New physics searches in the $\bar{B}_d \to \bar{K}^*(\to K\pi)\ell^+\ell^-$ decay

Marc Ramon
U.A.B.

In collaboration with U. Egede, T. Hurth, J. Matias and W. Reece

29th November 2010

Motivation for $\bar{B}_d \to \bar{K}^{*0}\ell^+\ell^-$

The exclusive process $\bar{B}_d \to \bar{K}^{*0}\ell^+\ell^-$ has very rich phenomenology. Several observables are available:

- the Forward-Backward Asymmetry (A_{FB})
- the Isospin Asymmetry (A_I)
- new observables built from $\bar{K}^{*0}$ spin amplitudes of the 4-body decay:
  - full angular fit (for $\int L dt > 2\,\mathrm{fb}^{-1}$)$\to$ unbinned analysis possible,
  - better resolution.

Goal: Identify signals of specific NP models in the flavour sector to complement direct searches.

Outline of the method used to build observables

Our aim is to construct quantities, using the $\bar{K}^{*0}$ spin amplitudes as building blocks, that

- maximise the sensitivity to certain types of new physics;
- minimise the dependence on certain hadronic uncertainties;

To this end it is necessary to:

(1) identify all the symmetries of the angular distribution;

(2) check that the quantities fulfill all symmetries $\Rightarrow$ observables;

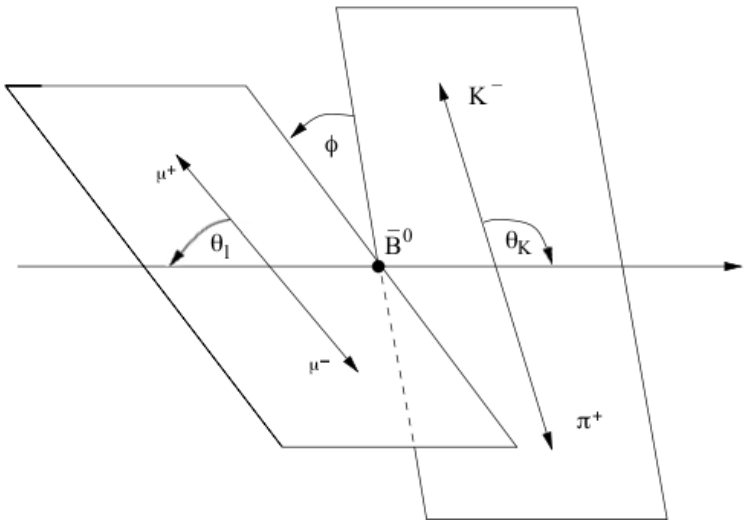
(3) express the observables in terms of the coefficients of the distribution using the symmetries;

(4) find hidden dependencies between the coefficients of the distribution. This:
   - improves the fit stability,
   - provides extra checks to experimental data.

Kinematics

The decay $\bar{B}_d \to \bar{K}^{*0}(\to K\pi)\ell^+\ell^-$ with the $\bar{K}^{*0}$ on the mass shell is described by q^2 and three angles θ_ℓ, θ_K and ϕ

$$\frac{d^4\Gamma_{\bar{B}_d}}{dq^2\, d\theta_\ell\, d\theta_K\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_\ell, \theta_K, \phi) \sin\theta_\ell \sin\theta_K$$



θ_ℓ: Angle between $\vec{p}_{\ell+}$ in the $\ell^+\ell^-$ rest frame and the dilepton's direction in the rest frame of $\bar{B}_d$.

θ_K: Angle between $\vec{p}_{K-}$ in the $\bar{K}^{*0}$ rest frame and the direction of $\bar{K}^{*0}$ in the rest frame of $\bar{B}_d$.

ϕ: Angle between the ℓ^+-ℓ^- plane and the K^--π^+ plane.

Angular coefficients

$$J = J_1 + J_2 \cos 2\theta_\ell + J_3 \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_\ell \cos\phi + J_5 \sin\theta_\ell \cos\phi + J_6 \cos\theta_\ell + J_7 \sin\theta_\ell \sin\phi + J_8 \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_\ell \sin 2\phi.$$

In the massless lepton limit without scalars:

$$J_1 = \frac{3}{4}\left[|A_{\perp L}|^2 + |A_{\parallel L}|^2 + (L \to R)\right]\sin^2\theta_K + \left[|A_{0L}|^2 + (L \to R)\right]\cos^2\theta_K$$

$$J_2 = \frac{1}{4}\left[|A_{\perp L}|^2 + |A_{\parallel L}|^2 + (L \to R)\right]\sin^2\theta_K - \left[|A_{0L}|^2 + (L \to R)\right]\cos^2\theta_K$$

$$J_3 = \frac{1}{2}\left[\left(|A_\perp|^2 - |A_{\parallel L}|^2\right) + (L \to R)\right]\sin^2\theta_K$$

$$J_4 = \frac{1}{\sqrt{2}}\left[\mathrm{Re}(A_{0L}A^*_{\parallel L}) + (L \to R)\right]\sin 2\theta_K \qquad J_7 = \sqrt{2}\left[\mathrm{Im}(A_{0L}A^*_{\parallel L}) - (L \to R)\right]\sin 2\theta_K$$

$$J_5 = \sqrt{2}\left[\mathrm{Re}(A_{0L}A^*_{\perp L}) - (L \to R)\right]\sin 2\theta_K \qquad J_8 = \frac{1}{\sqrt{2}}\left[\mathrm{Im}(A_{0L}A^*_{\perp L}) + (L \to R)\right]\sin 2\theta_K$$

$$J_6 = 2\left[\mathrm{Re}(A_{\parallel L}A^*_{\perp L}) - (L \to R)\right]\sin^2\theta_K \qquad J_9 = \left[\mathrm{Im}(A^*_{\parallel L}A_{\perp L}) + (L \to R)\right]\sin^2\theta_K$$

There are 6 complex amplitudes $A_{\perp,\parallel,0\,(L,R)}$ and 11 experimental inputs.

