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THE EXCLUSIVE $B \to K^*(\to K\pi)l^+l^-$ DECAY: CP-CONSERVING OBSERVABLES*

U. Egede[a], T. Hurth[b], J. Matias[c], M. Ramon[c], W. Reece[a]

[a]Imperial College London, London SW7 2AZ, United Kingdom
[b]CERN, Dept. of Physics, Theory Division, 1211 Geneva 23, Switzerland
[c]IFAE, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain

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We study the K^* polarization states in the exclusive 4-body B meson decay $B^0 \to K^{*0}(\to K^-\pi^+)l^+l^-$ in the low dilepton mass region working in the framework of QCDF. We review the construction of the CP-conserving transverse and transverse/longitudinal observables $A_{\rm T}^2$, $A_{\rm T}^3$ and $A_{\rm T}^4$. We focus here on analyzing their behaviour at large recoil energy in the presence of right-handed currents.

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1. Motivation

The exclusive decay $B \to K^*l^+l^-$ will play a central role in the near future at LHCb and also at Super-LHCb. This channel is particularly interesting because it provides information in different ways. It is used as a basis to construct different types of observables, such as the forward–backward (FB) asymmetry $A_{\rm FB}$ [1,2], the isospin asymmetry [3] and the angular distribution observables [4–9]. Here, we will focus on the observables derived from the 4-body decay distribution: $B \to K^*(\to K\pi)l^+l^-$ that provides information on the K^* spin amplitudes.

2. Differential decay distributions, K^* spin amplitudes and Non-minimal Supersymmetric model

The starting point is the differential decay distribution of the decay $\bar{B}_d \to \bar{K}^{*0}(\to K\pi)l^+l^-$. This distribution with the $\bar{K}^{*0}$ on its mass shell is described by $s \equiv q^2$ (dilepton invariant mass) and three angles (see Fig. 13

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in [6]): $\boldsymbol{\theta}_l$ (angle between μ^- and outgoing $\bar{K}^*$ — z direction — in the $\mu^+\mu^-$ frame), $\boldsymbol{\theta}_K$ (angle between K^- and z direction in the $\bar{K}^*$ frame) and ϕ (angle between normals to the $\mu^+\mu^-$ and $K\pi$ decay planes in the B rest frame),

$$\frac{d^4\Gamma}{dq^2\, d\theta_l\, d\theta_K\, d\phi} = \frac{9}{32\pi} I\left(q^2, \theta_l, \theta_K, \phi\right) \sin\theta_l \sin\theta_K \,, \tag{1}$$

where $I = \boldsymbol{I}_1 + \boldsymbol{I}_2 \cos 2\theta_l + \boldsymbol{I}_3 \sin^2\theta_l \cos 2\phi + \boldsymbol{I}_4 \sin 2\theta_l \cos\phi + \boldsymbol{I}_5 \sin\theta_l \cos\phi + {}$ $+\boldsymbol{I}_6 \cos\theta_l + \boldsymbol{I}_7 \sin\theta_l \sin\phi + \boldsymbol{I}_8 \sin 2\theta_l \sin\phi + \boldsymbol{I}_9 \sin^2\theta_l \sin 2\phi$. In the massless limit the Is are function of the K^* spin amplitudes [4] $A_{\perp\,\mathrm{L,R}}$, $A_{\parallel\,\mathrm{L,R}}$ and $A_{0\,\mathrm{L,R}}$. We have then 6 complex amplitudes, four symmetries (see [7]) and 9 I_i parameters, of which 8 are independent. At this point we can follow two alternatives to construct observables: (a) fit the parameters Is, use them as observables, and compare the predictions with data or (b) use the spin amplitudes as the key ingredient to construct a selected group of observables.

The first option (a) [8] is experimentally problematic as the resultant fit fails to capture correlations among the Is induced by the underlying K^* spin amplitudes. The second option (b) [6] aims at constructing selected observables from the K^* spin amplitudes that are extracted directly from the experimental fit. Certain criteria are considered: maximal sensitivity to right-handed currents (RH), minimal sensitivity to poorly known soft form factors, and good experimental resolution. We will always follow option (b) [6]. The procedure then is the following: choose a combination of spin amplitudes with maximal sensitivity to RH currents; check if the combination fulfills all the symmetries; and finally, analyze the observables and New Physics (NP) impact. Notice that these combinations of spin amplitudes may be simple functions of the Is (see [6]) or highly non-linear combinations showing up an interesting sensitivity to NP (see [7] for an example).

