. The structure of these coefficients depend on the form of amplitudes $A_{0,\parallel,\perp}(t)$, defined in Sec. III B. $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$ is decay-width difference between the light and heavy B_s^0 mass eigenstate, $\Gamma_s \equiv (\Gamma_L + \Gamma_H)/2$ is the average decay width and $\Delta m_s \equiv m_H - m_L$ is the mass difference between the heavy and light B_s^0 mass eigenstate, and also the $B_s^0 - \bar{B}_s^0$ oscillation frequency. Their values are $\Delta\Gamma_s = 0.086 \pm 0.006\ \mathrm{ps}^{-1}$ and $\Gamma_s = 0.6646 \pm 0.0020\ \mathrm{ps}^{-1}$ [20], and the oscillation frequency is constrained by the LHCb measurement to be $\Delta m_s = 17.768 \pm 0.023(\mathrm{stat}) \pm 0.006(\mathrm{syst})\ \mathrm{ps}^{-1}$ [22].

III. SEARCH FOR NEW PHYSICS VIA *CP* OBSERVABLES

A. *CP*-violating quantities in the Standard Model

Before looking at how to search for NP, we must know the SM predictions [23]. The phase in the interference of decay with and without mixing is almost zero in SM in $B_s^0 \to \phi\phi$ decays because the KM phase in B_s^0 decay amplitude cancels the one arising from the $B_s^0 - \bar{B}_s^0$ mixing box diagram (considering the dominant t-quark contribution). This makes $B_s^0 \to \phi\phi$ decay a very attractive null-test channel. But for a more accurate prediction of phase (to higher orders in λ), we need to consider the contribution of u and c-quarks too. These contributions can arise due to QCD rescattering $c\bar{c} \to q\bar{q}$ and $u\bar{u} \to q\bar{q}$ ($q = d, s$) from tree operators $\bar{b} \to \bar{c}c\bar{s}$ and $\bar{b} \to \bar{u}u\bar{s}$, respectively, and may have a contribution up to around 20–30% [24] of the dominant top amplitude. Taking into account these contributions, the SM amplitude for $\bar{b} \to \bar{s}$ decay for a given helicity 'k' can be written as

$$A_k^{\mathrm{SM}} = \lambda_t P_{t,k} + \lambda_c R_{c,k} + \lambda_u R_{u,k}, \quad (5)$$

where $\lambda_q = V_{qb}^* V_{qs}$ is the CKM matrix element. Here, while $P_{t,k}$ arises due to gluonic penguin with a $\bar{t}$-quark in the loop, $R_{c,k}$ and $R_{u,k}$ are the rescattering contribution. The existence of these contributions prevents the above-mentioned cancellation from occuring. In the following sections, we neglect the rescattering contributions; still, let us look at their possible impact.

Using the unitarity of the CKM matrix to eliminate the c-quark contribution in Eq. (5) and writing strong phases explicitly, we get

$$\begin{aligned} A_k^{\mathrm{SM}} &= |V_{tb}^* V_{ts}| e^{-i\beta_s} |PR_{tc,k}| e^{i\delta_{tc,k}} + |V_{ub}^* V_{us}| e^{i\gamma} |RR_{uc,k}| e^{i\delta_{uc,k}} \\ &= |V_{tb}^* V_{ts}| e^{-i\beta_s} |PR_{tc,k}| e^{i\delta_{tc,k}} [1 + r_k^{\mathrm{SM}} e^{i(\gamma+\beta_s)} e^{i(\delta_{uc,k}-\delta_{tc,k})}], \end{aligned} \quad (6)$$

where $PR_{tc,k} = P_{t,k} - R_{c,k}$, $RR_{uc,k} = R_{u,k} - R_{c,k}$, δ denote the SM strong phases, $\beta_s = \arg(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}) \approx \eta\lambda^2$, and $r_k^{\mathrm{SM}} = \frac{|V_{ub}^* V_{us}||RR_{uc,k}|}{|V_{tb}^* V_{ts}||PR_{tc,k}|}$. Assuming that the rescattering contribution is around 20–30% of the dominant penguin amplitude, we can write $\frac{|RR_{uc,k}|}{|PR_{tc,k}|} = O(\lambda)$, as $\lambda \approx 0.22$. Therefore, we have $r_k^{\mathrm{SM}} = O(\lambda^3)$. Thus, by defining $A_k^{\mathrm{SM}} \equiv |A_k^{\mathrm{SM}}| e^{i\phi^{\mathrm{SM}}} e^{i\delta_k^{\mathrm{SM}}}$, we find $\phi^{\mathrm{SM}} = -\beta_s + O(\lambda^3)$ and $\delta_k^{\mathrm{SM}} = \delta_{tc,k} + O(\lambda^3)$. This implies that the following discussion (and this form of amplitude) is valid for NP searches of order λ^2.

B. *CP*-violating quantities in the presence of new physics: Parametrization

In this study, as mentioned before, we are only probing *CP*-violating phases in the decay; thus, our parametrization is done accordingly. Here, for generality, we include both left- and right-handed currents (which could arise from several NP models), which could give rise to new *CP*-violating phase(s). Also, we assume $|\frac{q}{p}| = 1$ [25].

The helicity/transversity amplitudes, with helicity/transversity "k" are written as [26]

$$\begin{aligned} A_k(t) &= \langle(\phi\phi)_k|\mathcal{H}_{\mathrm{eff}}|B_s^0(t)\rangle = g_+(t)A_k + \frac{q}{p} g_-(t)\bar{A}_k, \\ \bar{A}_k(t) &= \langle(\phi\phi)_k|\mathcal{H}_{\mathrm{eff}}|\bar{B}_s^0(t)\rangle = g_+(t)\bar{A}_k + \frac{p}{q} g_-(t)A_k. \end{aligned} \quad (7)$$

where $g_+(t)$ and $g_-(t)$ describe the time evolution of B_s^0 and $\bar{B}_s^0$, respectively. Using Eq. (6) and adding a NP component, the amplitude at $t = 0$ can be written as

$$\begin{aligned} A_k(0) \equiv A_k &= A_k^{\mathrm{SM}} + A_k^{\mathrm{NP}} \\ &= |A_k^{\mathrm{SM}}| e^{i\delta_k^{\mathrm{SM}}} e^{i\phi^{\mathrm{SM}}} + |A_k^{\mathrm{NP}}| e^{i\delta_k^{\mathrm{NP}}} e^{i\phi_k^{\mathrm{NP}}} \\ &= |A_k^{\mathrm{SM}}| e^{i\delta_k^{\mathrm{SM}}} e^{i\phi^{\mathrm{SM}}} \left(1 + r_k^{\mathrm{NP}} e^{i(\phi_k^{\mathrm{NP}} - \phi^{\mathrm{SM}})} e^{i(\delta_k^{\mathrm{NP}} - \delta_k^{\mathrm{SM}})}\right) \\ &= |A_k^{\mathrm{SM}}| e^{i\delta_k^{\mathrm{SM}}} e^{i\phi^{\mathrm{SM}}} X_k e^{i\theta_k}, \end{aligned} \quad (8)$$

where in the last line, we denote the quantity in the parenthesis as $X_k e^{i\theta_k}$ and $r_k^{\mathrm{NP}} = \frac{|A_k^{\mathrm{NP}}|}{|A_k^{\mathrm{SM}}|}$. The phase θ_k is a mixture of weak and strong phases.[1] Similarly, for the *CP*-conjugate amplitude, the expression is (η_k is the *CP*

[1] Notice that if we assume $\delta_k^{\mathrm{SM}} = \delta_k^{\mathrm{NP}}$, then the phase θ_k would be a purely weak phase. In such a case the interference phase in Eq. (10) would not just tell us about the presence of NP, it would also tell us the value of *CP*-violating (weak) phase in the decay amplitude. However, we work in the most general case in this calculation, as we only wish to probe for NP.