$\bar{K}^{*0}$ spin amplitudes in "naïve" factorisation

The spin amplitudes $A_\perp$, $A_\parallel$ and A_0 are function of

(1) the Wilson Coefficients $\mathcal{C}_i^{(\text{eff})}$ and $\mathcal{C}_i'^{(\text{eff})}$ (with $i = 7, 9, 10$).

(2) the form factors $A_{1,2}(q^2)$, $V(q^2)$ and $T_{1,2,3}(q^2)$.

$$A_{\perp L,R} = N\sqrt{2}\lambda^{1/2}\left[\left(\tilde{\mathcal{C}}_{9+}^{(\text{eff})} \mp \tilde{\mathcal{C}}_{10+}^{(\text{eff})}\right)\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}\tilde{\mathcal{C}}_{7+}^{(\text{eff})} T_1(q^2)\right],$$

$$A_{\parallel L,R} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left[\left(\tilde{\mathcal{C}}_{9-}^{(\text{eff})} \mp \tilde{\mathcal{C}}_{10-}^{(\text{eff})}\right)\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}\tilde{\mathcal{C}}_{7-}^{(\text{eff})} T_2(q^2)\right],$$

$$\begin{aligned} A_{0L,R} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\Bigg[&\left(\tilde{\mathcal{C}}_{9-}^{(\text{eff})} \mp \tilde{\mathcal{C}}_{10-}^{(\text{eff})}\right)\Big\{(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})A_1(q^2) - \\ &-\lambda\frac{A_2(q^2)}{m_B + m_{K^*}}\Big\} + 2m_b\tilde{\mathcal{C}}_{7-}^{(\text{eff})}\Big\{(m_B^2 + 3m_{K^*}^2 - q^2)T_2(q^2) - \\ &-\frac{\lambda}{m_B^2 - m_{K^*}^2}T_3(q^2)\Big\}\Bigg], \end{aligned}$$

where the short-hand notation $\tilde{\mathcal{C}}_{i\pm}^{(\text{eff})} \equiv \mathcal{C}_i^{(\text{eff})} \pm \mathcal{C}_i'^{(\text{eff})}$ has been used.

Large recoil form factor relations at LO

In the limit $m_B \to \infty$ and $E_{K^*} \to \infty$ all form factors are related:

$$A_1(q^2) = \frac{2E_{K^*}}{m_B + m_{K^*}}\xi_\perp(E_{K^*}), \qquad A_2(q^2) = \frac{m_B}{m_B - m_{K^*}}\left[\xi_\perp(E_{K^*}) - \xi_\parallel(E_{K^*})\right],$$

$$A_0(q^2) = \frac{E_{K^*}}{m_{K^*}}\xi_\parallel(E_{K^*}), \qquad V(q^2) = \frac{m_B + m_{K^*}}{m_B}\xi_\perp(E_{K^*}),$$

$$T_1(q^2) = \xi_\perp(E_{K^*}), \quad T_2(q^2) = \frac{2E_{K^*}}{m_B}\xi_\perp(E_{K^*}), \quad T_3(q^2) = \xi_\perp(E_{K^*}) - \xi_\parallel(E_{K^*}).$$

So at large recoil and at LO the spin amplitudes simplify into

$$A_{\perp L,R} = \sqrt{2}Nm_B\left(1 - \frac{q^2}{m_B^2}\right)\left[\left(\tilde{\mathcal{C}}_{9+}^{(\text{eff})} \mp \tilde{\mathcal{C}}_{10+}^{(\text{eff})}\right) + \frac{2m_b m_B}{q^2}\tilde{\mathcal{C}}_{7+}^{(\text{eff})}\right]\xi_\perp(E_{K^*}),$$

$$A_{\parallel L,R} = -\sqrt{2}Nm_B\left(1 - \frac{q^2}{m_B^2}\right)\left[\left(\tilde{\mathcal{C}}_{9-}^{(\text{eff})} \mp \tilde{\mathcal{C}}_{10-}^{(\text{eff})}\right) + \frac{2m_b m_B}{q^2}\tilde{\mathcal{C}}_{7-}^{(\text{eff})}\right]\xi_\perp(E_{K^*}),$$

$$A_{0L,R} = -\frac{Nm_B^2}{2m_{K^*}\sqrt{q^2}}\left(1 - \frac{q^2}{m_B^2}\right)^2\left[\left(\tilde{\mathcal{C}}_{9-}^{(\text{eff})} \mp \tilde{\mathcal{C}}_{10-}^{(\text{eff})}\right) + 2\frac{m_b}{m_B}\tilde{\mathcal{C}}_{7-}^{(\text{eff})}\right]\xi_\parallel(E_{K^*}).$$

How to include higher order corrections in $A_{0,\perp,\parallel}$?

There are **two strategies**:

(1) Use the QCD sum rules for form factors and QCDf for α_s corrections.
$O(\Lambda_{\rm QCD}/m_b)$ corrections coming from QCDf are neglected.
(Altmannshofer et al. '09)

(2) Use large recoil form factor relations (LO) + QCDf (α_s-NLO corrections).
$O(\Lambda_{\rm QCD}/m_b)$ corrections estimated to add a maximum $\pm 10\%$ to each amplitude.

This allows to explore the impact of these corrections in the observables $\Rightarrow$ **more conservative**.
(Krüger, Matias '05; Lunghi, Matias '07; Egede et al. '08)

How to include higher order corrections in $A_{0,\perp,\parallel}$?

