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The Angular Distribution of $B^0 \to K^{*0}(\to K^-\pi^+)l^+l^-$ at Large Recoil in and Beyond the SM

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We discuss, in detail, the K^* polarization states in the exclusive B meson decay $B^0 \to K^{*0}(\to K^-\pi^+)l^+l^-$ $(l = e, \mu, \tau)$ in the low dilepton mass region. We focus on the study of the angular distribution of this decay that provides valuable information on the K^* spin amplitudes $A_\perp, A_\parallel, A_0$. This can give us a handle on non-standard interactions that cannot be proved through measurements of the branching ratio and lepton forward-backward asymmetry. We explore the transverse asymmetries $A_T^{(1)}(s)$, $A_T^{(2)}(s)$, K^* polarization parameter $\alpha_{K^*}(s)$, the fraction of K^* polarization $F_L(s)$ and $F_T(s)$ and the corresponding integrated observables at NLL order, including factorizable and non-factorizable corrections. We find, in particular, that the dependence on hadronic uncertainties for the transverse asymmetries turns out to be very small. This allow us to distinguish which observables are better suited to look for physics beyond the SM. Finally, we study in a model independent way the implications of New Physics for these observables.

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We have recently entered into a Precision Flavour Physics Era thanks to the huge experimental effort in present B-facilities and the improvement in our theoretical knowledge of certain B meson decays. This has changed our way of looking at New Physics (NP). We are moving from the simple yes/no question concerning the presence of NP to the *measurement* of NP parameters [1]. In particular, we are starting to design observables mostly sensitive to a specific type of NP (isospin breaking, right handed currents, etc.). The observables that we will discuss here, based on the decay $B^0 \to K^*(\to K\pi)l^+l^-$, are an example of this approach. They are built to test the chiral structure of the fundamental theory that is beyond the SM, in particular, the presence of right-handed currents [2, 3]. The decay $B^0 \to K^*(\to K\pi)l^+l^-$ provides valuable information in many different ways, by means of the branching ratio [4], the lepton forward-backward asymmetry [5] and, finally, the angular distribution of this decay [3, 6]. It has been shown that the study of the angular distribution of the 4-body final state provides information on the K^* spin amplitudes that are useful to search for right-handed currents [2, 3]. Our goal [3] will be to identify which are the most robust observables to search for this type of NP.

The effective hamiltonian for decays governed by the quark transition $b \to sl^+l^-$ is given by $\mathscr{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_{i=1}^{10}[C_i(\mu)\mathscr{O}_i(\mu) + C_i'(\mu)\mathscr{O}_i'(\mu)]$, where we have added together with the SM operators the chirally flipped partners to describe right-handed currents. Our main focus here will be the magnetic penguins and semi-leptonic operators: $\mathscr{O}_7 = \frac{e}{16\pi^2} m_b(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}$, $\mathscr{O}_9 = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)$ and $\mathscr{O}_{10} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu\gamma_5 l)$ together with the chirally flipped operator $\mathscr{O}_7' = \frac{e}{16\pi^2} m_b(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}$. We will also discuss how to include the chiral partners of the operators $\mathscr{O}_9, \mathscr{O}_{10}$ although they will not be considered in the analysis.

Given the effective Hamiltonian one can compute the matrix element:

$$\begin{aligned} \mathscr{M} \;=\; & \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^* \Bigg\{ \left[C_9^{\rm eff} \langle K\pi|(\bar{s}\gamma^\mu P_L b)|B\rangle - \frac{2m_b}{q^2}\langle K\pi|\bar{s} i\sigma^{\mu\nu} q_\nu (C_7^{\rm eff} P_R + C_7^{\rm eff\prime} P_L) b|B\rangle \right] (\bar{l}\gamma_\mu l) \\ & + C_{10}\langle K\pi|(\bar{s}\gamma^\mu P_L b)|B\rangle (\bar{l}\gamma_\mu\gamma_5 l) \Bigg\}, \end{aligned} \tag{1}$$

where q is the four-momentum of the lepton pair and $m_b(\mu)$ is the running mass in the MS scheme. The hadronic matrix elements entering Eq.(1) are parameterized by means of a narrow width approximation [6] in terms of seven $B \to K^*$ form factors (see [3, 4]). The crucial point is how to deal with the heavy to light form factors. Either, one can take the approach of QCD sum rules[7] and try to compute them. Or following the key observation that in the limit where the initial hadron is heavy and the final meson has a large energy it is possible to reduce the $A_i(s), T_i(s)$ and $V(s)$ form factors to only two universal form factors ($\xi_\perp$ and $\xi_{||}$)[8]. However, these relations are valid for the soft contribution to the form factors at large recoil, i.e, we are restricted to the kinematical region where E_{K^*} is large and the dilepton mass is small. Moreover, these relations are violated by symmetry breaking corrections of order α_s and $1/m_b$. We will include here the factorizable and non-factorizable corrections in α_s [9]. There are also possible quark-antiquark resonant intermediate states contributions as well as other long distance effects that will be presented elsewhere[10].