eigenvalue of the transversity state, with $\eta_\perp = -1$ and $\eta_{0,\parallel} = 1$)

$$\begin{aligned}\bar{A}_k &= \eta_k |A_k^{\rm SM}| e^{i\delta_k^{\rm SM}} e^{-i\phi^{\rm SM}} (1 + r_k^{\rm NP} e^{-i(\phi_k^{\rm NP}-\phi^{\rm SM})} e^{i(\delta_k^{\rm NP}-\delta_k^{\rm SM})}) \\ &= \eta_k |A_k^{\rm SM}| e^{i\delta_k^{\rm SM}} e^{-i\phi^{\rm SM}} X_k^c e^{i\theta_k^c}. \end{aligned} \quad (9)$$

Recalling that $\arg(q/p) = 2\beta_s \approx 2\phi^{\rm SM}$, we finally get

$$\frac{q}{p}\frac{\bar{A}_k}{A_k} = \eta_k \lambda_k e^{-i(\theta_k - \theta_k^c)}, \quad (10)$$

where $\lambda_k \equiv \frac{|\bar{A}_k|}{|A_k|} = \frac{X_k^c}{X_k}$ becomes the direct CP violation measurement parameter; $\lambda_k \neq 1$ implies direct CP violation is present in the decay. Since in SM, $\lambda_k = 1$ for all helicities, the deviation of this value from 1 [by more than $O(\lambda^3)$] would be a clear signal for NP, i.e., $\lambda_k - 1$ is a null-test parameter for NP. Another quantity that can be used for NP search is the interference phase $\theta_k - \theta_k^c$. In SM, this quantity is zero, as explained in Sec. III A. Therefore, the deviation of this quantity from zero [by more than $O(\lambda^3)$] would be a signal of NP, i.e., $\theta_k - \theta_k^c$ is also a null-test parameter for NP. One must note that there is one special case when neither of these two parameters would be able to detect the presence of NP; it is the case when $\phi_k^{\rm NP} = \phi^{\rm SM}$. In this case, $\lambda_k = 1$ and $\theta_k - \theta_k^c = 0$ and NP cannot be detected by CP-violating observables.

Here, we take a moment to explain the η_k factors used. When we write the CP-conjugate decay, we replace the particles by their antiparticles. The effect of this replacement on the helicity angle is $\phi \to 2\pi - \phi$, which gives rise to a negative sign in those terms which contain amplitudes having a negative CP parity ($A_\perp$ in our case). Therefore, using η_k in the definition of amplitude allows us to use the same angular functions for B_s^0 and $\bar{B}_s^0$ decays, which facilitates calculations in untagged samples [23].

The time-dependent amplitude is given by

$$\begin{aligned} A_k(t) &= A_k\left[g_+(t) + g_-(t)\frac{q}{p}\frac{\bar{A}_k}{A_k}\right], \\ A_k(t) &= |A_k^{\rm SM}| X_k e^{i\delta_k^{\rm SM}} e^{i\phi^{\rm SM}} e^{i\theta_k}\left[g_+(t) + g_-(t)\eta_k\lambda_k e^{-i(\theta_k-\theta_k^c)}\right]. \end{aligned} \quad (11)$$

The coefficients of the time-dependent terms in Eq. (4), obtained by using Eq. (11), are given in Table V. Our time-dependent amplitude differs from the one given by LHCb, because while LHCb has used the amplitude $A_k = |A_k| e^{i\delta_k}$, our amplitude contains both SM and NP contribution, and both contain strong and weak phases [see Eq. (8)].[2] Thus, we have the phase $\phi^{\rm SM} + \theta_k$ along with $\delta_k^{\rm SM}$ (contrary to LHCb equation where there only is $\delta_k^{\rm SM}$ outside the bracket). In addition, because we have both SM and NP amplitudes, we get two different mixed phases (θ_k and θ_k^c) coming from A_k and $\overline{A_k}$, and thus the interference phase is $\theta_k - \theta_k^c$, contrary to LHCb's equation, where the interference phase is simply $\phi_{s,k}$.[3] This changes the coefficients in Table V with respect to the ones given by LHCb [19].[4] For simplicity of notation, we simply denote $\delta_k^{\rm SM}$ as δ_k in the rest of the paper.

Another probe for measuring CP violation are the triple-product asymmetries. This arises from the fact that the scalar triple product of three-momentum or spin vectors are odd under time reversal. In $B_s^0 \to \phi\phi$ decay, we have two triple products U and V, and we measure the corresponding asymmetries A_U and A_V as follows [26],

$$\begin{aligned} U &\equiv \sin\Phi\cos\Phi, \\ A_U &\equiv \frac{\Gamma(U>0)-\Gamma(U<0)}{\Gamma(U>0)+\Gamma(U<0)} \propto \int_0^\infty {\rm Im}(A_\perp(t)A_\parallel^*(t) + \bar{A}_\perp(t)\bar{A}_\parallel^*(t)){\rm d}t, \\ V &\equiv \sin(\pm\Phi), \\ A_U &\equiv \frac{\Gamma(V>0)-\Gamma(V<0)}{\Gamma(V>0)+\Gamma(V<0)} \propto \int_0^\infty {\rm Im}(A_\perp(t)A_0^*(t) + \bar{A}_\perp(t)\bar{A}_0^*(t)){\rm d}t, \end{aligned} \quad (12)$$

[2] The mixing-induced CP violation (i.e., the CP violation in interference of decay with and without mixing) cannot tell us if the original source of this effect is coming from the dynamics of $\Delta B = 2$ (mixing) sector or that of $\Delta B = 1$ (decay) sector, as long as we are working with only one final state (or one pair of CP-conjugate final state). We need information from at least one more final state to decide unambiguously the presence of direct CP violation and/or CP violation in mixing [27].

[3] This increase in number of parameters will make the search more sensitive to NP. However, this comes at a price; it becomes more difficult to make the fit converge. Thus, we need model-dependent simplifying assumptions to reduce the free parameters, as we will show in the subsequent sections, to make the fit converge.

[4] If θ_k and θ_k^c are helicity independent, they will cancel out when we write terms of type $A_i(t)A_k^*(t)$ or $|A_i(t)|^2$. Then our formula and that of LHCb would exactly be the same.

Putting the amplitudes, and comparing it with Eq. (4) and Table V, we see that these triple products are related to the $K_4(t)$ and $K_6(t)$ terms in the decay amplitude.

IV. NEW PHYSICS MODEL

In this section, we see the new physics model and perform an helicity analysis on it to pinpoint its effect on the relevant CP observables. The model we choose to use in our study is that of the chromomagnetic dipole operator O_{8g}, which, for $\bar{b} \to \bar{s}g$ process, is given as follows:

$$O_{8g} = \frac{g_s}{8\pi^2} m_b \bar{b}_\alpha \sigma^{\mu\nu}(1+\gamma^5)\frac{\lambda^a_{\alpha\beta}}{2} s_\beta G^a_{\mu\nu}. \tag{13}$$

Though the chromomagnetic operator is a SM operator, it is suppressed by b-quark mass m_b (and its chirally flipped counterpart is suppressed by s-quark mass m_s). However, it is very sensitive to several NP models, like the left-right symmetric class of models or SUSY, where it can undergo chiral enhancement to overcome the quark mass suppression [28–35]. In addition, there are some NP models that give the same contribution to both decay and mixing amplitudes. This causes the contribution to cancel out in the interference phase, and they remain undetectable in $B_s^0 \to \phi\phi$ decay. However, since the chromomagnetic operator only contributes to the decay amplitudes, a NP contribution manifesting itself through this operator can be very well detected via this channel (the $B_s^0 - \bar{B}_s^0$ mixing amplitude has already been well constrained by previous measurements [36,37], so we do not focus on it in this work).