There are **two strategies**:

(1) Use the QCD sum rules for form factors and QCDf for α_s corrections.
$O(\Lambda_{\rm QCD}/m_b)$ corrections coming from QCDf are neglected.
(Altmannshofer et al. '09)

(2) Use large recoil form factor relations (LO) + QCDf (α_s-NLO corrections).
$O(\Lambda_{\rm QCD}/m_b)$ corrections estimated to add a maximum $\pm 10\%$ to each amplitude.

This allows to explore the impact of these corrections in the observables $\Rightarrow$ **more conservative**.
(Krüger, Matias '05; Lunghi, Matias '07; Egede et al. '08)

Types of corrections

- α_s-QCDf corrections to FF and HS kernels
  - The use of QCDf for computing these corrections restricts the invariant mass square of the leptonic pair to $1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$ (Beneke, Feldmann, Seidel '01).
- $O(\Lambda_{\mathrm{QCD}}/m_b)$ corrections to FFs and HS kernels
  - We take a set of 3 extra parameters c_i, one for each subamplitude inside the spin amplitude, along with 3 strong phases θ_i,

$$\begin{aligned} A_i &= A_i^{\mathrm{SM}}(\lambda_u = 0)(1 + c_1 e^{i\theta_1}) \\ &+ [A_i^{\mathrm{SM}}(\lambda_u \neq 0) - A_i^{\mathrm{SM}}(\lambda_u = 0)](1 + c_2 e^{i\theta_2}) \\ &+ [A_i^{\mathrm{NP}} - A_i^{\mathrm{SM}}](1 + c_3 e^{i\theta_3}) \end{aligned}$$

  - Pick up 3 random values from a uniform distribution over the ranges $-0.1 < c_i < 0.1$ and $-\pi < \theta_i < \pi$, evaluate the amplitudes, and repeat it 500 times to get an ensemble of amplitudes.
  - Compute the observable and calculate the 66% C.L. bands. These will be added in quadrature to hadronic uncertainties.

How many symmetries?

The experimental (J_i) and theoretical (A_i) degrees of freedom have to match:

$$n_C - n_d = 2n_A - n_s,$$

where n_C = number of coefficients in the differential distribution,
n_d = number of dependencies between different coefficients,
n_A = number of $\bar{K}^{*0}$ amplitudes (complex),
n_s = number of symmetries.

In the **massless case**

$$\begin{cases} n_C = 11 & (\text{the pieces in } J_i) \\ n_d = 3 & (\text{relations between experimental inputs}) \\ n_A = 6 & (\text{spin amplitudes } A_{\perp,\parallel,0\,(L,R)}) \end{cases}$$

so there must be 4 SYMMETRIES.

Which symmetries?

The differential distribution is invariant under the following independent symmetry transformations of the spin amplitudes:

(1) an independent phase transformation of the L-amplitudes,

$$A'_{\perp L} = e^{i\phi_L} A_{\perp L}, \qquad A'_{\parallel L} = e^{i\phi_L} A_{\parallel L}, \qquad A'_{0L} = e^{i\phi_L} A_L,$$

(2) an independent phase transformation of the R-amplitudes,

$$A'_{\perp R} = e^{i\phi_R} A_{\perp R}, \qquad A'_{\parallel R} = e^{i\phi_R} A_{\parallel R}, \qquad A'_{0R} = e^{i\phi_R} A_R,$$

(3) one continuous real $L \leftrightarrow R$ rotation

$$A'_{\perp L} = +\cos\theta A_{\perp L} + \sin\theta A^*_{\perp R} \qquad A'_{\perp R} = -\sin\theta A^*_{\perp L} + \cos\theta A_{\perp R}$$

$$A'_{\parallel L} = +\cos\theta A_{\parallel L} - \sin\theta A^*_{\parallel R} \qquad A'_{\parallel R} = +\sin\theta A^*_{\parallel L} + \cos\theta A_{\parallel R}$$

$$A'_{0L} = +\cos\theta A_{0L} - \sin\theta A^*_{0R} \qquad A'_{0R} = +\sin\theta A^*_{0L} + \cos\theta A_{0R}$$

Which symmetries?

The differential distribution is invariant under the following independent symmetry transformations of the spin amplitudes:

(1) an independent phase transformation of the L-amplitudes,

$$A'_{\perp L} = e^{i\phi_L} A_{\perp L}, \qquad A'_{\parallel L} = e^{i\phi_L} A_{\parallel L}, \qquad A'_{0L} = e^{i\phi_L} A_L,$$

(2) an independent phase transformation of the R-amplitudes,

$$A'_{\perp R} = e^{i\phi_R} A_{\perp R}, \qquad A'_{\parallel R} = e^{i\phi_R} A_{\parallel R}, \qquad A'_{0R} = e^{i\phi_R} A_R,$$

(3) one continuous real $L \leftrightarrow R$ rotation

$$A'_{\perp L} = +\cos\theta A_{\perp L} + \sin\theta A^*_{\perp R} \qquad A'_{\perp R} = -\sin\theta A^*_{\perp L} + \cos\theta A_{\perp R}$$

$$A'_{\parallel L} = +\cos\theta A_{\parallel L} - \sin\theta A^*_{\parallel R} \qquad A'_{\parallel R} = +\sin\theta A^*_{\parallel L} + \cos\theta A_{\parallel R}$$

$$A'_{0L} = +\cos\theta A_{0L} - \sin\theta A^*_{0R} \qquad A'_{0R} = +\sin\theta A^*_{0L} + \cos\theta A_{0R}$$

Which symmetries?