The key point is the evaluation of the relevant matrix elements that in naive factorization are functions of the form factors $V(q^2)$, $A_{0,1,2,3}(q^2)$ and $T_{1,2,3}(q^2)$. Then the spin amplitudes $A_{\perp,\parallel,0}$ can be written in terms of these form factors and the Wilson coefficients C_7^{eff}, $C_7^{\mathrm{eff}\prime}$, C_9^{eff} and C_{10} of an effective Hamiltonian that includes RH currents via the electromagnetic dipole operator $O_7' = (e/16\pi^2) m_b (\bar{s}\sigma_{\mu\nu} P_\mathrm{L} b) F^{\mu\nu}$:

$$\begin{aligned}
\boldsymbol{A}_{\perp\,\mathbf{L,R}} &= \hat{N}\lambda^{1/2}\left[\left(C_9^{\mathrm{eff}} \mp C_{10}\right)\frac{V\left(q^2\right)}{m_B + m_K^*} + \frac{2m_b}{q^2}\left(C_7^{\mathrm{eff}} + C_7^{\mathrm{eff}\prime}\right) T_1\left(q^2\right)\right], \\
\boldsymbol{A}_{\parallel\,\mathbf{L,R}} &= -\hat{N}\left(m_B^2 - m_{K^*}^2\right) \\
&\quad \times\left[\left(C_9^{\mathrm{eff}} \mp C_{10}\right)\frac{A_1\left(q^2\right)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}\left(C_7^{\mathrm{eff}} - C_7^{\mathrm{eff}\prime}\right) T_2\left(q^2\right)\right],
\end{aligned}$$

$$
\begin{aligned}
\boldsymbol{A_{0\,\mathrm{L,R}}} \;=\;& -\frac{\hat{N}}{2m_{K^*}\sqrt{2q^2}}\Bigg[\left(C_9^{\mathrm{eff}} \mp C_{10}\right)\Big\{\left(m_B^2 - m_{K^*}^2 - q^2\right)\left(m_B + m_{K^*}\right) \\
&\times A_1\left(q^2\right) - \lambda\frac{A_2\left(q^2\right)}{m_B + m_{K^*}}\Big\} + 2m_b\left(C_7^{\mathrm{eff}} - C_7^{\mathrm{eff}\prime}\right) \\
&\times\Big\{\left(m_B^2 + 3m_{K^*}^2 - q^2\right)T_2\left(q^2\right) - \frac{\lambda}{m_B^2 - m_{K^*}^2}T_3\left(q^2\right)\Big\}\Bigg].
\end{aligned}
$$

We are left again with two possible choices: either *(i)* use QCD light cone sum rules (LCSR) to estimate the required form factors adding the α_s corrections from QCDF or *(ii)* work consistently in the same framework of QCDF at the LO and NLO [2] and include a reasonable conservative size for the possible Λ/m_b corrections. The first option *(i)* [8] implies neglecting some $\mathcal{O}(\Lambda/m_b)$ corrections to QCDF and assume that the main part of those corrections are inside the soft form factors evaluated with QCD LCSR. The second option *(ii)* [6] allows us to explore the impact that $\mathcal{O}(\Lambda/m_b)$ corrections have on the observables.

In the limit $m_B \to \infty$ and $E_K^* \to \infty$, all the form factors are related to only two soft form factors $\xi_\perp$ and $\xi_\|$ [10]. Consequently, transversity amplitudes simplify enormously. It is then easy to construct observables where the soft form factors cancel out completely at the LO:

$$
\begin{aligned}
\boldsymbol{A_{\perp\,\mathrm{L,R}}} \;=\;& \hat{N}m_B(1-\hat{s})\left[\left(C_9^{\mathrm{eff}} \mp C_{10}\right) + \frac{2\hat{m}_b}{\hat{s}}\left(C_7^{\mathrm{eff}} + C_7^{\mathrm{eff}\prime}\right)\right]\xi_\perp(E_{K^*}), \\
\boldsymbol{A_{\|\,\mathrm{L,R}}} \;=\;& -\hat{N}m_B(1-\hat{s})\left[\left(C_9^{\mathrm{eff}} \mp C_{10}\right) + \frac{2\hat{m}_b}{\hat{s}}\left(C_7^{\mathrm{eff}} - C_7^{\mathrm{eff}\prime}\right)\right]\xi_\perp(E_{K^*}), \\
\boldsymbol{A_{0\,\mathrm{L,R}}} \;=\;& -\frac{\hat{N}m_B}{2\hat{m}_{K^*}\sqrt{2\hat{s}}}(1-\hat{s})^2\left[\left(C_9^{\mathrm{eff}} \mp C_{10}\right) + 2\hat{m}_b\left(C_7^{\mathrm{eff}} - C_7^{\mathrm{eff}\prime}\right)\right]\xi_\|(E_{K^*}),
\end{aligned}
$$

where $\hat{s} = q^2/m_B^2$, $\hat{m}_b = m_b/m_B$ and $\hat{m}_{K^*} = m_{K^*}/m_B$.

Finally, our BSM testing ground model will be a Supersymmetric model with non-minimal flavour violation in the down squark sector that induces RH currents [5]. We will focus on two scenarios [6]:

- **Scenario A**: Large-gluino and positive mass insertion scenario: $m_{\tilde{g}} = 1$ TeV, $m_{\tilde{d}} \in [200, 1000]$ GeV. Curve (a): $m_{\tilde{g}}/m_{\tilde{d}} = 2.5$, $(\delta^d_{\mathrm{LR}})_{32} = 0.016$. Curve (b): $m_{\tilde{g}}/m_{\tilde{d}} = 4$, $(\delta^d_{\mathrm{LR}})_{32} = 0.036$.

- **Scenario B:** Low-gluino mass or large squark mass: $m_{\tilde{d}} = 1$ Tev, $m_{\tilde{g}} \in [200, 800]$ Gev. Curve (c): $m_{\tilde{g}}/m_{\tilde{d}} = 0.7$, $(\delta^d_{\mathrm{LR}})_{32} = -0.004$. Curve (d): $m_{\tilde{g}}/m_{\tilde{d}} = 0.6$, $(\delta^d_{\mathrm{LR}})_{32} = -0.006$.

We also take: $\mu = M_1 = M_2 = m_{\tilde{u}R} = 1$ TeV and $\tan\beta = 5$. All the relevant constraints (from Higgs mass, vacuum stability, rare B decays, ...) have been checked, too.

3. Analysis of observables

In the framework of QCDF at the NLO we evaluate the K^* spin amplitudes to include α_s contributions to form factors, adding also possible Λ/m_b corrections according to option *(ii)* [6]. We are then in position to construct observables out of these spin amplitudes, the so called 'transverse and transverse/longitudinal asymmetries' [4–6]: A_T^2, A_T^3 and A_T^4. To fully understand the behaviour of these observables, it is very illuminating to analyze them in the large recoil limit using the heavy quark and large-E_{K^*} expressions for the spin amplitudes. This is the main goal of this section.

The transverse asymmetry A_T^2, first proposed in [4], probes the transverse spin amplitude $A_{\perp,\parallel}$ in a controlled way. It is defined by [4]:

$$A_T^2 = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2} . \tag{2}$$

This observable has a particularly simple form if one uses the heavy quark and large-E_{K^*} limit for the transverse amplitudes:

$$A_T^2 \sim 4C_7^{\mathrm{eff}\prime} \frac{m_b M_B}{q^2} \frac{\Delta_- + \Delta_+^*}{2C_{10}^2 + |\Delta_-|^2 + |\Delta_+|^2} , \tag{3}$$

where $\Delta_\pm = \mathcal{C}_9^{\mathrm{eff}} + 2\frac{m_b M_B}{s}(C_7^{\mathrm{eff}} \pm C_7^{\mathrm{eff}\prime})$ and the Wilson Coefficients are assumed to be real. It is then clear that in this observable $\xi_\perp(0)$ form factor dependence cancels at the LO, and the sensitivity to $C_7^{\mathrm{eff}\prime}$ is maximal.

