# $B \to K^* \ell^+ \ell^-$ decay at the low-$q^2$ endpoint

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# The interest of the $B \to K^* \ell^+ \ell^-$ low-$q^2$ endpoint

**Sensitivity to "wrong-helicity" photons at $q^2 \simeq 0$**

$$\mathcal{O}_7' = \frac{e}{4\pi^2}\,\hat{m}_b\,\bar{s}\sigma_{\mu\nu}P_L F^{\mu\nu}b$$

vs.

$$\mathcal{O}_7 = \frac{e}{4\pi^2}\,\hat{m}_b\,\bar{s}\sigma_{\mu\nu}P_R F^{\mu\nu}b$$

- The contribution of $\mathcal{O}_7^{(\prime)}$ is enhanced by $1/q^2$
  **Sensitivity to BSM right-handed FCNC?**
  Melikhov, Nikitin & Simula'98, ... Lunghi&Matias'06, Becirevic *et al.*'12
- **Hadron (light resonances) pollution in the observables?**
  Beneke, Feldmann & Seidel (BFS)'01

## Our Goal:

- Discuss cleanness around the low-$q^2$ end-point
- Estimate uncertainties

# Anatomy of the hadronic uncertainties

- Schematically and up to $\alpha_{\rm e.m.}^2$

$$\mathcal{A}(\bar{B}\to V\ell^-\ell^+) = \sum_i C_i\langle\ell^-\ell^+|\bar{l}\Gamma_i l|0\rangle\langle V|\bar{s}\Gamma_i' b|\bar{B}\rangle + \frac{e^2}{q^2}\langle\ell^-\ell^+|\bar{l}\gamma^\mu l|0\rangle F.T.\langle V|T(j_{\mu,\rm em}^{\rm had}(x)\mathcal{H}_W^{\rm had}(0))|\bar{B}\rangle$$

- We have the following contributions

$$\mathcal{A}\propto C_9\,\langle K^*(k)|(\bar{s}\gamma^\mu P_L b)|B(p)\rangle\times\langle\ell^+\ell^-|\bar{\ell}\gamma_\mu\ell|0\rangle$$

$$\mathcal{A}\propto\frac{1}{q^2}C_7\,\langle K^*(k)|(\bar{s}\sigma^{\mu\nu}q_\nu P_R b)|B(p)\rangle\times\langle\ell^+\ell^-|\bar{\ell}\gamma_\mu\ell|0\rangle$$

Hadronic matrix elements parameterized by **7** $q^2$ functions: **form factors**

- At large $q^2\simeq(m_B-m_{K^*})^2$ the form factors can be calculated in **LQCD**
- At low $q^2$ the form factors can be calculated in **LCSRs** and models

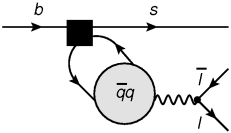
- The FFs are the major source of uncertainty in the treatment of exclusive $B$ decays

# Anatomy of the hadronic uncertainties

- Schematically and up to $\alpha^2_{\rm e.m.}$

$$\mathcal{A}(\bar{B} \to V \ell^- \ell^+) = \sum_i C_i \langle \ell^- \ell^+ | \bar{l} \Gamma_i l | 0 \rangle \langle V | \bar{s} \Gamma'_i b | \bar{B} \rangle + \frac{e^2}{q^2} \langle \ell^- \ell^+ | \bar{l} \gamma^\mu l | 0 \rangle F.T. \langle V | T(j^{\rm had}_{\mu,{\rm em}}(x) \mathcal{H}^{\rm had}_W(0)) | \bar{B} \rangle$$

- Non-local contribution from the contraction of $\mathcal{H}^{\rm had}_W$ with the EM current




$$\mathcal{A}^{(\rm had)} \propto \int d^4 y e^{iq\cdot y} \langle \bar{K}^* | j^{\rm em,had,\mu}(y) \mathcal{H}^{\rm had}(0) | \bar{B} \rangle$$

C. Bobeth

- At low $q^2 \leq 1$ GeV$^2$ one can treat this object in **QCDF** up to $\Lambda/m_b$ corrections
- Below $q^2 \simeq 1$ GeV$^2$ one can have uncontrolled contributions from light resonances
  **This region is usually cut off from phenomenological analysis**