The differential distribution is invariant under the following independent symmetry transformations of the spin amplitudes:

(1) an independent phase transformation of the L-amplitudes,

$$A'_{\perp L} = e^{i\phi_L} A_{\perp L}, \qquad A'_{\parallel L} = e^{i\phi_L} A_{\parallel L}, \qquad A'_{0L} = e^{i\phi_L} A_L,$$

(2) an independent phase transformation of the R-amplitudes,

$$A'_{\perp R} = e^{i\phi_R} A_{\perp R}, \qquad A'_{\parallel R} = e^{i\phi_R} A_{\parallel R}, \qquad A'_{0R} = e^{i\phi_R} A_R,$$

(3) one continuous real $L \leftrightarrow R$ rotation

$$A'_{\perp L} = +\cos\theta A_{\perp L} + \sin\theta A^*_{\perp R} \qquad A'_{\perp R} = -\sin\theta A^*_{\perp L} + \cos\theta A_{\perp R}$$
$$A'_{\parallel L} = +\cos\theta A_{\parallel L} - \sin\theta A^*_{\parallel R} \qquad A'_{\parallel R} = +\sin\theta A^*_{\parallel L} + \cos\theta A_{\parallel R}$$
$$A'_{0L} = +\cos\theta A_{0L} - \sin\theta A^*_{0R} \qquad A'_{0R} = +\sin\theta A^*_{0L} + \cos\theta A_{0R}$$

Which symmetries?

The differential distribution is invariant under the following independent symmetry transformations of the spin amplitudes:

(4) another continuous $L \leftrightarrow R$ transformation

$$A'_{\perp L} = +\cosh\tilde{\theta} A_{\perp L} + \sinh\tilde{\theta} A^*_{\perp R} \quad A'_{\perp R} = -\sinh\tilde{\theta} A^*_{\perp L} + \cosh\tilde{\theta} A_{\perp R}$$

$$A'_{\parallel L} = +\cosh\tilde{\theta} A_{\parallel L} - \sinh\tilde{\theta} A^*_{\parallel R} \quad A'_{\parallel R} = +\sinh\tilde{\theta} A^*_{\parallel L} + \cosh\tilde{\theta} A_{\parallel R}$$

$$A'_{0L} = +\cosh\tilde{\theta} A_{0L} - \sinh\tilde{\theta} A^*_{0R} \quad A'_{0R} = +\sinh\tilde{\theta} A^*_{0L} + \cosh\tilde{\theta} A_{0R}$$

with $\tilde{\theta} = i\theta'$.

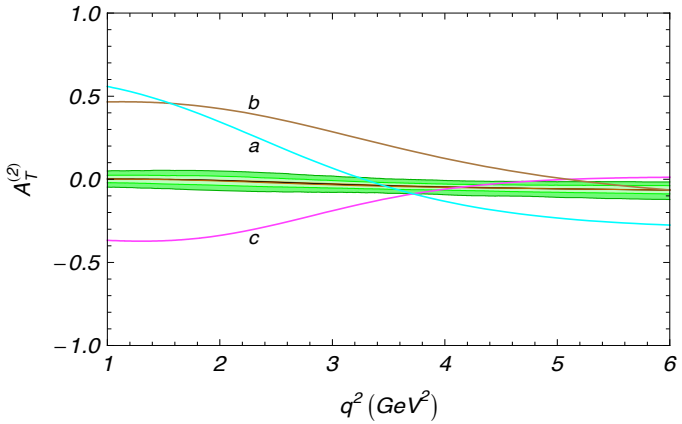
Any quantity constructed out of the $\bar{K}^{*0}$ spin amplitudes has to fulfill all the symmetries of the distribution to become an observable.

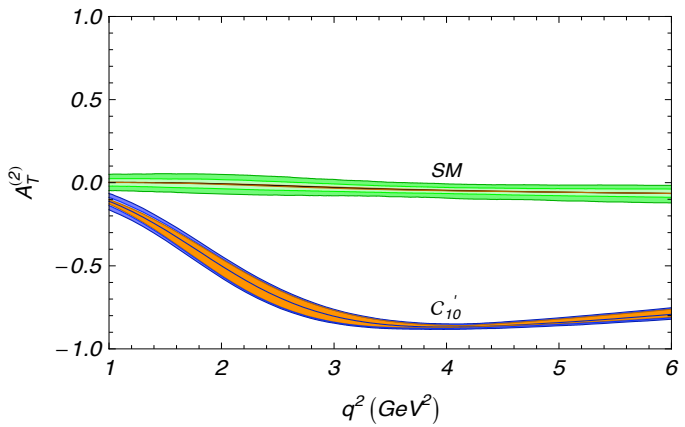
$A_T^{(2)}$: general properties

Definition (Krüger, Matias '05)

$$A_T^{(2)} = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}$$

- NP sensitivity: deviation from L-H structure of SM ($A_T^{(2)}\big|_{SM} \sim 0$).
- $\xi_\perp(0)$ dependence cancels at LO; very mild dependence at NLO.
- Exhibits an excellent sensitivity to R-H currents in $\mathcal{O}_7'$ and $\mathcal{O}_{10}'$.





Inner orange bands → Hadronic errors.

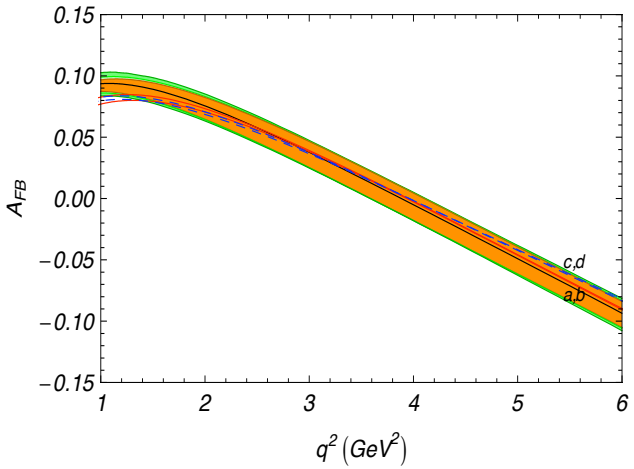
Outer bands → $O(\Lambda/m_b)$ corrections for SM and NP.