We restrict our analysis to the low dilepton mass region $1 \leq q^2 \leq 6$ GeV^2. We show that the most relevant features arise already at the LO. We will model the presence of NP using a non-zero contribution to the chirally flipped operator $\mathcal{O}_7'$ according to the previous section.

Some important remarks concerning A_T^2 are in order here. Eq. (3) makes explicit several of the most important features of this observables, namely:

- A_T^2 is sensitive to both the modulus and sign of $C_7^{\mathrm{eff}\prime}$, being approximately zero in the SM. This sensitivity is enhanced by a factor $4m_b M_B/q^2$ at low q^2 ($q^2 \sim 1$ GeV^2), and for larger values of q^2 ($1 < q^2 < 4$ GeV^2) the observable decreases as $1/s$. This is clearly shown in Fig. 1, looking at the curves a, b, c and d.

- $A_{\rm T}^2$ exhibits a zero at the point $\Delta_- + \Delta_+^* = 0$ corresponding exactly to the zero of the FB asymmetry ($A_{\rm FB}$) at the LO. Being this zero independent of $C_7^{\rm eff\prime}$, all the curves with SM-like C_7 should exhibit it (see Fig. 1). Finally, it was shown in [6] that contrary to the case of $A_{\rm T}^2$, the observable $A_{\rm FB}$ does not show any remarkable sensitivity to the presence of RH currents. This stresses the importance of $A_{\rm T}^2$ as one of the best indicators of the presence of this type of NP.

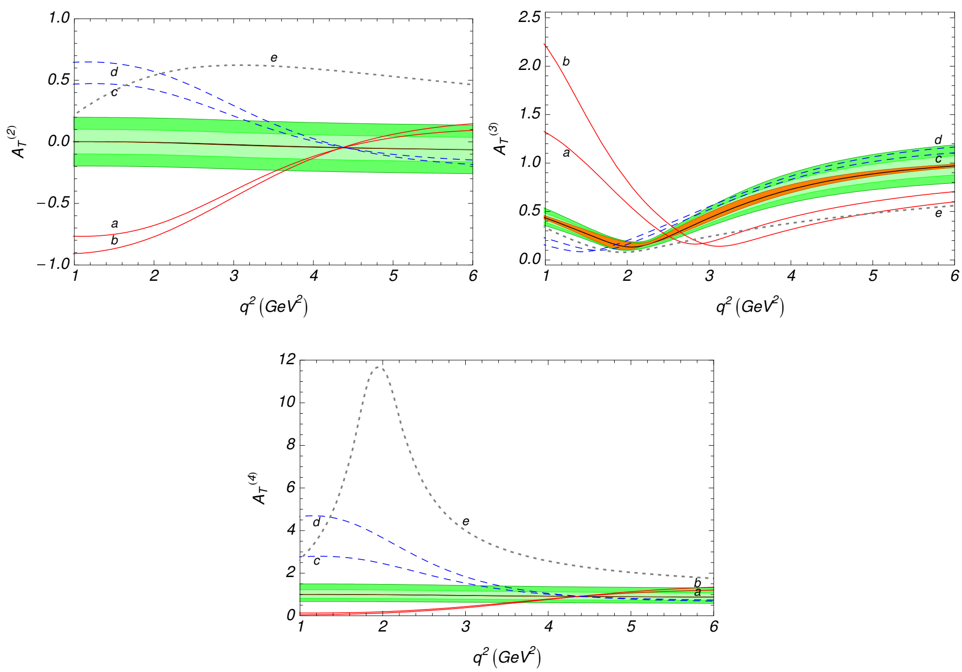

Fig. 1. $A_{\rm T}^2$ (a), $A_{\rm T}^3$(b) and $A_{\rm T}^4$(c) in SM and SUSY (curves a, b, c, d). The outer dark and light (green) bands are, respectively, the possible 5 and 10% Λ/m_b corrections to the amplitudes, varied independently for each amplitude and added in quadrature. The inner dark (orange) band around the SM prediction (black curve) contains the hadronic and renormalization scale uncertainties, also added in quadrature. The dotted curve (e) corresponds to the flipped sign solution $(C_7^{\rm eff}, C_7^{\rm eff\prime}) = (0.04, 0.31)$.