# Anatomy of the hadronic uncertainties

- Schematically and up to $\alpha_{\mathrm{e.m.}}^2$

$$\mathcal{A}(\bar{B} \to V\ell^-\ell^+) = \sum_i C_i \langle \ell^-\ell^+|\bar{l}\Gamma_i l|0\rangle\langle V|\bar{s}\Gamma'_i b|\bar{B}\rangle + \frac{e^2}{q^2}\langle \ell^-\ell^+|\bar{l}\gamma^\mu l|0\rangle F.T.\langle V|T(j_{\mu,\mathrm{em}}^{\mathrm{had}}(x)\mathcal{H}_W^{\mathrm{had}}(0))|\bar{B}\rangle$$

Re-assess hadronic uncertainties to the $B \to K^*\ell^+\ell^-$ decay at low $q^2$

- Hadronic parameters (**form factors**)
  - **QCDf** + estimated power-corrections BFS'01, Egede *et al.*'08
  - Theoretical prediction (LCSRs) Altmannshofer *et al.*'09, Ball&Zwicky'05
- Non-local contribution from $\mathcal{H}_W^{\mathrm{had}}$ in **QCDf**
  - Non-factorizable charm-loop effects BFS'01, Khodjamiran *et al.*'10
  - Non-factorizable chromomagnetic-penguin effects Dimou et *al.*
  - Non-factorizable light-quark effects BFS'01

# Connecting with the experimental data: The helicity amplitudes

- Helicity decomposition

$$\mathcal{A} = -\sum_{\lambda=\pm1,0} \mathcal{L}_V(\lambda) H_V(\lambda) - \sum_{\lambda=\pm1,0} \mathcal{L}_A(\lambda) H_A(\lambda) + L_P H_P$$

$$L_V^\mu = \langle \ell^+ \ell^- | \bar{l} \gamma^\mu l | 0 \rangle,\ L_A^\mu = \langle \ell^+ \ell^- | \bar{l} \gamma^\mu \gamma^5 l | 0 \rangle,\ L_P = \langle \ell^+ \ell^- | \bar{l} \gamma^5 l | 0 \rangle$$

- Helicity amplitudes $\lambda = \pm 1, 0$

$$H_V(\lambda) = -iN \Big\{ C_{9V} \tilde{V}_{L\lambda} + C'_{9V} \tilde{V}_{R\lambda} - \frac{m_B^2}{q^2} \Big[ \frac{2\,\hat{m}_b}{m_B} ( C_{7\gamma} \tilde{T}_{L\lambda} + C'_{7\gamma} \tilde{T}_{R\lambda} ) - 16\pi^2 h_\lambda \Big] \Big\},$$

$$H_A(\lambda) = -iN ( C_{10A} \tilde{V}_{L\lambda} + C'_{10A} \tilde{V}_{R\lambda} ),$$

$$H_P = iN \frac{2\, m_l \hat{m}_b}{q^2} C_{10A} \left( \tilde{S}_L + \frac{m_s}{m_b} \tilde{S}_R \right)$$

- **Short-range:** Wilson coefficients
- **Long-range (QCD):** FFs and the non-local piece $h_\lambda$

# Form Factors

$$\begin{aligned} -im_B V_\lambda(q^2) &= \langle M(\lambda)|\bar{s}\not\epsilon^*(\lambda)P_L b|\bar{B}\rangle, \\ m_B^2 T_\lambda(q^2) &= \epsilon^{*\mu}(\lambda)q^\nu \langle M(\lambda)|\bar{s}\sigma_{\mu\nu}P_R b|\bar{B}\rangle, \\ im_B S(q^2) &= A\,\langle M(\lambda=0)|\bar{s}P_R b|\bar{B}\rangle. \end{aligned}$$

