The exclusive $\boldsymbol{B \to K^*(\to K\pi) l^+ l^-}$ decay: CP conserving observables.*

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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_T^2, A_T^3 and A_T^4. We focus here, on analyzing their behaviour at large recoil energy in 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 type of observables, such as the forward-backward (FB) asymmetry [1, 2], the isospin asymmetry [3] and the angular distribution observables [4, 5, 6, 7, 8, 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 $\mathbf{\bar{B}_d} \to \mathbf{\bar{K}^{*0}}(\to \mathbf{K}\pi)\mathbf{l^+l^-}$. This distribution with the K^{*0} on the mass shell

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is described by s and three angles $\theta_{\mathbf{l}}$ (angle between μ^- and the direction of the outgoing K^* in $\mu\mu$ frame) , $\theta_{\mathbf{K}}$ (angle between K^- and outgoing K^* in $\bar{K}^*$ frame) and ϕ (angle between the two planes),

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

where $I = \mathbf{I_1} + \mathbf{I_2}\cos 2\theta_l + \mathbf{I_3}\sin^2\theta_l \cos 2\phi + \mathbf{I_4}\sin 2\theta_l \cos\phi + \mathbf{I_5}\sin\theta_l\cos\phi +$ $+\mathbf{I_6}\cos\theta_l + \mathbf{I_7}\sin\theta_l\sin\phi + \mathbf{I_8}\sin 2\theta_l \sin\phi + \mathbf{I_9}\sin^2\theta_l\sin 2\phi$. In the massless limit the I's are function of the K* spin amplitudes[4] $A_{\perp L,R}$, $A_{\| L,R}$ and $A_{0L,R}$, we have then 6 complex amplitudes, four symmetries (see [7]) and 9 $\mathrm{I_i}$ parameters, of which 8 are independent. At this point we can follow two alternatives to construct observables: a) fit the parameters I's, 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 the correlation between the I's 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 in this case is the following: choose the combination of spin amplitudes with maximal sensitivity to RH currents; check if the combination fulfills all symmetries; and finally, analyse the observables and New Physics (NP) impact. Notice that these combinations of spin amplitudes may be simple functions of the I's (see [6]) or highly non-linear combinations showing up an interesting sensitivity to NP (see [7] for an example).

The keypoint 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 $A_{\perp,\|,0}$ 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 $O_7' = (e/16\pi^2)m_b(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}$:

$$\mathbf{A}_{\perp\mathbf{L},\mathbf{R}} = \hat{N}\lambda^{1/2}\Big[(C_9^{\mathrm{eff}} \mp C_{10})\frac{V(q^2)}{m_B + m_K^*} + \frac{2m_b}{q^2}(C_7^{\mathrm{eff}} + C_7^{\mathrm{eff}\prime})T_1(q^2)\Big]$$

$$\mathbf{A}_{\|\mathbf{L},\mathbf{R}} = -\hat{N}(m_B^2 - m_{K^*}^2)\Big[(C_9^{\mathrm{eff}} \mp C_{10})\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\mathrm{eff}} - C_7^{\mathrm{eff}\prime})T_2(q^2)\Big]$$

$$\mathbf{A_{0L,R}} = -\frac{\hat{N}}{2m_{K^*}\sqrt{2q^2}}\Big[(C_9^{\rm eff} \mp C_{10})\Big\{(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})A_1(q^2) \\ -\lambda\frac{A_2(q^2)}{m_B + m_{K^*}}\Big\} + 2m_b(C_7^{\rm eff} - C_7^{\rm eff\prime})\Big\{(m_B^2 + 3m_{K^*}^2 - q^2)T_2(q^2) \\ -\frac{\lambda}{m_B^2 - m_{K^*}^2}T_3(q^2)\Big\}\Big],$$

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 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 form factors are related to only two soft form factors $\xi_\perp$ and $\xi_\|$ [10] and consequently transversity amplitudes simplify enormously; then observables can be easily constructed in which the soft form factors cancel out completely at LO:

$$\mathbf{A_{\perp L,R}} = \hat{N}m_B(1-\hat{s})\Big[(C_9^{\rm eff} \mp C_{10}) + \frac{2\hat{m}_b}{\hat{s}}(C_7^{\rm eff} + C_7^{\rm eff\prime})\Big]\xi_\perp(E_{K^*}),$$

$$\mathbf{A_{\| L,R}} = -\hat{N}m_B(1-\hat{s})\Big[(C_9^{\rm eff} \mp C_{10}) + \frac{2\hat{m}_b}{\hat{s}}(C_7^{\rm eff} - C_7^{\rm eff\prime})\Big]\xi_\perp(E_{K^*}),$$

$$\mathbf{A_{0L,R}} = -\frac{\hat{N}m_B}{2\hat{m}_{K^*}\sqrt{2\hat{s}}}(1-\hat{s})^2\Big[(C_9^{\rm eff} \mp C_{10}) + 2\hat{m}_b(C_7^{\rm eff} - C_7^{\rm eff\prime})\Big]\xi_\|(E_{K^*}),$$

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: $m_{\tilde{g}} =$ 1TeV, $m_{\tilde{d}} \in [200, 1000]$GeV,. Curve (a): $m_{\tilde{g}}/m_{\tilde{d}} = 2.5$, $\left(\delta^d_{LR}\right)_{32} = 0.016$. Curve (b): $m_{\tilde{g}}/m_{\tilde{d}} = 4$, $\left(\delta^d_{LR}\right)_{32} = 0.036$.