Starting from the effective Hamiltonian for $\Delta B = 1$ decay, it is given by $(q \in \{d, s\})$

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V^*_{tb} V_{tq}\left[\sum_{i=3}^{6}(C_i^{\text{SM}} O_i) + C_{8g}O_{8g} + \tilde{C}_{8g}\tilde{O}_{8g}\right] + \text{H.c.} \tag{14}$$

The operators are given by $(q' \in \{u, d, s, c\})$

$$\begin{aligned}
O_3 &= (\bar{b}_\alpha q_\alpha)_{V-A}\sum_{q'}(\bar{q}'_\beta q'_\beta)_{V-A},\\
O_4 &= (\bar{b}_\beta q_\alpha)_{V-A}\sum_{q'}(\bar{q}'_\alpha q'_\beta)_{V-A},\\
O_5 &= (\bar{b}_\alpha q_\alpha)_{V-A}\sum_{q'}(\bar{q}'_\beta q'_\beta)_{V+A},\\
O_6 &= (\bar{b}_\beta q_\alpha)_{V-A}\sum_{q'}(\bar{q}'_\alpha q'_\beta)_{V+A},
\end{aligned} \tag{15}$$

with the notation $(\bar{a}b)_{V\pm A}(\bar{c}d)_{V\pm A} = \bar{a}\gamma^\mu(1\pm\gamma^5)b \times \bar{c}\gamma_\mu(1\pm\gamma^5)d$.

Here, we only include the gluonic penguin operators. The operator with tilde is obtained by changing the sign of γ_5 term in the definition of O_{8g} to obtain the chirally flipped counterpart.

A. Helicity analysis

Once we have the model clearly defined with Hamiltonian and amplitudes, we can move on to the helicity analysis. As mentioned before, the advantage in $P \to VV$ type decays is that the final state can be split into three helicity states, which gives us access to three amplitudes, whose sum makes up the total amplitude. The general form of helicity amplitude for the process $B(M, p) \to V_1(\epsilon_1, M_1, k_1) + V_2(\epsilon_2, M_2, k_2)$ is given by [38][5]

$$H_\lambda = a(\epsilon_1^*(\lambda)\cdot\epsilon_2^*(\lambda)) + \frac{b}{M_1M_2}(\epsilon_1^*(\lambda)\cdot k_2)(\epsilon_2^*(\lambda)\cdot k_1) + \frac{ic}{M_1M_2}\epsilon_{\mu\nu\rho\sigma}\epsilon_1^{*\mu}(\lambda)\epsilon_2^{*\nu}(\lambda)k_1^\rho k_2^\sigma, \tag{16}$$

where $\lambda = \{+, -, 0\}$ is the polarization of final state. a, b, and c are the invariant amplitudes. Putting the polarization vectors for the three different polarizations, we get

$$H_0 = ax + b(x^2 - 1), \qquad H_\pm = a \pm c\sqrt{x^2-1}, \tag{17}$$

where $x = \frac{M_B^2 - M_1^2 - M_2^2}{2M_1M_2}$. A more convenient basis to work than helicity basis is transversity basis [21]. To go there, we first note that by angular momentum conservation, the final-state helicities could only be $|++\rangle, |--\rangle$, and $|00\rangle$. Since $P|++\rangle = |--\rangle$ and $P|00\rangle = |00\rangle$, we can define parity eigenstates with eigenvalues ±1 as [27]

$$\begin{aligned}
|\|\rangle &= \frac{1}{\sqrt{2}}(|++\rangle + |--\rangle),\\
|\perp\rangle &= \frac{1}{\sqrt{2}}(|++\rangle - |--\rangle).
\end{aligned} \tag{18}$$

These are called transversity amplitudes, denoted by A_k, with $k = \{0, \|, \perp\}$, as given in Eq. (1). Clearly

$$\mathcal{A}_{\|,\perp} = \frac{1}{\sqrt{2}}(H_+ \pm H_-), \qquad \mathcal{A}_0 = H_0. \tag{19}$$

Thus,

$$\begin{aligned}
A_0 &= ax + b(x^2-1), \qquad A_\| = \sqrt{2}a,\\
A_\perp &= \sqrt{2(x^2-1)}c.
\end{aligned} \tag{20}$$

[5] We use the convention $\epsilon^{0123} = 1$. The opposite convention would simply interchange the definition of H_+ and H_-, without affecting H_0.

Let us see the hierarchy of amplitudes predicted by the $V-A$ structure of current. The hierarchy is $H_0 > H_+ > H_-$ (interchange $+$ and $-$ signs for $\bar{B}_s^0$ decay) [39], with the approximate ratio $H_0\colon H_+\colon H_- \sim 1\colon(\frac{m_\phi}{m_B})\colon(\frac{m_\phi}{m_B})^2$ [39,40]. However, it is well known that this hierarchy is not observed experimentally in $B \to VV$ decays. A large transverse polarization was first observed in $B_d \to \phi K^*$ [41] (and then later in $B_d \to J/\psi\phi$ [37], $B_s \to \phi\phi$ [19], etc.) which gave rise to intense theoretical and experimental studies of charmless $B \to VV$ decays. Several theoretical papers have been written to go beyond the naive factorization method and use more sophisticated tools (like QCDf, pQCD, SCET, etc.) to compute these decays more accurately [16–18,39]. It has been pointed out in [17,39,42] that a major contributor to transverse amplitudes are the annihilation diagrams which can explain the large fraction of transverse amplitudes observed experimentally.

On the other hand, the contribution from the chromomagnetic operator is suppressed in transverse penguin amplitudes (originally pointed out in [39], and verified by pQCD approach in [43]). Therefore, the NP contributions manifesting via the chromomagnetic operator should predominantly contribute to longitudinal polarization amplitude. This is a key point, that we would use in the subsequent sections for our fit.

The total amplitude for SM, left- and right-handed currents can be written as follows, where, as discussed above, we neglect the transverse contributions $\mathcal{M}_{\parallel,\perp}^{L,R}$ in NP amplitudes:

$$\begin{aligned}
\mathcal{M}_{\phi\phi}^{\mathrm{SM,Total}} &= \mathcal{M}_{0,\phi\phi}^{\mathrm{SM}} + \mathcal{M}_{\parallel,\phi\phi}^{\mathrm{SM}} + \mathcal{M}_{\perp,\phi\phi}^{\mathrm{SM}} \\
&= -\frac{G_F}{\sqrt{2}} V_{tb}^* V_{ts} \left(\xi_0^{\mathrm{SM}} \mathcal{F}_0^{\mathrm{SM}} + \xi_\parallel^{\mathrm{SM}} \mathcal{F}_\parallel^{\mathrm{SM}} + \xi_\perp^{\mathrm{SM}} \mathcal{F}_\perp^{\mathrm{SM}}\right), \\
\mathcal{M}_{\phi\phi}^{L,\mathrm{Total}} &= \mathcal{M}_{0,\phi\phi}^{\mathrm{L}} \\
&= -\frac{G_F}{\sqrt{2}} V_{tb}^* V_{ts} \left(\xi_0^{\mathrm{L}} \mathcal{F}_0^{\mathrm{NP}}\right), \\
\mathcal{M}_{\phi\phi}^{R,\mathrm{Total}} &= \mathcal{M}_{0,\phi\phi}^{\mathrm{R}} \\
&= -\frac{G_F}{\sqrt{2}} V_{tb}^* V_{ts} \left(-\xi_0^{\mathrm{R}} \mathcal{F}_0^{\mathrm{NP}}\right),
\end{aligned} \tag{21}$$

where $\mathcal{F}^{\mathrm{SM}}$ and $\mathcal{F}^{\mathrm{NP}}$ contains the contribution from the matrix elements for SM and NP case, respectively. The ξ_k^p ($k = \{0, \parallel, \perp\}$ and $p \in \{\mathrm{SM, L, R}\}$) are combinations of Wilson coefficients, and contain the weak phases. The actual form of ξ and $\mathcal{F}$ depend upon the model chosen to compute the matrix elements, but it is not important for our purposes. The important thing to notice is the sign change in the longitudinal component of right-handed amplitude. This sign change occurs due to the sign change in the axial part of the current; we have verified this for longitudinal amplitude by both naive factorization and pQCD approach.