Assuming the K^* to be on the mass shell, the differential decay rate of the decay $B^0 \to K^*(\to K\pi)l^+l^-$ is described in terms of four independent kinematical variables: the lepton-pair invariant mass, s, and the three angles θ_l, θ_{K^*}, ϕ. In terms of these variables, the differential decay rate can be written as [6] $\frac{d^4\Gamma}{ds\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi}\sum_{i=1}^{9} I_i(s,\theta_{K^*})\, f_i(\theta_l,\phi)$, within the physical region of phase space. I_i depend on products of the four K^* spin amplitudes $A_\perp$, $A_\|$, A_0, A_t, and f_i are the corresponding angular distribution functions. Given the matrix element Eq.(1) one can compute the transversity amplitudes (see [3] for A_0, A_t) at LO that reads:

$$A_{\perp L,R} = N\sqrt{2}\lambda^{1/2}\left[(C_9^{\rm eff} \mp C_{10})\frac{V(s)}{m_B + m_{K^*}} + \frac{2m_b}{s}(C_7^{\rm eff} + C_7^{\rm eff\prime})T_1(s)\right], \tag{2}$$

$$A_{\| L,R} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left[(C_9^{\rm eff} \mp C_{10})\frac{A_1(s)}{m_B - m_{K^*}} + \frac{2m_b}{s}(C_7^{\rm eff} - C_7^{\rm eff\prime})T_2(s)\right]. \tag{3}$$

In the SM (in particular $C_7^{\rm eff\prime} = 0$) we recover the naive quark-model prediction $A_\perp = -A_\|$ in the LEET limit. Notice also that, in this limit, the transverse (longitudinal and time-like) K^* polarizations involve only $\xi_\perp$ ($\xi_\|$). Finally, the chirality-flipped operators $\mathscr{O}'_{9,10}$ can be included in the above amplitudes by the replacements $C_{9,10}^{\rm (eff)} \to C_{9,10}^{\rm (eff)} + C_{9,10}^{\rm (eff)\prime}$ in $A_{\perp L,R}$ and $C_{9,10}^{\rm (eff)} \to C_{9,10}^{\rm (eff)} - C_{9,10}^{\rm (eff)\prime}$ in $A_{\| L,R}$.

1. Observables

We consider a series of observables constructed on the basis of the K^* spin amplitudes, whose magnitude and relative phases are obtained from the study of the angular distribution of this decay [3]. In order to minimize the uncertainties due to hadronic form factors we consider observables that involve ratios of amplitudes. Using $A_iA_j^* \equiv A_{iL}(s)A_{jL}^*(s) + A_{iR}(s)A_{jR}^*(s) \quad (i,j = 0,\|,\perp)$ we investigate the following observables: (i) Transverse asymmetries $A_T^{(1)}(s) = \frac{-2{\rm Re}(A_\| A_\perp^*)}{|A_\perp|^2+|A_\||^2}$, $A_T^{(2)}(s) = \frac{|A_\perp|^2-|A_\||^2}{|A_\perp|^2+|A_\||^2}$. (ii) K^* polarization parameter $\alpha_{K^*}(s) = \frac{2|A_0|^2}{|A_\||^2+|A_\perp|^2} - 1$. (iii) Fraction of K^* polarization $F_L(s) = \frac{|A_0|^2}{|A_0|^2+|A_\||^2+|A_\perp|^2}$ and $F_T(s) = \frac{|A_\perp|^2+|A_\||^2}{|A_0|^2+|A_\||^2+|A_\perp|^2}$, so that $\alpha_{K^*} = 2F_L/F_T - 1$. (iv) Integrated quantities $\mathscr{A}_T^{(1)}$, $\mathscr{A}_T^{(2)}$, α_{K^*}, and $\mathscr{F}_{L,T}$, which are obtained from (i) to (iii) by integrating numerator and denominator separately over the dilepton invariant mass.