In summary, $A_{\rm T}^2$ provides different information depending on the region of q^2 analyzed: at low q^2 ($q^2 \sim 1$ GeV^2) basically sets the size of the coefficient $C_7^{\rm eff\prime}$, and at high q^2 ($q^2 \sim 4$ GeV^2) behaves as $A_{\rm FB}$, with a zero in the energy axis. This last point implies obviously that in the case of flipped sign solution for $C_7^{\rm eff}$, the behaviour of $A_{\rm T}^2$ changes drastically. This is shown by the dotted curve (e) in Fig. 1(a) that does not have a zero, like in the FB asymmetry. In this sense $A_{\rm T}^2$ goes beyond the $A_{\rm FB}$ because it contains the most important features of this observable, and also shows up a dramatic dependence on the presence of RH currents (O_7') invisible to $A_{\rm FB}$.

A similar exercise can be done with the observables $A_{\rm T}^3$ and $A_{\rm T}^4$ [6]. Those are particularly interesting because they open sensitivity to the longitudinal spin amplitude A_0, at the same time minimizing sensitivity to the other soft form factor $\xi_{\|}(0)$. Both observables can be very easily measured from the angular distribution. Their explicit form in the heavy quark and large-E_{K^*} limit for the spin amplitudes, even if less illuminating, still shows clearly the different way they depend on the RH currents:

$$A_{\rm T}^3 = \frac{|A_{0\,\rm L}A^*_{\|\,\rm L}+A^*_{0\,\rm R}A_{\|\,\rm R}|}{\sqrt{|A_0|^2|A_\perp|^2}} \sim \frac{q^2\left(\tilde{\Delta}^- + f_1\right) + \tilde{\Delta}^-\left(f_2 + \tilde{\Delta}^- f_3\right)}{\sqrt{f_4\tilde{\Delta}^{-2}+f_5\tilde{\Delta}^-+f_6}\sqrt{\tilde{\Delta}^+q^2+f_7q^4+f_8\tilde{\Delta}^{+2}}}\,,$$

$$A_{\rm T}^4 = \frac{|A_{0\,\rm L}A^*_{\perp\,\rm L}-A^*_{0\,\rm R}A_{\perp\,\rm R}|}{|A_{0\,\rm L}A^*_{\|\,\rm L}+A^*_{0\,\rm R}A_{\|\,\rm R}} \sim \frac{f_9\tilde{\Delta}^+ + q^2\left(f_{10}\tilde{\Delta}^- + f_{11}\right)}{q^2\left(\tilde{\Delta}^- + f_1\right) + \tilde{\Delta}^-\left(f_2 + \tilde{\Delta}^- f_3\right)}\,,$$

where $f_i = f(\mathcal{C}_9^{\rm eff}, C_{10})$ with $i = 1, \ldots 11$ are simple functions easy to obtain from the large recoil expression of the spin amplitudes and $\tilde{\Delta}^\pm = C_7^{\rm eff} \pm C_7^{\rm eff\prime}$. Here a small weak phase has been neglected. As can be seen from their defining expressions and from the Figs. 1(b)–1(c), $A_{\rm T}^3$ and $A_{\rm T}^4$ play a complementary role: where $A_{\rm T}^3$ shows a minimum, $A_{\rm T}^4$ has a maximum, and *vice versa*. For example, in the specific SUSY cases discussed, it is clear from Figs. 1(a)–1(b) that the low-gluino scenario with negative mass insertion is clearly enhanced in the low-q^2 region for $A_{\rm T}^4$, while the large-gluino scenario with positive mass insertion is clearly signaled in the low-q^2 region for $A_{\rm T}^3$. Finally, from the set of functions f_i, it is easy to obtain at the LO positions of the maxima/minima with good precision. The way the sensitivity to RH currents is manifested is through positions of the maxima/minima in $A_{\rm T}^3$ and $A_{\rm T}^4$. In the case of flipped sign solution (dotted curve (e) in Fig. 1) this is also shown by the position of more prominent peak in $A_{\rm T}^4$, as seen in Fig. 1(c).

The same philosophy as in [6] can be applied to CP-violating observables (see [7, 11] for a detailed discussion). The excellent experimental sensitivity at LHCb, especially for $A_{\rm T}^2$ from a full angular analysis, will allow to disentangle cleanly the presence of RH currents [6, 7, 12].

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