V. NEW PHASE SCHEME FROM THE CHROMOMAGNETIC OPERATOR

Let us now clarify the observables which are sensitive to our NP model. Following Eq. (21), the total longitudinal transversity amplitude in the presence of NP manifested via the chromomagnetic operator is now given by

$$\begin{aligned}
\mathcal{M}_{0,\phi\phi}^{\mathrm{Total}} &= -\frac{G_F}{\sqrt{2}} V_{tb}^* V_{ts} \left(\xi_0^{\mathrm{SM}} \mathcal{F}_0^{\mathrm{SM}} + \xi_0^{\mathrm{L}} \mathcal{F}_0^{\mathrm{NP}} - \xi_0^{\mathrm{R}} \mathcal{F}_0^{\mathrm{NP}}\right) \\
&= \mathcal{M}_{0,\phi\phi}^{\mathrm{SM}} \left(1 + r^{\mathrm{L}} e^{i(\omega_{\mathrm{L}}+\sigma)} - r^{\mathrm{R}} e^{i(\omega_{\mathrm{R}}+\sigma)}\right),
\end{aligned} \tag{22}$$

where we parametrize the NP contribution as follows:

$$\frac{\xi_0^{\mathrm{L}} \mathcal{F}_0^{\mathrm{NP}}}{\xi_0^{\mathrm{SM}} \mathcal{F}_0^{\mathrm{SM}}} = r^{\mathrm{L}} e^{i(\omega_{\mathrm{L}}+\sigma)} \qquad \frac{\xi_0^{\mathrm{R}} \mathcal{F}_0^{\mathrm{NP}}}{\xi_0^{\mathrm{SM}} \mathcal{F}_0^{\mathrm{SM}}} = r^{\mathrm{R}} e^{i(\omega_{\mathrm{R}}+\sigma)}. \tag{23}$$

$\omega_{\mathrm{L,R}}$ are the weak/CP-odd phases and σ is a strong/CP-even phase. Recalling the definition of interference phase from Eq. (10) and putting Eq. (22) in it, we can write

$$\begin{aligned}
\frac{q}{p} \frac{\bar{\mathcal{M}}_{0,\phi\phi}^{\mathrm{Total}}}{\mathcal{M}_{0,\phi\phi}^{\mathrm{Total}}} &= \lambda_0 e^{-i(\theta_0 - \theta_0^c)} \\
&= \frac{1 + 2\cos\sigma(r^{\mathrm{L}} e^{-i\omega_{\mathrm{L}}} - r^{\mathrm{R}} e^{-i\omega_{\mathrm{R}}})}{1 + 2r^{\mathrm{L}}\cos(\omega_{\mathrm{L}}+\sigma) - 2r^{\mathrm{R}}\cos(\omega_{\mathrm{R}}+\sigma)}.
\end{aligned} \tag{24}$$

Therefore, only λ_0 and $\theta_0 - \theta_0^c$ would get contributions from NP, while other transversities CP-violating parameters would assume their SM values, i.e., $\theta_\parallel = \theta_\parallel^c = \theta_\perp = \theta_\perp^c = 0$ and $\lambda_\parallel = \lambda_\perp = 1$. As we can see, the five theoretical parameters ($r^{\mathrm{L,R}}$, $\omega_{\mathrm{L,R}}$ and σ) cannot be determined, as we do not have sufficient observables (only λ_0 and $\theta_0 - \theta_0^c$). Nevertheless, an observation of nonzero value of $\lambda_0 - 1$ and/or $\theta_0 - \theta_0^c$ would clearly indicate the presence of NP.

Let us now compare the phase scheme that LHCb used in their fit to ours. Before comparing with our parametrization, we note that the interference phase in LHCb is defined as

$$\frac{q}{p} \frac{\bar{\mathcal{M}}_{k,\phi\phi}^{\mathrm{Total}}}{\mathcal{M}_{k,\phi\phi}^{\mathrm{Total}}} = \eta_k \lambda_k e^{-i\phi_k^{\mathrm{LHCb}}}, \tag{25}$$

where k is the transversity and η_k is the CP parity of the transversity state. Comparing Eq. (25) with Eq. (10), we find $\phi_k^{\mathrm{LHCb}} \equiv \theta_k - \theta_k^c$. LHCb uses the following two different fit configurations:

(i) LHCb *helicity-dependent* (HD) scheme: $\phi_0^{\mathrm{LHCb}} = 0$, $\lambda_k = 1\ \forall\ k$ ($\phi_\perp^{\mathrm{LHCb}}$ and $\phi_\parallel^{\mathrm{LHCb}}$ are the CP-violating fit parameters).

(ii) LHCb *helicity-independent* (HI) scheme: $\phi = \phi_k^{\mathrm{LHCb}}\ \forall\ k$, $\lambda = \lambda_k\ \forall\ k$ (ϕ and λ are the *CP*-violating fit parameters).

The new fit configuration we are proposing is

(i) NP manifested via the chromomagnetic operator: $\phi_\perp^{\mathrm{LHCb}} = \phi_\parallel^{\mathrm{LHCb}} = 0$ or equivalently $\theta_\parallel = \theta_\parallel^c = \theta_\perp = \theta_\perp^c = 0$, $\lambda_\perp = \lambda_\parallel = 1$ (ϕ_0^{LHCb} and λ_0 are the *CP*-violating fit parameters).

The LHCb fit configuration does not match to ours, and a new fit of LHCb data with this new scheme based on our model would be very interesting. We emphasize that neither of the two LHCb schemes above fit ϕ_0^{LHCb} and λ_0 simultaneously; therefore, our phase scheme is a new avenue to search for NP manifesting itself via the chromomagnetic operator.

VI. SENSITIVITY STUDY WITH THE NEW FIT CONFIGURATION

In this section, we illustrate an analysis with the new phase scheme we proposed in Sec. V. To start, let us list all the possible fit parameters before considering any model assumptions; $(|A_{0,\perp,\parallel}|^2, \delta_{0,\perp,\parallel}, \theta_{0,\perp,\parallel}, \theta^c_{0,\perp,\parallel}, \lambda_{0,\perp,\parallel})$. First, using the relation $|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2 = 1$, we remove one of the amplitudes, e.g., $|A_\parallel|^2$. Next, we notice that in Table V, the phases always appear as combinations of $\theta_k - \theta_k^c$ and $\psi_i - \psi_j$ where $\psi_k \equiv \theta_k + \delta_k$. For example, the combination $\theta_k^c + \delta_k$ can be rewritten as $\psi_k - (\theta_k - \theta_k^c)$. Now, let us use the results of our model introduced in Sec. IV; the chromomagnetic operator contributes predominantly to longitudinal polarization, giving us $\theta_\parallel = \theta_\parallel^c = \theta_\perp = \theta_\perp^c = 0$. Then, the arguments of trigonometric functions in Table V can be expressed by the three parameters, $(\theta_0 - \theta_0^c, \delta_\parallel - \delta_\perp, \delta_\parallel - \delta_0 - \theta_0)$. As explained in Sec. III B, the first parameter is the phase in the interference of decay with and without mixing, which is a *CP*-violating quantity, while the last two contain strong phases. Thus, only the first one can be used for a null test. Finally, our model also imposes $\lambda_{\perp,\parallel} = 1$. As a result, we are left with six parameters to fit

$$(\lambda_0, \theta_0 - \theta_0^c, \delta_\parallel - \delta_\perp, \delta_\parallel - \delta_0 - \theta_0, |A_0|^2, |A_\perp|^2).$$

Only the first two can be used for a null test; $\lambda_0 \neq 1$ and/or $\theta_0 - \theta_0^c \neq 0$ are/is a clear signal of new physics.

To illustrate the fit, we first construct two *pseudodatasets* by using the LHCb best-fit values, denoted as Data HI and Data HD for the LHCb helicity-independent and helicity-dependent fit, respectively. The details of the statistical procedure applied in this study are given in Appendix B.

Our fit results are shown in Table I, and the correlation matrices are given in Tables III and IV in Appendix C. We note that the results using Data HI and Data HD agree relatively well. The obtained uncertainty of $\sigma(\lambda_0) = 6$–7% and $\sigma(\theta_0 - \theta_0^c) = 5$–$6\%$ with the currently available LHCb statistics (5 fb^{-1}) may be used as an indication for future studies.

TABLE I. Fit results based on our model assumptions, i.e., longitudinal component dominance for NP contributions coming from the chromomagnetic operator ($\theta_\parallel^c = \theta_\parallel = \theta_\perp^c = \theta_\perp = 0$ and $\lambda_\parallel = \lambda_\perp = 1$).