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

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

3. Analysis of observables

In the framework of QCDF at 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 the position to construct observables out of these spin amplitudes, the so called 'transverse and transverse/longitudinal asymmetries' [4, 5, 6]: A_T^2, A_T^3 and A_T^4. In order 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:

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

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

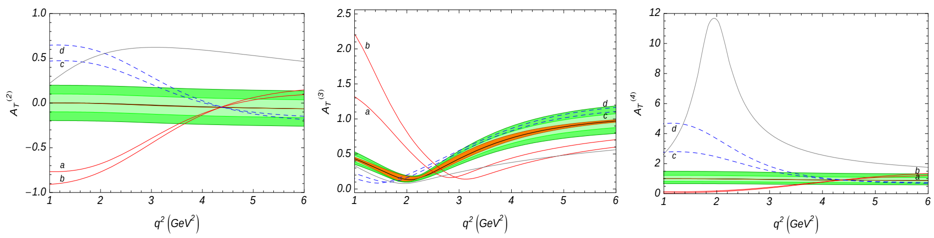

Fig. 1. A_T^2 (a), A_T^3(b) and A_T^4(c) in SM and SUSY (curves a,b,c,d). The outer dark and light (green) bands are, respectively, the possible 5 and 10% Λ/m_b corrections to the amplitudes, varied independently for each amplitude and added in quadrature. The inner (orange) band around the SM prediction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

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

- Finally A_T^2 exhibits a zero, at the point $\Delta_- + \Delta_+^* = 0$ corresponding exactly to the zero of the FB asymmetry at LO. Being this zero independent of $C_7^{\rm eff\prime}$, all 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_T^2 the observable A_{FB} does not show any remarkable sensitivity to the presence of RH currents. This stress the importance of A_T^2 as one of the best indicators of the presence of this type of NP.

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

A similar exercise can be done with the observables A_T^3 and A_T^4 [6]. Those are particularly interesting because they open the sensitivity to the longitudinal spin amplitude A_0 minimizing, at the same time, the sensitivity to the other soft form factor $\xi_\parallel(0)$.

Both can be very easily measured from the angular distribution and their explicit form in the heavy quark and large-E_{K^*} limit for the spin amplitudes, even if less iluminating, still shows clearly the different way they depend on the RH currents. They are:

$$A_T^3 = \frac{|A_{0L}A^*_{\|L} + A^*_{0R}A_{\|R}|}{\sqrt{|A_0|^2|A_\perp|^2}} \sim \frac{q^2\left(\tilde{\Delta}^- + f_1\right) + \tilde{\Delta}^-\left(f_2 + \tilde{\Delta}^- f_3\right)}{\sqrt{f_4\tilde{\Delta}^{-2} + f_5\tilde{\Delta}^- + f_6}\sqrt{\tilde{\Delta}^+ q^2 + f_7 q^4 + f_8\tilde{\Delta}^{+2}}}$$

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

where $f_i = f(\mathcal{C}_9^{\rm eff}, C_{10})$ with $i = 1,..11$ [7] are simple functions of these coefficients 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. 1b-1c, A_T^3 and A_T^4 play a complementary role, where A_T^3 shows a minimum A_T^4 has a maximum, and viceversa. For example, in the specific SUSY cases discussed, it is clear from Figs. 1a-1b that the low-gluino scenario with negative mass insertion is clearly enhanced in the low-q^2 region for A_T^4, while the large-gluino scenario with positive mass insertion is clearly signaled in the low-q^2 region for A_T^3 and in the large-q^2 region for A_T^4. Finally, from the set of functions f_i[7] it is easy at LO to obtain with good precision the position of the maxima/minima. The way the sensitivity to RH currents is manifested is through the position of the maxima/minima in A_T^3 and A_T^4. In the case of the flipped sign solution (grey curve of Fig. 1) this is shown also by the position of more prominent peak in A_T^4 (as seen in Fig 1c).

The same philosophy as in [6] can be applied to CP violating observables (see [7, 11] for a detailed discussion). Finally the excellent experimental sensitivity at LHCb specially for A_T^2 from a full angular analysis will allow to disentangle cleanly the presence of RH currents [6, 7, 12].

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