Bharucha it et al., Jäeger and JMC

- $T_\pm$ related to $T_{1,2}$, $T_0$ related to $T_{2,3}$
- $V_\pm$ related to $V$, $A_1$ and $V_0$ to $A_{1,2}$, $S$ related to $A_0$
- The form factors in the helicity basis verify

$$T_+(0) = 0, \qquad V_0(0) = S(0)$$

- **Moreover**, in the **heavy-quark** and **large-recoil** ($K^*$) limit (Charles *et al.* '99) The **7** $B \to K^*$ FFs to **2** soft form factors $\xi_\parallel(q^2)$ and $\xi_\perp(q^2)$:

$$T_- = V_- = \frac{2E}{m_B}\xi_\perp, \qquad T_0 = V_0 = S = \frac{E}{m_{K^*}}\xi_\parallel$$
$$T_+ = V_+ = 0$$

- Thus

$$\begin{aligned} T_+(q^2) &= \mathcal{O}(q^2) \times \mathcal{O}(\Lambda/m_b), \\ V_+(q^2) &= \mathcal{O}(\Lambda/m_b). \end{aligned}$$

- We fix (for numerics) $\xi_\perp(0)$ with $\mathcal{B}(\bar{B}^0 \to K^{*0}\gamma)_{\rm expt}$ and $C_7^{\rm SM}$ (BFS'01)
- We fix $\xi_\parallel(0)$ using (normalized) theoretical predictions on $A_0$

$$\xi_\perp(0) = T_1(0) = 0.275(26), \qquad \xi_\parallel(0) = \frac{2m_{K^*}}{m_B} A_0(0) = 0.09(2)$$

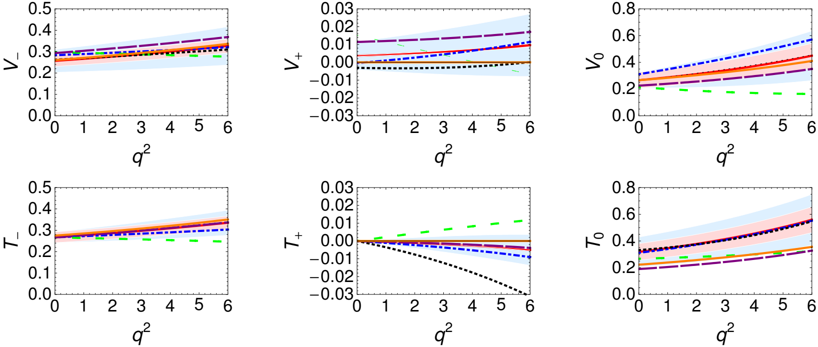
- These relations receive **calculable** $\alpha_s$ **corrections** and **unknown** $\Lambda/m_b$ corrections
  Beneke et al. '01
  We model $\Lambda/m_b$ corrections

$$F^{\rm p.c.,\pm} = \pm a_F \pm b_F \frac{q^2}{m_B^2}$$

$T_+(q^2)$ has a negligible uncertainty at low $q^2$ ($a_{T_+} \equiv 0$!)

# Factorizable power-corrections

- Power corrections to the HQ-LE relations $a_F$ and $b_F$≡spread of th.predictions

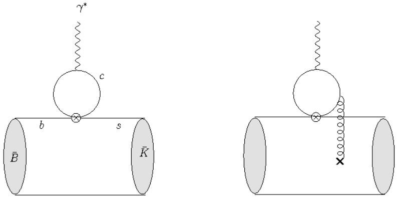



- **Light-cone SRs** (Ball&Zwicky'05, Khodjamirian *et al.*'10)
- **QCD SRs** (Colangelo *et al.*'96)
- **Dyson-Schwinger** (Ivanov *et al.*'07)

# Long-distance charm-loop contribution

- The non-local charm contributions can be important away from the $c\bar{c}$ threshold
  Khodjamirian *et al.*'10

$$\mathcal{H}_W^{c\bar{c}} = -\frac{G_F}{\sqrt{2}} V_{cs}^* V_{cb} (C_1\, Q_1 + C_2\, Q_2)$$




- The LHS diagram and $\alpha_s$ corrections are treated in **QCDF** (Beneke *et al.*'01)
  One finds $h_{+|c\bar{c},\mathrm{QCDSF}} \sim \mathcal{O}(\frac{\Lambda}{m_b})$
- Long-distance contribution in **LCSRs**: $h_{+|c\bar{c},\mathrm{LD}} \sim \mathcal{O}(\frac{\Lambda}{m_b})\, h_{-|c\bar{c},\mathrm{LD}}$!!
  **Next talk by S. Jäger**
- This suppression of the helicity " + " is extensible to the nonlocal contributions of the chromomagnetic operator