	Data HD		Data HI	
Fit parameter	Central value	σ	Central value	σ
λ_0	0.978	0.058	0.984	0.070
$\lvert A_0\rvert^2$	0.386	0.025	0.385	0.032
$\lvert A_\perp\rvert^2$	0.287	0.018	0.288	0.036
$\theta_0 - \theta_0^c$	−0.002	0.055	0.066	0.053
$\delta_\parallel - \delta_\perp$	−0.259	0.054	−0.261	0.056
$\delta_\parallel - \delta_0 - \theta_0$	2.560	0.071	2.589	0.079

VII. LEFT OR RIGHT: $B_d^0 \to \phi K_S$ DECAY

A decay very similar to $B_s^0 \to \phi\phi$ decay is the $B_d^0 \to \phi K_s$ decay, since at the quark level, both contain a $\bar{b} \to \bar{s}s\bar{s}$ decay. We thus expect the weak interaction to be the same in both the decays, while strong interaction may differ. In this section, we investigate how the experimental results of $B_d^0 \to \phi K_s$ complements the $B_s^0 \to \phi\phi$ results, within the left- and right-handed chromomagnetic operator model.

We start with the $B_d^0 \to \phi K_s$ decay. The phase in the interference of decay with and without mixing in SM is $2\phi_1$, where ϕ_1 is the unitary triangle angle. However, NP contributions may deviate its value from ϕ_1, and what we measure experimentally should then be called $2\phi_1^{\mathrm{eff}}$. Using Eq. (D3), we can thus write

$$\frac{q}{p}\frac{\bar{\mathcal{M}}^{\mathrm{Total}}_{\phi K_s}}{\mathcal{M}^{\mathrm{Total}}_{\phi K_s}} = -\lambda_{\phi K_s} e^{-2i\phi_1^{\mathrm{eff}}}$$
$$= -e^{-2i\phi_1}\left(\frac{1+\hat{r}^{\mathrm{L}}e^{i(-\hat{\omega}_{\mathrm{L}}+\hat{\sigma})}+\hat{r}^{\mathrm{R}}e^{i(-\hat{\omega}_{\mathrm{R}}+\hat{\sigma})}}{1+\hat{r}^{\mathrm{L}}e^{i(\hat{\omega}_{\mathrm{L}}+\hat{\sigma})}+\hat{r}^{\mathrm{R}}e^{i(\hat{\omega}_{\mathrm{R}}+\hat{\sigma})}}\right), \quad (26)$$

where the negative sign is present as ϕK_s is a *CP*-odd state. Rearranging and rationalising the right-hand side, we get

$$\lambda_{\phi K_s} e^{-2i(\phi_1^{\mathrm{eff}}-\phi_1)} = \frac{1+2\cos\hat{\sigma}(\hat{r}^{\mathrm{L}}e^{-i\hat{\omega}_{\mathrm{L}}}+\hat{r}^{\mathrm{R}}e^{-i\hat{\omega}_{\mathrm{R}}})}{1+2\hat{r}^{\mathrm{L}}\cos(\hat{\omega}_{\mathrm{L}}+\hat{\sigma})+2\hat{r}^{\mathrm{R}}\cos(\hat{\omega}_{\mathrm{R}}+\hat{\sigma})}. \quad (27)$$

We can now compare Eqs. (24) and (27). As mentioned before, we assume the weak interaction contribution from NP to be the same for both the decays, thus making $\omega_{\mathrm{L,R}} = \hat{\omega}_{\mathrm{L,R}}$. In addition, we assume that $r^{\mathrm{L,R}}$ and $\hat{r}^{\mathrm{L,R}}$ are small and positive. This implies that the sign of the strong interaction (coming from the ratio of matrix elements $\frac{\mathcal{F}_0^{\mathrm{NP}}}{\mathcal{F}_0^{\mathrm{SM}}}$ and $\frac{\mathcal{F}_{\phi K_s}^{\mathrm{NP}}}{\mathcal{F}_{\phi K_s}^{\mathrm{SM}}}$) is contained in the terms $\cos\sigma$ and $\cos\hat{\sigma}$, respectively. In addition, we see in Eqs. (24) and (27) that the right-handed contribution from NP has opposite signs for the two cases in the denominator. Therefore, if we can theoretically predict the sign of $\cos\sigma$ and $\cos\hat{\sigma}$ (which could be done, for example, by pQCD approach [44]), we can tell the chirality of NP in the following two cases:

Case 1: Only left-handed NP is present ($r^{\mathrm{R}} = \hat{r}^{\mathrm{R}} = 0$)

Taking the ratio of real and imaginary parts of Eqs. (24) and (27), and expanding in r^{L} and $\hat{r}^{\mathrm{L}}$, we get

$$\tan(\theta_0 - \theta_0^c) \approx 2r^{\mathrm{L}} \sin\omega_{\mathrm{L}} \cos\sigma + \mathrm{O}((r^{\mathrm{L}})^2),$$
$$\tan(2\phi_1^{\mathrm{eff}} - 2\phi_1) \approx 2\hat{r}^{\mathrm{L}} \sin\hat{\omega}_{\mathrm{L}} \cos\hat{\sigma} + \mathrm{O}((\hat{r}^{\mathrm{L}})^2). \tag{28}$$

At this point we can define a quantity $\Sigma \equiv [\tan(\theta_0 - \theta_0^c)\tan(2\phi_1^{\mathrm{eff}} - 2\phi_1)]$. As we defined r^L and $\hat{r}^L$ to be positive and the chromomagnetic operator leads to $\omega_L = \hat{\omega}_L$, we obtain the relation

$$\mathrm{sign}(\Sigma) = \mathrm{sign}(\cos\sigma\cos\hat{\sigma}). \tag{29}$$

Case 2: Only right-handed NP is present ($r^{\mathrm{L}} = \hat{r}^{\mathrm{L}} = 0$)

Taking the ratio of real and imaginary parts of Eqs. (24) and (27), and expanding in r^{R} and $\hat{r}^{\mathrm{R}}$, we get

$$\tan(\theta_0 - \theta_0^c) \approx -2r^{\mathrm{R}} \sin\omega_{\mathrm{R}} \cos\sigma + \mathrm{O}((r^{\mathrm{R}})^2),$$
$$\tan(2\phi_1^{\mathrm{eff}} - 2\phi_1) \approx 2\hat{r}^{\mathrm{R}} \sin\hat{\omega}_{\mathrm{R}} \cos\hat{\sigma} + \mathrm{O}((\hat{r}^{\mathrm{R}})^2). \tag{30}$$

Thus, in this case, we find an opposite relative sign with respect to the left-handed model,

$$\mathrm{sign}(\Sigma) = -\mathrm{sign}(\cos\sigma\cos\hat{\sigma}). \tag{31}$$

Hence, if the experiments show nonzero CP-violating phase results, one can test the chirality of the NP contribution by combining the $B_s^0 \to \phi\phi$ and $B_d^0 \to \phi K_s$ decay measurements, along with the relative sign of $\cos\delta$ and $\cos\hat{\delta}$, which might be obtained theoretically. This conclusion is summarized in Table II.

TABLE II. Table demonstrating the chirality of NP arising from different combinations of signs of $\cos\sigma$, $\cos\hat{\sigma}$ and $\Sigma \equiv [\tan(\theta_0 - \theta_0^c)\tan(2\phi_1^{\mathrm{eff}} - 2\phi_1)]$, under the assumption that only left-handed or right-handed NP is present. σ and $\hat{\sigma}$ denote the strong-phase difference between NP and SM in $B_s^0 \to \phi\phi$ and $B_d^0 \to \phi K_s$ decays, respectively [see Eq. (23)]. $\theta_0 - \theta_0^c$ and $2\phi_1^{\mathrm{eff}}$ are the phase in the interference of decays with and without mixing in $B_s^0 \to \phi\phi$ and $B_d^0 \to \phi K_s$ decays, respectively. ϕ_1 is the unitary triangle angle.

