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Implications from $B \to K^* \ell^+ \ell^-$ observables using $3\mathrm{fb}^{-1}$ of LHCb data.

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The decay mode $B \to K^* \ell^+ \ell^-$ is regarded as one of the attractive mode to look for physics beyond standard model (SM) due to the measurement of large number of observables in experiments. Starting with the most general parametric form of the decay amplitude within SM, two different analyses have been carried out. First we show how recent LHCb data can be used without any approximations to extract theoretical parameters describing the decay. We find significant discrepancies in the form factor values obtained from experimental data when compared with theoretical expectations in several dilepton invariant mass squared (q^2) bins. We emphasize that the discrepancy observed in certain variables cannot arise due to resonances and non-factorizable contributions from charm loops. Secondly, the same model independent framework has been implemented in the maximum q^2 limit to highlight strong evidence of right-handed currents, which are absent in the SM. The conclusions derived are free from hadronic corrections. Our approach differs from other approaches that probe new physics at low q^2 as it does not require estimates of hadronic parameters but relies instead on heavy quark symmetries that are reliable at the maximum q^2 kinematic endpoint.

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1. Introduction

The rare decay $B \to K^* \ell^+ \ell^-$ involves a $b \to s$ flavor changing loop induced transition and hence are very suppressed in the standard model (SM). The rich angular analysis of this mode leads us to measure plethora of observables at experiments and thus currently is of great interest to both theory as well as experimental groups. In this note, we briefly discuss the results obtained in our recent studies on this mode and refer the reader to Refs. [1, 2, 3] for detailed description.

2. Model Independent Framework

In this section we briefly discuss the theoretical framework adopted to comprehensively consider almost all possible contributions within SM for the decay $B \to K^* \ell^+ \ell^-$. We start with the observables as defined in Ref. [1] to be F_L, $F_\perp$, A_4, A_5, $A_{\rm FB}$ related to the CP averaged observables S_3, S_4, S_5, $A_{\rm FB}^{\rm LHCb}$ measured by LHCb [4] as follows:

$$F_\perp = \frac{1-F_L+2S_3}{2}, \quad A_4 = -\frac{2}{\pi}S_4, \quad A_5 = \frac{3}{4}S_5, \quad A_{\rm FB} = -A_{\rm FB}^{{\rm LHC}b}. \tag{2.1}$$

The observables are functions of transversity amplitudes and in the massless lepton limit the decay is described by six transversity amplitudes which can be written in the most general form as [1],

$$\mathscr{A}_\lambda^{L,R} == (\widetilde{C}_9^\lambda \mp C_{10})\mathscr{F}_\lambda - \widetilde{\mathscr{G}}_\lambda. \tag{2.2}$$

This parametric form of SM amplitude includes all short-distance and long-distance effects, factorizable and non-factorizable contributions and resonance contributions. In Eq. (2.2) C_9 and C_{10} are Wilson coefficients with $\widetilde{C}_9^\lambda$ being the redefined "effective" Wilson coefficient defined [1] as

$$\widetilde{C}_9^\lambda = C_9 + \Delta C_9^{\rm (fac)}(q^2) + \Delta C_9^{\lambda,\rm (non\text{-}fac)}(q^2), \tag{2.3}$$

where $\Delta C_9^{\rm (fac)}(q^2)$, $\Delta C_9^{\lambda,\rm (non\text{-}fac)}(q^2)$ correspond to factorizable and soft gluon non-factorizable contributions. $\mathscr{F}_\lambda$ and $\widetilde{\mathscr{G}}_\lambda$ are the form factors for the decay mode.

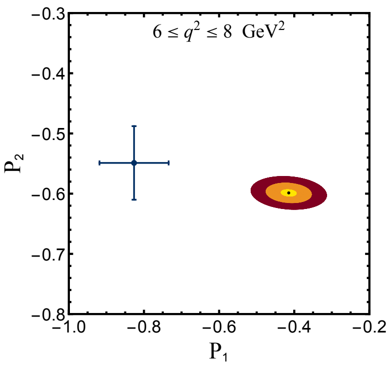
2.1 Hadronic parameter extraction

The amplitude given in Eq. (2.2) can be used to extract out the hadronic parameters which are involved in this mode. The observables $F_\perp$, F_L, $A_{\rm FB}$, A_5 and A_4 can be written [1, 2] as