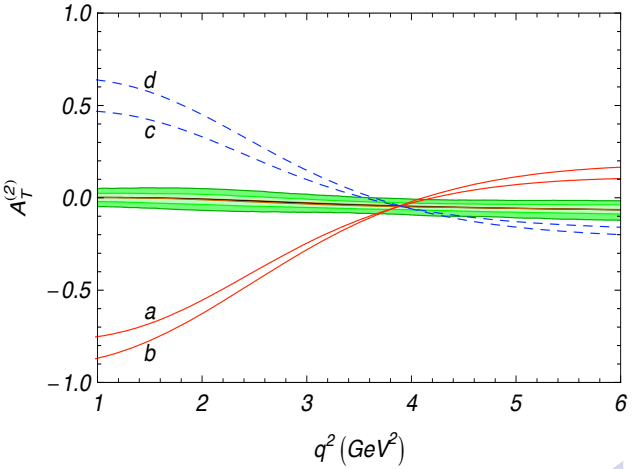
$A_T^{(2)}$ vs. A_{FB}: large recoil expressions for $\mathcal{C}_7'$

If there is NP entering $\mathcal{O}_7'$ but $\mathcal{O}_7$ is SM-like:

$$A_T^{(2)} = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2} \simeq \frac{\frac{4m_b M_B}{q^2}\left(\frac{2m_b M_B}{q^2}\mathcal{C}_7^{(\text{eff})} + \mathcal{C}_9\right)|\mathcal{C}_7'|\cos(\phi_7')}{\mathcal{C}_{10}^2 + \left(\frac{2m_b M_B}{q^2}\right)^2 |\mathcal{C}_7'^{(\text{eff})}|^2 + \left(\frac{2m_b M_B}{q^2}\mathcal{C}_7^{(\text{eff})} + \mathcal{C}_9\right)^2}.$$

- Sensitive to both the modulus and the phase (sign) of $\mathcal{C}_7'$.
- Has a zero independent of $\mathcal{C}_7'$ given by $\frac{2m_b m_B}{q_0^2}\mathcal{C}_7^{(\text{eff})} + \mathcal{C}_9 = 0$, which is the **same** as the zero of A_{FB} at LO.





a: $(\mathcal{C}_7^{(\text{NP})\,\text{eff}}, \mathcal{C}_7'^{\text{eff}}) = (0.10, 0.19)$

b: $(\mathcal{C}_7^{(\text{NP})\,\text{eff}}, \mathcal{C}_7'^{\text{eff}}) = (0.10, 0.29)$

c: $(\mathcal{C}_7^{(\text{NP})\,\text{eff}}, \mathcal{C}_7'^{\text{eff}}) = (0.10, -0.08)$

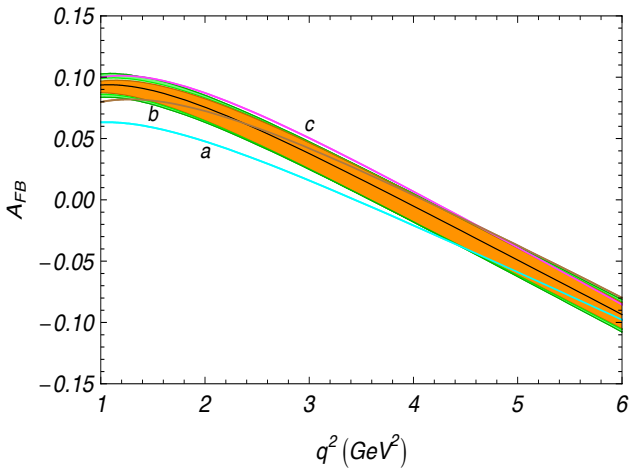
d: $(\mathcal{C}_7^{(\text{NP})\,\text{eff}}, \mathcal{C}_7'^{\text{eff}}) = (0.10, -0.11)$

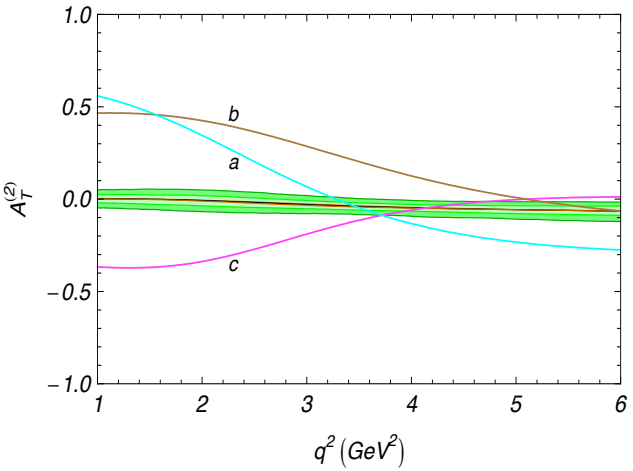
$A_T^{(2)}$ vs. A_{FB}: large recoil expressions for $\mathcal{C}_7'$ and $\mathcal{C}_7^{\rm NP}$