# Long-distance light-quark contribution (vector resonances)

- Light-quark conts. are double CKM-suppressed or weighed by small QCD penguins
- **However**, at low $q^2$ one can have uncontrolled long-distance contributions from e.g. light resonances

$$a_\mu^{\mathrm{had,\,l-q}} = \int d^4x\, e^{-iq\cdot x} \langle K^* | T\{ j_\mu^{\mathrm{em,\,l-q}}(x),\, H_W^{\mathrm{had}}(0)\} | B\rangle$$

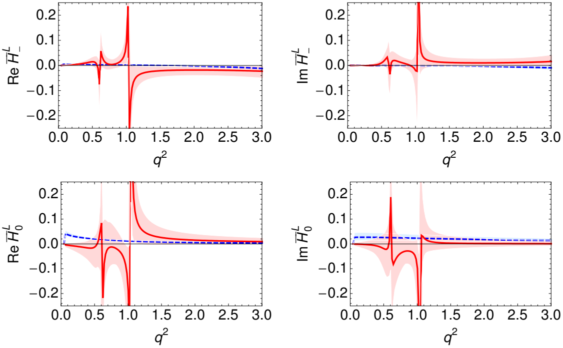
$$a_\mu^{\mathrm{had,\,l-q}} \approx \int d^4x\, e^{-iq\cdot x} \sum_{P,P'} \langle 0 | j_\mu^{\mathrm{em,\,l-q}}(x) | P'\rangle \langle P'(x) | P(0)\rangle \langle K^* P | \, H_W^{\mathrm{had}}(0) | B\rangle$$

- We assume **Vector-Meson Dominance** $P,\ P' \equiv \rho^0,\ \omega,\ \phi$ (Korchin *et al.*'10)
  - $\langle 0 | j_\mu^{\mathrm{em,\,l-q}}(x) | P'\rangle \equiv f_V$
  - $\langle P'(x) | P(0)\rangle \equiv$(Dressed) $V$ propagator
  - $\langle K^* P | \, H_W^{\mathrm{had}}(0) | B\rangle \equiv B \to V K^{*0}$ computed in **QCDF** (Beneke *et al.*'06*)
- We treat these contributions as **uncertainties**

* **QCDf** predictions are consistent within errors with experimental data

$$H^{0,\pm}_{\mathrm{sl},\,L,R} = \frac{\alpha_{\mathrm{em}}\; G_F\; \lambda}{2\sqrt{2}} \overbrace{\frac{8\pi\; Q_V\; f_{K^*}\; f_V}{\left(q^2 - m_V^2 + i m_V \Gamma_V\right)}}^{F(q^2)} \left(\frac{m_B}{m_V}\right) H_V^{0,\pm}$$

- $H_V^{0,\pm}$ *CKM* suppressed or hadronic-penguin dominated: $\lambda \sim \mathcal{O}(0.01)$
- However in $\sqrt{q^2} \sim m_V$ and $\Gamma_{\phi,\omega} \sim 1$ MeV$\rightarrow$ $F(q^2)$ is $\sim \mathcal{O}(100)$



- **V−A structure of the hadronic weak decays**

$$H_V^0 : H_V^- : H_V^+ = 1 : \frac{\Lambda}{m_b} : \left(\frac{\Lambda}{m_b}\right)^2$$

- Suppression of the $H_+$ amplitude is seen experimentally in angular analysis of $B \to K\phi$ (but not of $H_-$!)