2. SM predictions for the observables and New Physics Impact

We included factorizable and non-factorizable corrections at NLL order by replacing $C_7^{\rm eff}T_i \to \mathscr{T}_i$, and $C_9^{\rm eff} \to C_9 \quad (i = 1,2,3)$ in the transversity amplitudes [3] and taking $C_{9,10}$ at NNLL order ($\mathscr{T}_i$ are defined in [9]). We are interested here in exploring the impact of NLL corrections on the observables and the sensitivity to the variation of the theoretical parameters. The main sources of uncertainties are the dependence on soft form factors $\xi_{\perp,\|}(0)$, the scale dependence, the ratio m_c/m_b that mainly affects the matrix elements of the chromomagnetic operator, and the error associated to the rest of input parameters (masses and decay constants) which are taken in quadrature.

The results are that $A_T^{(1,2)}(s)$ are the most promising observables [3]: the impact of NLL corrections are negligible including uncertainties (see Fig 1). On the contrary, $\alpha_{K^*}(s)$ receives a strong impact of the NLL correction and a wide error band mainly due to the poorly known $\xi_\perp(0)$ form factor. Concerning F_L and F_T the fact that A_0 enters as a normalization factor moderates slightly the influence of $\xi_\perp(0)$. We have also computed the SM predictions for the integrated observables over the low dimuon mass region $2m_\mu \leq M_{\mu+\mu-} \leq 2.5$GeV at NLL: $\mathscr{A}_T^{(1)} = 0.9986 \pm 0.0002$, $\mathscr{A}_T^{(2)} = -0.043 \pm 0.003$, $\alpha_{K^*} = 3.47 \pm 0.71$, $\mathscr{F}_L = 0.69 \pm 0.03$ and $\mathscr{F}_T = 0.31 \pm 0.03$.

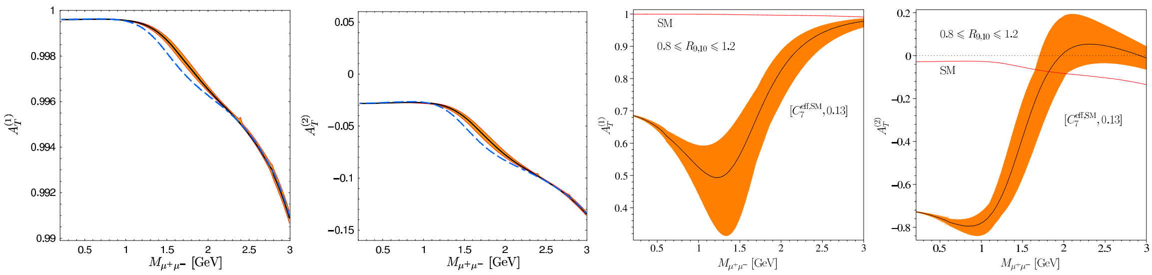

Figure 1: First and second: SM predictions for the asymmetries $A_T^{(1)}$ and $A_T^{(2)}$ as a function of the dimuon mass at LL (dashed line) and NLL (solid line) including errors (shaded area). Third and forth: NP impact of RH currents in $A_T^{(1)}$ and $A_T^{(2)}$ allowing for a NP contribution into $C_{9,10}$ up to 20 % as described in [3]

Finally, we performed a model independent analysis [3] of the implications of right-handed currents for these observables. Since the low dimuon mass region is dominated by the photon pole $C_7^{\mathrm{eff}\prime}/s$, the contribution from chirality flipped operators $\mathcal{O}_{9,10}$ will be subdominant. We imposed also the constrain coming from $BR(B \to X_s\gamma)$. The results were that even a small contribution from RH currents in $C_7^{\mathrm{eff}\prime}$ produces a striking effect in both asymmetries $\mathscr{A}_T^{(1)}$ and $\mathscr{A}_T^{(2)}$ (see Fig.1). Moreover, the latter is sensitive also to the sign of $C_7^{\mathrm{eff}\prime}$. Interestingly, even if we allow for the presence of NP in $\mathcal{O}_{9,10}$ up to 20% still it is possible to use these asymmetries to determine the magnitude and sign of the contribution of RH currents into $\mathcal{O}_7$. On the contrary, $F_{L,T}$ and specially α_{K*} are not particularly suitable to disentangle this type of NP effects from hadronic uncertainties due to their strong dependence on the poorly unknown parameter $\xi_\perp(0)$. In conclusion, we have shown that $\mathscr{A}_T^{(1,2)}$ are a useful probe of the electromagnetic penguin operator $\mathcal{O}_7$.
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