$$\begin{gathered} F_\perp = u_\perp^2 + 2\zeta, \quad F_L \mathsf{P}_2^2 = u_0^2 + 2\zeta, \\ A_{\rm FB}^2 = \frac{9\zeta}{2\mathsf{P}_1^2}\left(u_\parallel \pm u_\perp\right)^2, \;\; A_5^2 = \frac{9\zeta}{4\mathsf{P}_2^2}\left(u_0 \pm u_\perp\right)^2, \;\; A_4 = \frac{\sqrt{2}}{\pi \mathsf{P}_1\mathsf{P}_2}\left(2\zeta \pm u_0 u_\parallel\right). \end{gathered} \tag{2.4}$$

where, $\mathsf{P}_1 = \dfrac{\mathscr{F}_\perp}{\mathscr{F}_\parallel}$, $\mathsf{P}_2 = \dfrac{\mathscr{F}_\perp}{\mathscr{F}_0}$, $\zeta = \dfrac{\mathscr{F}_\perp^2 C_{10}^2}{\Gamma_f}$, $u_\lambda^2 = \dfrac{2}{\Gamma_f}\dfrac{\mathscr{F}_\perp^2}{\mathscr{F}_\lambda^2}\Big({\rm Re}(\widetilde{\mathscr{G}}_\lambda) - {\rm Re}(\widetilde{C}_9^\lambda)\mathscr{F}_\lambda\Big)^2$, $\Gamma_f \equiv \dfrac{d\Gamma}{dq^2}$.

We find the solutions for five independent hadronic parameters P_1, P_2, ζ, u_0 and $u_\perp$ from these five set of equations of observables using 3fb^{-1} of LHCb data. The allowed region for the solution in P_1–P_2 plane for $q^2 \in \{6, 8\}{\rm GeV}^2$ is shown in the left panel of Fig. 1. For the detailed description of extraction procedure and regions for all eight bins in q^2, in different planes of variables, we refer the reader to Ref. [2]. It should be noted that the contribution arising from charmonium resonances can be parametrized in Wilson coefficient C_9 [5] and by definition the parameters P_1, P_2 are independent of $\widetilde{C}_9^\lambda$, implies their solutions are also independent of resonance contributions. Hence any discrepancy observed in P_1–P_2 plane can not be accounted by resonance effects. With the obtained solutions for P_1, P_2, ζ and using measured branching fraction Γ_f, the form factors $\mathscr{F}_\lambda$ can be extracted which are related to the well known form factors V, A_1 and A_{12} [6]. The extracted values are given in right panel of Fig. 1 and show discrepancies in several q^2 bins in comparison with the estimate from light-cone-sum rule (LCSR) and lattice results [6].



q^2 range in GeV^2	$V(q^2)$	$A_1(q^2)$	$A_{12}(q^2)$
$0.1 \le q^2 \le 0.98$	0.677 ± 0.092 3.05σ	0.570 ± 0.077 3.40σ	0.246 ± 0.034 0.88σ
$1.1 \le q^2 \le 2.5$	0.625 ± 0.071 2.78σ	0.409 ± 0.046 2.00σ	0.326 ± 0.047 0.69σ
$6.0 \le q^2 \le 8.0$	0.485 ± 0.045 1.27σ	0.598 ± 0.073 3.18σ	0.252 ± 0.025 1.78σ
$11.0 \le q^2 \le 12.5$	0.166 ± 0.018 5.64σ	0.560 ± 0.065 1.76σ	0.450 ± 0.054 1.81σ
$15.0 \le q^2 \le 17.0$	0.828 ± 0.120 2.79σ	0.649 ± 0.098 1.38σ	0.496 ± 0.074 1.51σ

Figure 1: (right panel) The solutions obtained using LHCb data in P_1–P_2 plane where the yellow, orange and red regions denote 1σ, 3σ, and 5σ confidence level regions for $q^2 \in \{6,8\}\,\mathrm{GeV}^2$, respectively. The blue error bar is the prediction from LCSR calculations [6]. (left panel) The mean and $\pm 1\sigma$ errors (upper line) for the LHCb data extracted values of form factors V, A_1, A_{12} and the deviation in confidence level (lower line) with their theoretical estimates are highlighted for some q^2 bins where the discrepancies are significant.