- **Binned results** s

$$\begin{aligned} |\mathcal{M}_{\mathrm{T}}|^2 &= |\mathcal{M}|^2 + \lambda^2 F(q^2)^2 |\mathcal{M}'|^2 \\ &+ 2\lambda F(q^2) \left\{ (q^2 - m_V^2) \mathrm{Re}[\mathcal{M}^* \mathcal{M}'] + m_V \Gamma_V \mathrm{Im}[\mathcal{M}^* \mathcal{M}'] \right\} \end{aligned}$$

  - Contribution in $q^2$-integrals is suppressed by $\sim m_V \Gamma_V / \Delta q^2$ ($m_{\omega\phi} \Gamma_{\omega,\phi} \sim 0.005$ GeV$^2$)

- Hadronic contributions
  - **Do not pollute $H_+$!**
  - **Get diluted in binned results!**

# In summary so far ...

- Heavy-quark/high energy limit **QCDF** recovers the naïve expectation that $H_+ = 0$ (for the $\bar{B}$ decay) Burdman and Hiller'01, Beneke *et al.*'01
  - $V - A$ creates helicity $-1/2$ ($\sim$massless) $s$-quarks
  - Perturbative QCD corrections don't change helicity

1. This is realized in the form factors

$$T_+(q^2) = \mathcal{O}(q^2) \times \mathcal{O}(\Lambda/m_b),$$
$$V_+(q^2) = \mathcal{O}(\Lambda/m_b).$$

2. But also on potentially sizable long-distance $c\bar{c}$
   - **LCSRs** give $|h_{-|c\bar{c},\mathrm{LD}}| \sim 7\%\ C_7^{\mathrm{eff,SM}}$ Khodjamirian *et al.*'10
   - We found that in **LCSRs** $h_{+|c\bar{c},\mathrm{LD}} \sim \mathcal{O}(\Lambda/m_b) h_{-|c\bar{c},\mathrm{LD}}$ Jäeger and JMC'12
   - We model the long-distance charm contribution at the level of the amplitude as

$$\delta h_{-|c\bar{c},\mathrm{LD}} = 0.1 e^{i\,\phi_-} C_7^{\mathrm{eff,SM}}, \qquad \delta h_{+|c\bar{c},\mathrm{LD}} = 0.02 e^{i\,\phi_+} C_7^{\mathrm{eff,SM}}$$

3. And also the long-distance light quark contributions $H_+^V \sim \mathcal{O}(\Lambda^2/m_b^2)$

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$$

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# SM predictions on the angular coefficients $I_i$ for the $\mu$-mode

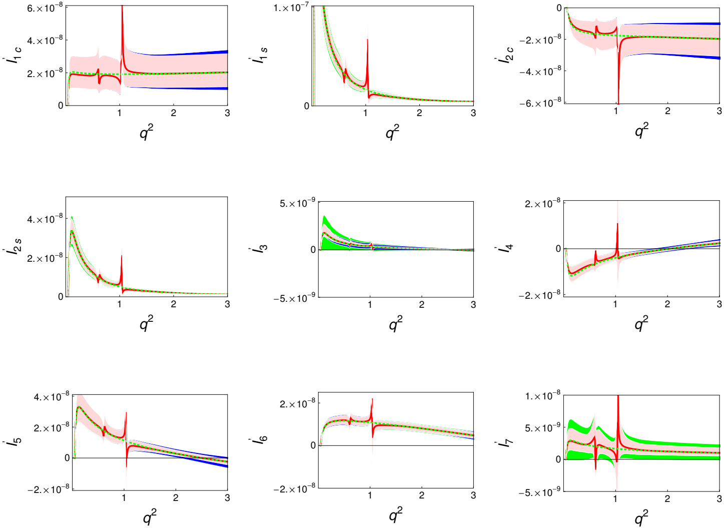


Figure: Red: soft-form factors; blue: factorizable power corrections; green : non-local charm-loop.

# A "clean" set of observables

- One can use ratios of $I_i's$ to reduce theoretical uncertainties
  Kruger et al '05
- The $P$-basis is composed by the combinations
  Matias *et al.*, Decotes-Genon *et al.* '12

$$P_1 = \frac{I_3}{2I_{2s}}, \qquad P_2 = \frac{I_6}{8I_{2s}}, \qquad P_3 = -\frac{I_9}{4I_{2s}},$$

$$P'_4 = \frac{I_4}{\sqrt{-I_{2s}I_{2c}}}, \qquad P'_5 = \frac{I_5}{2\sqrt{-I_{2s}I_{2c}}}, \qquad P'_6 = -\frac{I_7}{2\sqrt{-I_{2s}I_{2c}}}.$$

plus

$$\Gamma' = \frac{d\Gamma + d\bar{\Gamma}}{dq^2} = \frac{1}{4}\left((3I_{1c} - I_{2c}) + 2\,(3I_{1s} - I_{2s})\right)$$

$$F_L = \frac{3I_{1c} - I_{2c}}{4\Gamma'},$$

- These observables are defined such that $\xi_\perp$ and $\xi_\|$ factor out
- **However** these are still prone to $\Lambda/m_b$ uncertainties