If both $\mathcal{O}_7$ and $\mathcal{O}_7'$ are switched on:

$$\text{Num}(A_T^{(2)}) \sim \left[\left(\frac{2m_b M_B}{q^2}\mathcal{C}_7^{(\text{eff})} + \mathcal{C}_9\right)|\mathcal{C}_7'|\cos\phi_7' + \frac{2m_b M_B}{q^2}|\mathcal{C}_7'||\mathcal{C}_7^{\rm NP}|\cos(\phi_7' - \phi_7^{\rm NP})\right]$$

$$\text{Num}(A_{FB}) \sim 4\,\mathcal{C}_{10}\left[\left(\frac{2m_b M_B}{q^2}\mathcal{C}_7^{(\text{eff})} + \mathcal{C}_9\right) + \frac{2m_b M_B}{q^2}|\mathcal{C}_7^{\rm NP}|\cos\phi_7^{\rm NP}\right]$$





a: $(0.26e^{-i\frac{7\pi}{16}}, -0.2)$

b: $(0.26e^{-i\frac{3\pi}{5}}, 0.3e^{-i\frac{3\pi}{5}})$

c: $(-0.03, -0.07)$

- $\mathbf{A_{FB}}$ **only** protected from SFF at $q_0^2 \simeq 4\,\text{GeV}^2$. Has a **mild** sensitivity to $\mathcal{C}_7'$.
- $\mathbf{A_T^{(2)}}$ **protected** from SFF in $1 \leq q^2 \leq 6\,\text{GeV}^2$. Displays the same q_0^2. Has a **strong** sensitivity to $\mathcal{C}_7'$.

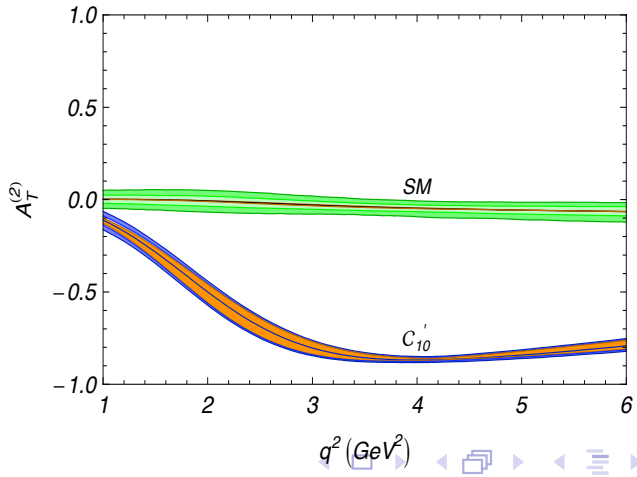
$A_T^{(2)}$: large recoil expression for $\mathcal{C}'_{10}$

$A_T^{(2)}$ may serve also as an excellent test of $\mathcal{O}'_{10}$ if switched on. In the large recoil limit

$$A_T^{(2)} = \frac{2\,\mathcal{C}_{10}|\mathcal{C}'_{10}|\cos\phi'_{10}}{{\mathcal{C}_{10}}^2 + |\mathcal{C}'_{10}|^2 + \left(2m_b M_B \mathcal{C}_7^{(\mathrm{eff})}/q^2 + \mathcal{C}_9\right)^2}$$

- $A_T^{(2)}$ shows a linear dependence on $\mathcal{C}'_{10}$ (like for $\mathcal{C}'_7$).
- The NP q^2-dependence is different:
  - it does not have a zero;
  - it has a maximum around q_0^2.

All uncertainties included:
Green $\rightarrow$ SM
Orange/Blue $\rightarrow \mathcal{C}'_{10} = 3e^{i\pi/8}$



Measuring $A_T^{(2)}$ with low luminosity

$A_T^{(2)}$ (together with F_L, A_{FB} and A_{im}) could be measured already before the one-year shutdown in 2011 using projection fits

$$\begin{aligned}
\frac{d^2\Gamma}{dq^2 d\phi} &= \frac{d\Gamma}{dq^2}\frac{1}{2\pi}\left(1+\frac{1}{2}(1-F_L)A_T^{(2)}\cos 2\phi + A_{im}\sin 2\phi\right), \\
\frac{d^2\Gamma}{dq^2 d\theta_\ell} &= \frac{d\Gamma}{dq^2}\left(\frac{3}{4}F_L\sin^2\theta_\ell + \frac{3}{8}(1-F_L)(1+\cos^2\theta_\ell) + A_{FB}\cos\theta_\ell\right)\sin\theta_\ell, \\
\frac{d^2\Gamma}{dq^2 d\theta_K} &= \frac{d\Gamma}{dq^2}\frac{3}{4}\left(2F_L\cos^2\theta_K + (1-F_L)\sin^2\theta_K\right)\sin\theta_K.
\end{aligned}$$

- These fits can be performed with data binned in q^2.
- However, the sensitivity to $A_T^{(2)}$ **is reduced** by $(1-F_L)$ in the region where $F_L \simeq 1$.

A new observable: $A_T^{(5)}$

Definition:

$$A_T^{(5)} = \frac{|A_{\perp L} A_{\parallel R}^* + A_{\perp R}^* A_{\parallel L}|}{|A_\perp|^2 + |A_\parallel|^2}$$

(1) There is no angular coefficient J_i mixing L/R with $\perp/\parallel$ simultaneously $\Rightarrow$ **symmetries** can be used to obtain

$$A_T^{(5)}\Big|_{m_\ell=0} = \frac{\sqrt{16 {J_1}^s{}^2 - 9 {J_6}^s{}^2 - 36({J_3}^2 + {J_9}^2)}}{8 {J_1}^s}.$$

(2) For the SM, in the large recoil limit:

$$A_T^{(5)}\Big|_{SM} \simeq \frac{\left|-\mathcal{C}_{10}^2 + (2 m_b M_B \mathcal{C}_7^{\rm eff}/q^2 + \mathcal{C}_9)^2\right|}{2\left[\mathcal{C}_{10}^2 + (2 m_b M_B \mathcal{C}_7^{\rm eff}/q^2 + \mathcal{C}_9)^2\right]}.$$

- Maximum of $A_T^{(5)}$ at LO given by $-\mathcal{C}_9 = 2 m_b M_B \mathcal{C}_7^{(\rm eff)}/q_0^2$ $\Rightarrow$ **same** as A_{FB} zero; $A_T^{(5)}(q_0^2) = 1/2$ (LO and NLO).
- Minimum of $A_T^{(5)}$ at LO : $-\mathcal{C}_{10}^2 = (2 m_b M_B \mathcal{C}_7^{(\rm eff)}/q_1^2 + \mathcal{C}_9)^2$ $\Rightarrow$ **new relation**.