2.2 Endpoint analysis

In this section we use the model independent framework to look for a possible new physics (NP) scenario. We begin with general form of the amplitude from Eq. (2.2) modified with the presence of right-handed (RH) currents as,

$$\mathscr{A}_\perp^{L,R} = \big((\widetilde{C}_9^\perp + C_9') \mp (C_{10} + C_{10}')\big)\mathscr{F}_\perp - \widetilde{\mathscr{G}}_\perp, \quad \mathscr{A}_{\|,0}^{L,R} = \big((\widetilde{C}_9^{\|,0} - C_9') \mp (C_{10} - C_{10}')\big)\mathscr{F}_{\|,0} - \widetilde{\mathscr{G}}_{\|,0} \quad (2.5)$$

where C_9' and C_{10}' are the new couplings associated with RH operator O_9' and O_{10}', respectively. With the introduction of some notation; $r_\lambda = \mathrm{Re}(\widetilde{\mathscr{G}}_\lambda)/\mathscr{F}_\lambda - \mathrm{Re}(\widetilde{C}_9^\lambda)$, $\xi = C_{10}'/C_{10}$, and $\xi' = C_9'/C_{10}$, we construct the following variables,

$$R_\perp = \left(\frac{r_\perp}{C_{10}} - \xi'\right) \Big/ (1+\xi)\,, \; R_{\|,0} = \left(\frac{r_{\|,0}}{C_{10}} + \xi'\right) \Big/ (1-\xi)\,. \qquad (2.6)$$

At low recoil energy of K^* meson, only three independent form factors describe the whole $B \to K^* \ell^+ \ell^-$ decay and there exist a relation among the form factors at leading order in $1/m_B$ expansion given by [7], $\widetilde{\mathscr{G}}_\|/\mathscr{F}_\| = \widetilde{\mathscr{G}}_\perp/\mathscr{F}_\perp = \widetilde{\mathscr{G}}_0/\mathscr{F}_0 = -\kappa\, 2 m_b m_B C_7/q^2$, where $\kappa \approx 1$. Hence at the maximum point in q^2 i.e the kinematic endpoint $q^2_{\max}$, one defines r such that $r_0 = r_\| = r_\perp \equiv r$. Therefore Eq. (2.6) implies that in the presence of RH currents one should expect $R_0 = R_\| \neq R_\perp$

at $q^2 = q^2_{\rm max}$ without any approximation. Interestingly, this relation is unaltered by non-factorizable and resonance contributions [8] at this kinematic endpoint. To test the relation among R_λ's in light of LHCb data, first defining $\delta \equiv q^2_{\rm max} - q^2$, we expand the observables F_L, $F_\perp$, $A_{\rm FB}$ and A_5 around $q^2_{\rm max}$ as follows:

$$F_L = \frac{1}{3} + F_L^{(1)}\delta + F_L^{(2)}\delta^2 + F_L^{(3)}\delta^3, \quad F_\perp = F_\perp^{(1)}\delta + F_\perp^{(2)}\delta^2 + F_\perp^{(3)}\delta^3,$$
$$A_{\rm FB} = A_{\rm FB}^{(1)}\delta^{1/2} + A_{\rm FB}^{(2)}\delta^{3/2} + A_{\rm FB}^{(3)}\delta^{5/2}, \quad A_5 = A_5^{(1)}\delta^{1/2} + A_5^{(2)}\delta^{3/2} + A_5^{(3)}\delta^{5/2}. \tag{2.7}$$

The zeroth order coefficients of the observable expansions are assumed from the constraints arising from Lorentz invariance and decay kinematics derived in Ref. [8], whereas all the higher order coefficients are extracted by fitting the polynomials [3] with 14 bin LHCb data as shown in Fig. 2.

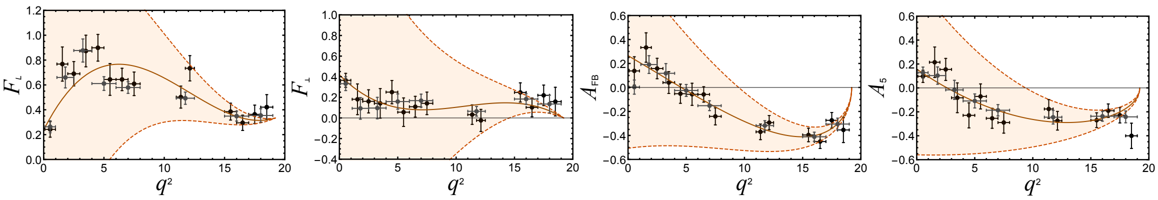


Figure 2: An analytic fit to 14-bin LHCb data using Taylor expansion at $q^2_{\rm max}$ for the observables F_L, $F_\perp$, $A_{\rm FB}$ and A_5 are shown as the brown curves. The $\pm 1\sigma$ error bands are indicated by the light brown shaded regions. The points with the black and gray error bars are LHCb 14-bin and 8-bin measurements [4], respectively.