$\cos\sigma$	$\cos\hat{\sigma}$	Σ	NP chirality
+	+	+	LH
+	−	+	RH
+	+	−	RH
+	−	−	LH
−	+	−	LH
−	−	−	RH
−	+	+	RH
−	−	+	LH

VIII. CONCLUSIONS

In this article, we investigate a new physics search with the CP-violation measurements of the $B_s^0 \to \phi\phi$ decay. The large statistics of the LHCb experiment allows one to perform the time-dependent angular analysis of this decay channel. Such an analysis gives access to the information of the helicity amplitudes, which are sensitive to different types of NP effects. In the LHCb analysis, two types of NP scenarios have been investigated, called helicity-dependent and helicity-independent assumptions. In this work, we propose a new search scenario based on the NP model induced by the left- and right-handed chromomagnetic operators, producing a new quark level $b \to s\bar{s}s$ diagram with an extra source of CP violation. Using the fact that the NP coming from this type of operator is dominated by the longitudinal amplitude, we derive a new scheme of phase assumptions which can be tested by the LHCb experiment. The same NP effects can manifest itself in the time-dependent CP asymmetry measurement of $B_d^0 \to \phi K_s$ decay. We found that Belle(II)'s $B_d^0 \to \phi K_s$ decay measurements could complement LHCb's $B_s^0 \to \phi\phi$ measurement to obtain the chirality of NP operator, under the condition that the signs of the strong phases of these decays can be predicted by the theory. Finally, we present a sensitivity study of the CP-violating parameters of our proposed model in order to illustrate how the fit can actually be performed. We show that on top of the two CP-violating parameters, there are four extra parameters to be fitted simultaneously; two amplitudes and two phases. The theoretical predictions for these extra parameters depend heavily on the models describing the strong interaction. On the other hand, a nonzero measurement of the former two CP violating parameters can be interpreted immediately as a signal of NP. Our sensitivity study shows that LHCb with current statistics can determine these two parameters at 5–7% precision. These numbers are obtained using two pseudodatasets and they might not reflect the reality, though, the sensitivities obtained could be used as an indication for future studies. Even though the current measurements do not show a clear signal of NP, further theoretical and experimental efforts would shed more light on these results, and would pave the way for future studies.

ACKNOWLEDGMENTS

We would like to express our gratitude to François Le Diberder for his careful reading of the manuscript and help in doing the statistical analysis. We would also like to thank Franz Muheim for the helpful correspondence.

APPENDIX A: ANGULAR CONVENTIONS

In $B_s^0 \to \phi\phi$ decay, since the two $\phi' s$ are indistinguishable, we can randomly assign them (and their decay products) the subscripts 1 and 2. $\theta_{1(2)}$ is the angle between the $K^+_{1(2)}$ meson momentum in the $\phi_{1(2)}$ meson rest frame and $\phi_{1(2)}$ meson momentum in B_s^0 meson rest frame. Mathematically, we can write it as

$$\cos\theta_{1(2)} = \hat{p}^{(\phi_{1(2)})}_{K^+_{1(2)}} . \hat{p}^{(B_s^0)}_{\phi_{1(2)}}, \tag{A1}$$

where the notation $\hat{p}^{(x)}_y$ means momentum of particle y in the frame of particle x. The angle Φ, which is the angle between the two decay planes (or between the perpendiculars of the planes), can be defined as follows:

$$\cos\Phi = (\hat{p}_{K_1^+} \times \hat{p}_{K_1^+}) \cdot (\hat{p}_{K_2^+} \times \hat{p}_{K_2^+}),$$
$$\sin\Phi\hat{z} = \left[(\hat{p}_{K_1^+} \times \hat{p}_{K_1^-}) \times (\hat{p}_{K_2^+} \times \hat{p}_{K_2^-})\right], \tag{A2}$$

where we choose to define the z-direction by the direction of ϕ_1 momentum [26].

APPENDIX B: STATISTICAL PROCEDURE

The LHCb experimental observables (a_i, b_i, c_i, and d_i) are given in Table V; they are the LHCb observables. The only available information from LHCb is the result of fit of those measurements to the theory parameters ($|A_k|^2, \delta_k, \phi_k$), given in [19]. Therefore, in our study, we first construct *pseudodataset*, i.e., the central values and the covariance matrices for the LHCb observables, from this available information. The covariance matrix is obtained by using

$$V_{ij}^{-1} = N \int \left(\frac{\partial \hat{f}(x)_{\vec{v}}}{\partial v_i} \frac{\partial \hat{f}(x)_{\vec{v}}}{\partial v_j} \frac{1}{\hat{f}(x)_{\vec{v}}} \right) \bigg|_{\vec{v}=\vec{v}^*} dx \tag{B1}$$

where

(i) $\hat{f}$ is the normalized probability distribution function, which in our case is the angular decay distribution given by Eq. (2). Integration over x represents integration over the complete phase space and time.
(ii) $\vec{v}$ is the vector of LHCb observables (a_i, b_i, c_i and d_i) that LHCb measures.
(iii) $\vec{v}^*$ is the values of $\vec{v}$ obtained by using the best-fit values of the theoretical parameters obtained by LHCb [19]. Note that there are two fits performed by LHCb with the so-called helicity-independent and helicity-dependent assumptions, and we use both to construct two pseudodatasets.
(iv) N is the number of events.

Finally, using this *pseudodataset*, we perform a χ^2 fit using $\vec{v}_i$ with our model assumptions, which we call $\vec{v}_i^{\rm model}$,

$$\chi^2 = \sum_{i,j} \left(\vec{v}_i^{\rm model} - \vec{v}_i^*\right) V_{ij}^{-1} \left(\vec{v}_j^{\rm model} - \vec{v}_j^*\right). \tag{B2}$$

APPENDIX C: CORRELATION MATRICES

TABLE III. Correlation matrix based on our model assumptions, i.e., longitudinal component dominance for NP contributions from the chromomagnetic operator ($\theta^c_\parallel = \theta_\parallel = \theta^c_\perp = \theta_\perp = 0$ and $\lambda_\parallel = \lambda_\perp = 1$). Pseudodataset used; Data HD.

	$\theta_0-\theta_0^c$	$\delta_\parallel-\delta_\perp$	$\delta_\parallel-\delta_0-\theta_0$	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	λ_0
$\theta_0-\theta_0^c$	1.00	0.01	−0.33	0.00	0.00	−0.03
$\delta_\parallel-\delta_\perp$	0.01	1.00	0.38	−0.11	0.13	−0.01
$\delta_\parallel-\delta_0-\theta_0$	−0.33	0.38	1.00	−0.24	0.23	−0.03
$\lvert A_0\rvert^2$	0.00	−0.11	−0.24	1.00	−0.72	−0.67
$\lvert A_\perp\rvert^2$	0.00	0.13	0.23	−0.72	1.00	0.49
λ_0	−0.03	−0.01	−0.03	−0.67	0.49	1.00

TABLE IV. Correlation matrix based on our model assumptions, i.e., longitudinal component dominance for NP contributions from the chromomagnetic operator ($\theta^c_\parallel = \theta_\parallel = \theta^c_\perp = \theta_\perp = 0$ and $\lambda_\parallel = \lambda_\perp = 1$). Pseudodataset used; Data HI.