A new observable: $A_T^{(5)}$

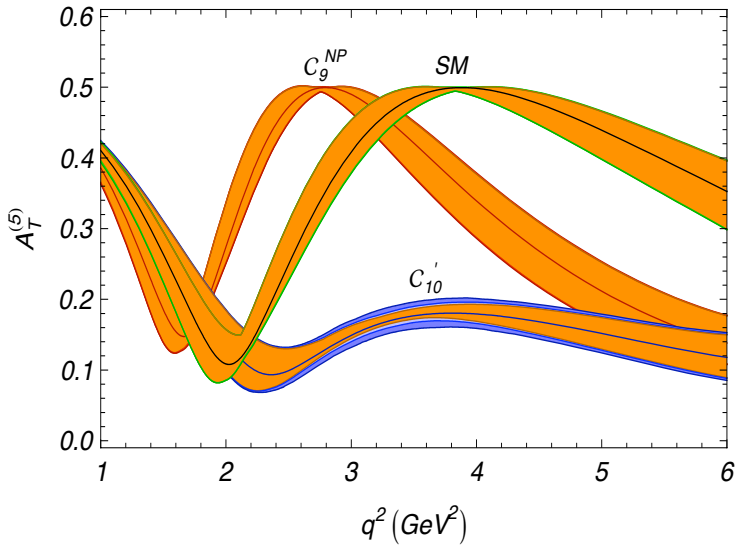
$A_T^{(5)}$ has weaker sensitivity to $\mathcal{C}_7'$ than $A_T^{(2)}$ but can display bigger departures from SM behaviour in $\mathcal{C}_9$, $\mathcal{C}_{10}$ and $\mathcal{C}_{10}'$.

In the large recoil limit, with NP entering only in $\mathcal{O}_{10}'$

$$A_T^{(5)}\Big|_{10'} \simeq \frac{\left|-\mathcal{C}_{10}^2+|\mathcal{C}_{10}'|^2+(2m_b M_B \mathcal{C}_7^{\rm eff}/q^2+\mathcal{C}_9)^2\right|}{2\left[\mathcal{C}_{10}^2+|\mathcal{C}_{10}'|^2+(2m_b M_B \mathcal{C}_7^{\rm eff}/q^2+\mathcal{C}_9)^2\right]}.$$

- Minimum of $A_T^{(5)}$ at LO:
  $|\mathcal{C}_{10}'|^2 = \mathcal{C}_{10}^2-(2m_b M_B \mathcal{C}_7^{\rm eff}/q^2+\mathcal{C}_9)^2$.
- If $|\mathcal{C}_{10}'| < |\mathcal{C}_{10}|$

  $\Delta(\max_{\rm SM}, \max_{\mathcal{O}_{10}'}) = \dfrac{|\mathcal{C}_{10}'|^2}{\mathcal{C}_{10}^2+|\mathcal{C}_{10}'|^2}$.



The transverse-longitudinal asymmetries $A_T^{(3)}$ and $A_T^{(4)}$

These observables test the longitudinal spin amplitude A_0 in a protected way.

$$A_T^{(3)} = \frac{|A_{0L}A_{\parallel L}^* + A_{0R}^* A_{\parallel R}|}{\sqrt{|A_0|^2|A_\perp|^2}} \qquad A_T^{(4)} = \frac{|A_{0L}A_{\perp L}^* - A_{0R}^* A_{\perp R}|}{|A_{0L}A_{\parallel L}^* + A_{0R}^* A_{\parallel R}|}$$

- Constructed to cancel both $\xi_\perp(0)$ and $\xi_\parallel(0)$ dependence at LO.
- Invariant under massless symmetries and offering high experimental resolution.
- Built in such way that they offer different sensitivity to NP :
  - $A_T^{(3)}$ exhibits a minimum $\rightarrow$ maximum of $A_T^{(4)}$,
  - $A_T^{(4)}$ exhibits a minimum $\rightarrow$ maximum of $A_T^{(3)}$.
- Can be used, together with $A_T^{(2)}$ and $A_T^{(5)}$, to disentangle NP entering in different Wilson coefficients.

Conclusions

- The method used to construct QCD-protected observables for the exclusive 4-body B-meson decay $\bar{B}_d \to \bar{K}^{*0}(\to K\pi)\ell^+\ell^-$ in the low dilepton mass region has been presented.
- The study of the angular distribution's symmetries allows
  - to construct non-trivial observables,
  - to extract hidden dependences between angular coefficients.
- NP sensitivities of $A_T^{(2)}$ and $A_T^{(5)}$ have been explored in depth
  - $A_T^{(2)}$ emerges as an improved version of A_{FB}.
  - $A_T^{(2)}$ could be obtained with data taken before LHC shutdown.
  - The combined analysis of $A_T^{(i)}$ $(i = 1, ..., 5)$ together with A_{FB} may help in disentangling NP contributions to each Wilson coefficient.

*All Wilson coefficient values used are compatible with those in arXiv:0805.2525.