The limiting analytic expressions for R_λ at $q^2 = q^2_{\rm max}$ are

$$R_\perp(q^2_{\rm max}) = \frac{\omega_2 - \omega_1}{\omega_2\sqrt{\omega_1 - 1}}, \quad R_\parallel(q^2_{\rm max}) = \frac{\sqrt{\omega_1 - 1}}{\omega_2 - 1} = R_0(q^2_{\rm max}) \tag{2.8}$$

$$\text{where} \quad \omega_1 = 3F_\perp^{(1)}/2A_{\rm FB}^{(1)2} \quad \text{and} \quad \omega_2 = 4\left(2A_5^{(2)} - A_{\rm FB}^{(2)}\right)\Big/ 3A_{\rm FB}^{(1)}\left(3F_L^{(1)} + F_\perp^{(1)}\right). \tag{2.9}$$

It can be seen that as ω_1, ω_2 contain coefficients which are extracted from data, the variables R_λ's can be estimated using data only and the allowed region is shown in gray bands in Fig. 3 left panel. A significant deviation is seen from a slope of 45$^{\rm o}$ line (red line) which denotes $R_\perp = R_\parallel = R_0$ and thus hints towards the presence of RH currents without *using any estimate of hadronic contributions*. To quantify the RH couplings, we use Eq. (2.6) and the results are shown in last two panels of Fig. 3. The middle panel uses the SM estimate of parameter r/C_{10} and the SM prediction for C'_{10}/C_{10} and C'_9/C_{10} (the origin) is at more than 5σ confidence level. However for the last panel we consider extra NP contribution to Wilson coefficient C_9 i.e. $C_9^{\rm NP} \simeq -1$ as hinted from the global fit analysis [9]. The decreased value of r/C_{10} reduces the significance of deviation of RH current to 3σ level, however with the scan over all r/C_{10} values we find that this is the least possible deviation that can be obtained using recent experimental measurements of observables from LHCb .

3. Summary

- A formalism has been developed to incorporate almost all possible effects within the SM. The approach we have adopted in our work differs from the other approaches in literature as we have no or minimal dependency on hadronic uncertainties.

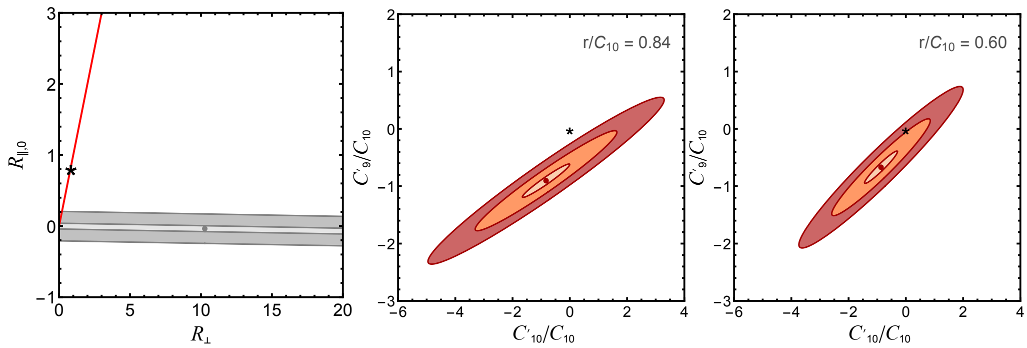


Figure 3: (left panel) Allowed regions in $R_{\perp} - R_{\|,0}$ plane are shown in light and dark gray bands at 1σ and 5σ confidence level, respectively. The red straight line corresponds to the case $R_{\perp} = R_{\|,0}$ i.e. the absence of RH couplings. (middle panel) In $C'_{10}/C_{10} - C'_9/C_{10}$ plane, the yellow, orange and red regions correspond to 1σ, 3σ and 5σ significance level, respectively where SM input for r/C_{10} [6] is used. The best fit values of C'_{10}/C_{10} and C'_9/C_{10}, with $\pm 1\sigma$ errors are -0.83 ± 0.82 and -0.90 ± 0.28, respectively. (right panel) Same color code as the middle panel figure. The chosen value of r/C_{10} includes $C_9^{\rm NP} \simeq -1$. The SM predictions for all the three plots are indicated by the stars. Strong evidence of RH current is pronounced from the plots.

- Discrepancies are found in form-factor values extracted form data compared to its theoretical estimates. Our study includes complex contributions of the amplitudes and systematics have also been added for bin-bias. We have argued that resonances can not affect all of them by definition.

- We find strong evidence of RH currents derived at endpoint limit. A systematic study has been performed by varying the polynomial order (Eq. (2.7)) and the number of bins used to fit the polynomials. The coefficients show a very good convergence. The finite width effect of K^* meson has also been considered. A detailed study of resonance systematics and inclusion of experimental correlation among observables can reduce the significance of deviation.

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