	$\theta_0-\theta_0^c$	$\delta_\parallel-\delta_\perp$	$\delta_\parallel-\delta_0-\theta_0$	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	λ_0
$\theta_0-\theta_0^c$	1.00	−0.02	−0.37	0.03	−0.04	−0.01
$\delta_\parallel-\delta_\perp$	−0.02	1.00	0.40	−0.06	0.07	−0.04
$\delta_\parallel-\delta_0-\theta_0$	−0.37	0.40	1.00	−0.19	0.21	−0.04
$\lvert A_0\rvert^2$	0.03	−0.06	−0.19	1.00	−0.85	−0.76
$\lvert A_\perp\rvert^2$	−0.04	0.07	0.21	−0.85	1.00	0.65
λ_0	−0.01	−0.04	−0.04	−0.76	0.65	1.00

APPENDIX D: $B_d^0 \to \phi K_S$ DECAY

The amplitude for $B_d^0 \to \phi K_S$ for SM, left-handed NP and right-handed NP case respectively, can be written as

$$\mathcal{M}^{\rm SM}_{\phi K_s} = -\frac{G_F}{\sqrt{2}} V_{tb}^* V_{ts} \hat{\xi}^{\rm SM} \mathcal{F}^{\rm SM}_{\phi K_s},$$
$$\mathcal{M}^{\rm L}_{\phi K_s} = -\frac{G_F}{\sqrt{2}} V_{tb}^* V_{ts} \hat{\xi}^{\rm L} \mathcal{F}^{\rm NP}_{\phi K_s},$$
$$\mathcal{M}^{\rm R}_{\phi K_s} = -\frac{G_F}{\sqrt{2}} V_{tb}^* V_{ts} \hat{\xi}^{\rm R} \mathcal{F}^{\rm NP}_{\phi K_s}, \tag{D1}$$

where $\hat{\xi}^p (p \in \{\mathrm{SM}, \mathrm{L}, \mathrm{R}\})$ are combination of the Wilson coefficients, which contain weak phases, and their exact form depends upon the model chosen to evaluate the matrix elements. Like for the case of $B_s^0 \to \phi\phi$ decay, the variables $\mathcal{F}^{\rm SM}_{\phi K_s}$ and $\mathcal{F}^{\rm NP}_{\phi K_s}$ contain all the information about the matrix elements. Note that K_0 is a flavor eigenstate, which, by Kaon oscillation, oscillates between K_0 and $\bar{K}_0$ and we see the mass eigenstate K_S in detectors.

Now the total amplitude, which is the sum of all three amplitudes, can be written as

$$\mathcal{M}^{\rm Total}_{\phi K_s} = \mathcal{M}^{\rm SM}_{\phi K_s} \left(1 + \frac{\hat{\xi}^{\rm L} \mathcal{F}^{\rm NP}_{\phi K_s}}{\hat{\xi}^{\rm SM} \mathcal{F}^{\rm SM}_{\phi K_s}} + \frac{\hat{\xi}^{\rm R} \mathcal{F}^{\rm NP}_{\phi K_s}}{\hat{\xi}^{\rm SM} \mathcal{F}^{\rm SM}_{\phi K_s}} \right). \tag{D2}$$

Using similar parametrization for NP as in Eq. (23) (but putting hats to differentiate from $B_s^0 \to \phi\phi$ case), we get

$$\mathcal{M}^{\rm Total}_{\phi K_s} = \mathcal{M}^{\rm SM}_{\phi K_s} \left(1 + \hat{r}^{\rm L} e^{i(\hat{\omega}_{\rm L} + \hat{\sigma})} + \hat{r}^{\rm R} e^{i(\hat{\omega}_{\rm R} + \hat{\sigma})} \right). \tag{D3}$$

APPENDIX E: COEFFICIENTS OF TIME-DEPENDENT TERMS

The terms in the Table V are the coefficients of time-dependent terms in Eq. (4), which are functions of CP-violating parameters. The various quantities used here are defined as follows ($k = \{\parallel, \perp, 0\}$):

(i) $|A_k|$: magnitude of the complete transversity amplitude [see Eqs. (8) and (9)].
(ii) δ_k: strong phase of SM transversity amplitude.
(iii) θ_k: a mixture of weak and strong phase, as defined in Eqs. (8) and (9), arising due to presence of NP strong and weak phases.

TABLE V. Coefficients of the time-dependent terms and angular functions used in Eq. (4). Amplitudes are defined at $t = 0$.

i	N_i	a_i	b_i	c_i	d_i	f_i
1	$\|A_0\|^2$	$(1+\lambda_0^2)/2$	$-\lambda_0 \cos(\theta_0^c - \theta_0)$	$(1-\lambda_0^2)/2$	$-\lambda_0 \sin(\theta_0^c - \theta_0)$	$4\cos^2\theta_1 \cos^2\theta_2$
2	$\|A_\parallel\|^2$	$(1+\lambda_\parallel^2)/2$	$-\lambda_\parallel \cos(\theta_\parallel^c - \theta_\parallel)$	$(1-\lambda_\parallel^2)/2$	$-\lambda_\parallel \sin(\theta_\parallel^c - \theta_\parallel)$	$\sin^2\theta_1 \sin^2\theta_2 (1+\cos 2\Phi)$
3	$\|A_\perp\|^2$	$(1+\lambda_\perp^2)/2$	$\lambda_\perp \cos(\theta_\perp^c - \theta_\perp)$	$(1-\lambda_\perp^2)/2$	$\lambda_\perp \sin(\theta_\perp^c - \theta_\perp)$	$\sin^2\theta_1 \sin^2\theta_2 (1-\cos 2\Phi)$
4	$\|A_\parallel\|\|A_\perp\|/2$	$\sin(\delta_\perp - \delta_\parallel + \theta_\perp - \theta_\parallel)$ $-\lambda_\perp\lambda_\parallel \sin(\delta_\perp - \delta_\parallel + \theta_\perp^c - \theta_\parallel^c)$	$\lambda_\perp \sin(\delta_\perp - \delta_\parallel + \theta_\perp^c - \theta_\parallel)$ $-\lambda_\parallel \sin(\delta_\perp - \delta_\parallel + \theta_\perp - \theta_\parallel^c)$	$\sin(\delta_\perp - \delta_\parallel + \theta_\perp - \theta_\parallel)$ $+\lambda_\perp\lambda_\parallel \sin(\delta_\perp - \delta_\parallel + \theta_\perp^c - \theta_\parallel^c)$	$-\lambda_\perp \cos(\delta_\perp - \delta_\parallel + \theta_\perp^c - \theta_\parallel)$ $-\lambda_\parallel \cos(\delta_\perp - \delta_\parallel + \theta_\perp - \theta_\parallel^c)$	$-2\sin^2\theta_1 \sin^2\theta_2 \sin 2\Phi$
5	$\|A_\parallel\|\|A_0\|/2$	$\cos(\delta_0 - \delta_\parallel + \theta_0 - \theta_\parallel)$ $+\lambda_0\lambda_\parallel \cos(\delta_0 - \delta_\parallel + \theta_0^c - \theta_\parallel^c)$	$-\lambda_0 \cos(\delta_0 - \delta_\parallel + \theta_0^c - \theta_\parallel)$ $-\lambda_\parallel \cos(\delta_0 - \delta_\parallel + \theta_0 - \theta_\parallel^c)$	$\cos(\delta_0 - \delta_\parallel + \theta_0 - \theta_\parallel)$ $-\lambda_0\lambda_\parallel \cos(\delta_0 - \delta_\parallel + \theta_0^c - \theta_\parallel^c)$	$-\lambda_0 \sin(\delta_0 - \delta_\parallel + \theta_0^c - \theta_\parallel)$ $+\lambda_\parallel \sin(\delta_0 - \delta_\parallel + \theta_0 - \theta_\parallel^c)$	$\sqrt{2}\sin 2\theta_1 \sin 2\theta_2 \cos\Phi$
6	$\|A_0\|\|A_\perp\|/2$	$\sin(\delta_\perp - \delta_0 + \theta_\perp - \theta_0)$ $-\lambda_\perp\lambda_0 \sin(\delta_\perp - \delta_0 + \theta_\perp^c - \theta_0^c)$	$\lambda_\perp \sin(\delta_\perp - \delta_0 + \theta_\perp^c - \theta_0)$ $-\lambda_0 \sin(\delta_\perp - \delta_0 + \theta_\perp - \theta_0^c)$	$\sin(\delta_\perp - \delta_0 + \theta_\perp - \theta_0)$ $+\lambda_\perp\lambda_0 \sin(\delta_\perp - \delta_0 + \theta_\perp^c - \theta_0^c)$	$-\lambda_\perp \cos(\delta_\perp - \delta_0 + \theta_\perp^c - \theta_0)$ $-\lambda_0 \cos(\delta_\perp - \delta_0 + \theta_\perp - \theta_0^c)$	$-\sqrt{2}\sin 2\theta_1 \sin 2\theta_2 \sin\Phi$