Backup slides

Hadronic matrix elements

The hadronic matrix elements involved in the $\bar{B}_d \to \bar{K}^{*0}\ell^+\ell^-$ decay are:

$$\langle K^*(p_{K^*})|\bar{s}\gamma_\mu P_{L,R} b|B(p)\rangle = i\epsilon_{\mu\nu\alpha\beta}\epsilon^{\nu *} p^\alpha q^\beta \frac{V(q^2)}{m_B + m_{K^*}} \mp$$

$$\mp \frac{1}{2}\Bigg\{ \epsilon^*_\mu (m_B + m_{K^*}) A_1(q^2) - (\epsilon^* \cdot q)(2p-q)_\mu \frac{A_2(q^2)}{m_B + m_{K^*}} -$$

$$- \frac{2m_{K^*}}{q^2}(\epsilon^* \cdot q)\left[A_3(q^2) - A_0(q^2)\right] q_\mu \Bigg\},$$

$$\langle K^*(p_{K^*})|\bar{s} i\sigma_{\mu\nu} q^\nu P_{R,L} b|B(p)\rangle = -i\epsilon_{\mu\nu\alpha\beta}\epsilon^{\nu *} p^\alpha q^\beta T_1(q^2) \pm$$

$$\pm \frac{1}{2}\Bigg\{ \left[\epsilon^*_\mu (m_B^2 - m_{K^*}^2) - (\epsilon^* \cdot q)(2p-q)_\mu\right] T_2(q^2) +$$

$$+ (\epsilon^* \cdot q)\left[q_\mu - \frac{q^2}{m_B^2 - m_{K^*}^2}(2p-q)_\mu\right] T_3(q^2) \Bigg\}.$$

Physical meaning of the $\bar{K}^{*0}$ spin amplitudes

The $\bar{K}^{*0}$ spin amplitudes ($A_{0,\perp,\parallel}$) are related to the helicity amplitudes ($H_{0,\pm}$) by

$$A_0 = H_0, \qquad A_{\perp,\parallel} = \frac{H_+ \mp H_-}{\sqrt{2}}.$$

In the limit $m_B \to \infty$ and $E_{K^*} \to \infty$, the left-handed structure of weak interactions in the SM guarantees:

$$h(s) = -\tfrac{1}{2} \text{ in the transition } b \to s \text{ (in the limit } m_s \to 0)$$

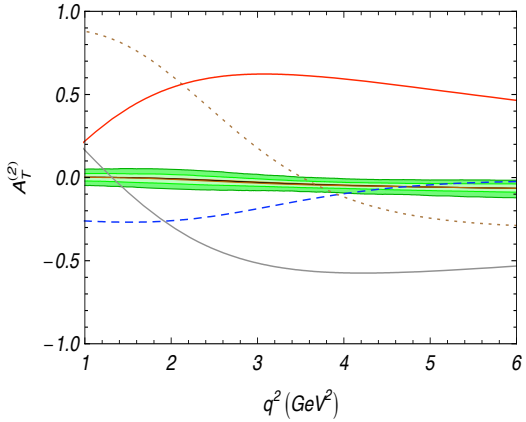
This s quark combines with the d quark of the $\bar{B}_d$ meson to form the $\bar{K}^{*0}$ meson, so

$$h(\bar{K}^{*0}) = -1, 0 \text{ but } \textbf{not } +1$$

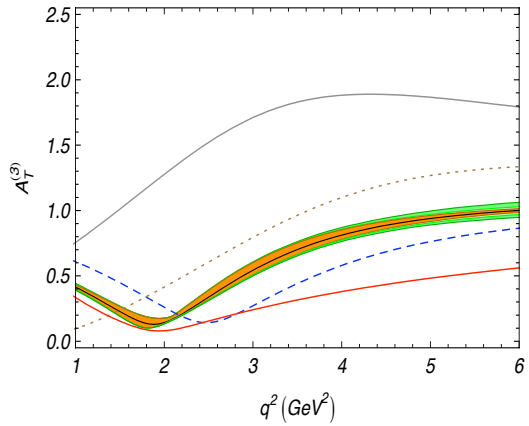
Thus, at quark level $H_+ = 0 \Rightarrow A_\perp = -A_\parallel$ and $A_\perp \approx -A_\parallel$ at hadron level.

Example: flip sign solution of $\mathcal{C}_7^{(\mathrm{eff})}$

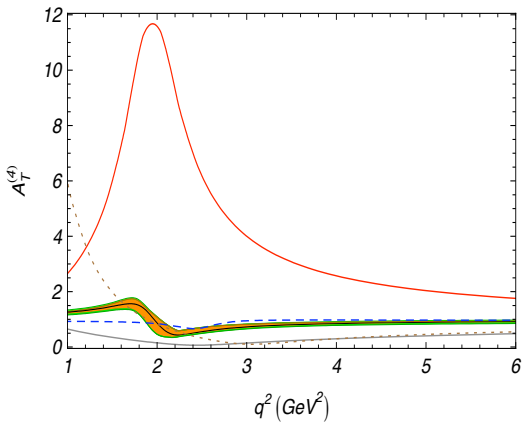
The red line corresponds to the flipped sign solution $(\mathcal{C}_7^{\mathrm{eff}}, \mathcal{C}_7'^{\mathrm{eff}}) = (0.04, 0.32)$:



No zero in $A_T^{(2)}$



Minimum invisible



Sizeable peak

However, it may be difficult to distinguish this flipped solution from NP appearing, for instance, in $\mathcal{C}_{10}' = 3e^{i\frac{7\pi}{8}}$.

Forward-backward asymmetry and longitudinal polarisation fraction

The forward-backward asymmetry (A_{FB}) of the dilepton pair is defined as

$$A_{FB} = \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_\ell \frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} \Big/ \frac{d\Gamma}{dq^2}.$$

In the massless limit without scalars this expression simplifies into

$$A_{FB} = \frac{3}{2}\frac{\mathrm{Re}(A_{\parallel L}A^*_{\perp L}) - \mathrm{Re}(A_{\parallel R}A^*_{\perp R})}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}.$$

On the other hand, the $\bar{K}^{*0}$ longitudinal polarisation fraction (F_L) is

$$F_L = |A_0|^2 \Big/ \frac{d\Gamma}{dq^2},$$

which, in the massles limit without scalars, reduces to

$$\frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}.$$