[1] N. Cabibbo, Unitary symmetry and leptonic decays, Phys. Rev. Lett. **10**, 531 (1963).
[2] M. Kobayashi and T. Maskawa, *CP* violation in the renormalizable theory of weak interaction, Prog. Theor. Phys. **49**, 652 (1973).
[3] A. D. Sakharov, Violation of *CP* invariance, C asymmetry, and baryon asymmetry of the universe, Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32 (1967).
[4] M. Beneke, J. Rohrer, and D. Yang, Enhanced electroweak penguin amplitude in $B \to VV$ decays, Phys. Rev. Lett. **96**, 141801 (2006).
[5] H.-Y. Cheng and K.-C. Yang, Charmless $B_(s) \to VV$ decays in QCD factorization: Implications of recent $B \to \phi K^*$ measurement, Phys. Lett. B **511**, 40 (2001).
[6] R. Fleischer and M. Gronau, Studying new physics amplitudes in charmless $B_(s)$ decays, Phys. Lett. B **660**, 212 (2008).
[7] A. Datta, M. Duraisamy, and D. London, New physics in $b \to s$ transitions and the $B^0_{d,s} \to V_1 V_2$ angular analysis, Phys. Rev. D **86**, 076011 (2012).
[8] A. Datta and D. London, Measuring new physics parameters in B penguin decays, Phys. Lett. B **595**, 453 (2004).
[9] A. Datta and D. London, Triple-product correlations in $B \to V_1 V_2$ decays and new physics, Int. J. Mod. Phys. A **19**, 2505 (2004).
[10] R. Fleischer and I. Dunietz, *CP* violation and CKM phases from angular distributions for B_s decays into admixtures of *CP* eigenstates, Phys. Rev. D **55**, 259 (1997).
[11] A. Datta, M. Duraisamy, and D. London, Searching for new physics with *B*-decay fake triple products, Phys. Lett. B **701**, 357 (2011).
[12] I. Dunietz, R. Fleischer, and U. Nierste, In pursuit of new physics with B_s decays, Phys. Rev. D **63**, 114015 (2001).
[13] P. Ball and R. Fleischer, An analysis of B_s decays in the left-right symmetric model with spontaneous *CP* violation, Phys. Lett. B **475**, 111 (2000).
[14] R. Aleksan and L. Oliver, Remarks on the penguin decay $B_s \to \phi\phi$ with prospects for FCCee, arXiv:2205.07823.
[15] D. London, N. Sinha, and R. Sinha, Bounds on new physics from $B \to V_{(1)} V_{(2)}$ decays, Phys. Rev. D **69**, 114013 (2004).
[16] M. Bartsch, G. Buchalla, and C. Kraus, $B \to V_L V_L$ decays at next-to-leading order in QCD, arXiv:0810.0249.
[17] M. Beneke, J. Rohrer, and D. Yang, Branching fractions, polarisation and asymmetries of $B \to VV$ decays, Nucl. Phys. **B774**, 64 (2007).
[18] H.-Y. Cheng and C.-K. Chua, QCD factorization for charmless hadronic B_s decays revisited, Phys. Rev. D **80**, 114026 (2009).
[19] LHCb Collaboration, Measurement of *CP* violation in the $B_s^0 \to \phi\phi$ decay and search for the $B^0 \to \phi\phi$ decay, J. High Energy Phys. 12 (2019) 155.
[20] HFLAV Collaboration, Averages of *b*-hadron, *c*-hadron, and τ-lepton properties as of 2021, Phys. Rev. D **107**, 052008 (2023).
[21] I. Dunietz, H. R. Quinn, A. Snyder, W. Toki, and H. J. Lipkin, How to extract *CP* violating asymmetries from angular correlations, Phys. Rev. D **43**, 2193 (1991).
[22] LHCb Collaboration, Precision measurement of the $B_s^0 - \bar{B}_s^0$ oscillation frequency with the decay $B_s^0 \to D_s^- \pi^+$, New J. Phys. **15**, 053021 (2013).
[23] B. Bhattacharya, A. Datta, M. Duraisamy, and D. London, Searching for new physics with $B_s^0 \to V_1 V_2$ penguin decays, Phys. Rev. D **88**, 016007 (2013).
[24] H.-Y. Cheng, C.-K. Chua, and A. Soni, Final state interactions in hadronic B decays, Phys. Rev. D **71**, 014030 (2005).
[25] LHCb Collaboration, Measurement of the *CP* asymmetry in $B_s^0 - \bar{B}_s^0$ mixing, Phys. Rev. Lett. **117**, 061803 (2016).
[26] M. Gronau and J. L. Rosner, Triple product asymmetries in K, $D_{(s)}$ and $B_{(s)}$ decays, Phys. Rev. D **84**, 096013 (2011).
[27] I. Bigi and A. Sanda, *CP Violation*, Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology (Cambridge University Press, Cambridge, England, 2000).
[28] Y. Y. Keum, New physics search in B meson decays, in *3rd International Conference on B Physics and CP Violation (BCONF99)* (1999), p. 140.
[29] T. Moroi, *CP* violation in $B_d \to \phi K_s$ in SUSY GUT with right-handed neutrinos, Phys. Lett. B **493**, 366 (2000).
[30] M.-B. Causse, Supersymmetric penguin contributions to the process $B_d \to \phi K_s$ in SUSY GUT with right-handed neutrino, arXiv:hep-ph/0207070.
[31] G. L. Kane, P. Ko, H.-B. Wang, C. Kolda, J.-H. Park, and L.-T. Wang, $B_d \to \phi K_s$ and supersymmetry, Phys. Rev. D **70**, 035015 (2004).
[32] R. Harnik, D. T. Larson, H. Murayama, and A. Pierce, Atmospheric neutrinos can make beauty strange, Phys. Rev. D **69**, 094024 (2004).
[33] S. Baek, *CP* violation in $B \to \phi K_s$ decay at large $\tan\beta$, Phys. Rev. D **67**, 096004 (2003).
[34] S. Khalil and E. Kou, A possible supersymmetric solution to the discrepancy between $B \to \phi K_s$ and $B \to \eta' K_{(s)}$ *CP* asymmetries, Phys. Rev. Lett. **91**, 241602 (2003).
[35] M. Raidal, *CP* asymmetry in $B \to \phi K_s$ decays in left-right models and its implications on B_s decays, Phys. Rev. Lett. **89**, 231803 (2002).
[36] LHCb Collaboration, Implications of LHCb measurements and future prospects, Eur. Phys. J. C **73**, 2373 (2013).
[37] LHCb Collaboration, Updated measurement of time-dependent *CP*-violating observables in $B_s^0 \to J/\psi K^+ K^-$ decays, Eur. Phys. J. C **79**, 706 (2019).
[38] G. Kramer and W. F. Palmer, Branching ratios and *CP* asymmetries in the decay $B \to VV$, Phys. Rev. D **45**, 193 (1992).
[39] A. L. Kagan, Polarization in $B \to VV$ decays, Phys. Lett. B **601**, 151 (2004).
[40] J. G. Korner and G. R. Goldstein, Quark and particle helicities in hadronic charmed particle decays, Phys. Lett. **89B**, 105 (1979).
[41] LHCb Collaboration, Measurement of polarization amplitudes and *CP* asymmetries in $B^0 \to \phi K^*(892)^0$, J. High Energy Phys. 05 (2014) 069.
[42] Z.-T. Zou, A. Ali, C.-D. Lu, X. Liu, and Y. Li, Improved estimates of the $B_{(s)} \to VV$ decays in perturbative QCD approach, Phys. Rev. D **91**, 054033 (2015).
[43] D.-C. Yan, X. Liu, and Z.-J. Xiao, Anatomy of $B_s \to VV$ decays and effects of next-to-leading order contributions in the perturbative QCD factorization approach, Nucl. Phys. **B935**, 17 (2018).
[44] S. Mishima and A. I. Sanda, Calculation of magnetic penguin amplitudes in $B \to \phi K$ decays using PQCD approach, Prog. Theor. Phys. **110**, 549 (2003).