# SM predictions for the $P$-basis and the $\mu$-mode

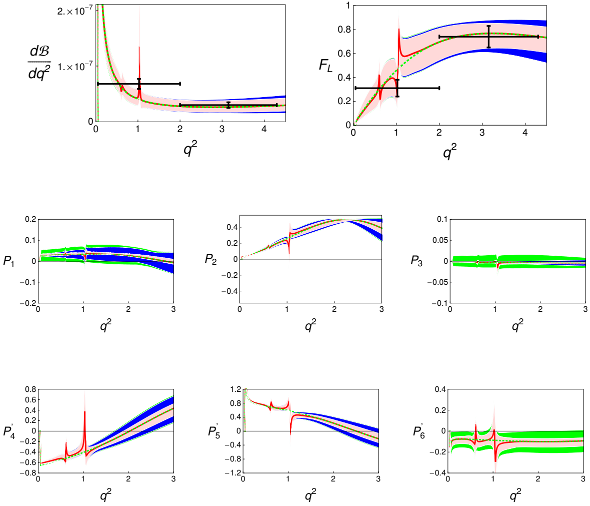


Figure: Red: soft-form factors; blue: factorizable power corrections; green : non-local charm-loop. Data from LHCb-CONF-2012-008

Table: Results and error budget on the binned CP-averaged observables of the muonic mode.

| Obs. | $[q^2_{min}, q^2_{max}]$ | Result | Hadronic | Fact. | $c$-quark | Light-quark |
|---|---|---|---|---|---|---|
| $10^7 \times \langle \frac{d\mathcal{B}}{dq^2} \rangle$ | [0.1, 1] | $0.81^{+0.23}_{-0.20}$ | $^{+0.20}_{-0.17}$ | $^{+0.03}_{-0.03}$ | $^{+0.10}_{-0.10}$ | $\pm 0.00$ |
| | [0.1, 2] | $1.13^{+0.39}_{-0.38}$ | $^{+0.36}_{-0.24}$ | $^{+0.08}_{-0.07}$ | $^{+0.13}_{-0.12}$ | $\pm 0.02$ |
| | [2, 4.3] | $0.62^{+0.33}_{-0.26}$ | $^{+0.27}_{-0.21}$ | $^{+0.19}_{-0.15}$ | $^{+0.02}_{-0.01}$ | $\pm 0.00$ |
| | [1, 6] | $1.5^{+0.8}_{-0.6}$ | $^{+0.6}_{-0.5}$ | $^{+0.46}_{-0.37}$ | $^{+0.05}_{-0.05}$ | $\pm 0.02$ |
| $10^2 \times \langle P_1 \rangle$ | [0.1, 1] | $2.9^{+3.2}_{-3.1}$ | $^{+0.8}_{-0.1}$ | $^{+1.2}_{-1.3}$ | $^{+2.9}_{-2.8}$ | $\pm 0.0$ |
| | [0.1, 2] | $3.0^{+3.5}_{-3.4}$ | $^{+0.8}_{-0.2}$ | $^{+1.7}_{-1.7}$ | $^{+2.9}_{-2.9}$ | $\pm 0.1$ |
| | [2, 4.3] | $-1.0^{+7}_{-5}$ | $^{+1.6}_{-0.8}$ | $^{+7}_{-5}$ | $^{+1.8}_{-1.6}$ | $\pm 0.0$ |
| | [1, 6] | $-2^{+8}_{-6}$ | $^{+1.3}_{-0.8}$ | $^{+8}_{-6}$ | $^{+1.6}_{-1.4}$ | $\pm 0.0$ |
| $10 \times \langle P_2 \rangle$ | [0.1, 1] | $1.02^{+0.15}_{-0.17}$ | $^{+0.08}_{-0.13}$ | $^{+0.10}_{-0.09}$ | $^{+0.08}_{-0.07}$ | $\pm 0.00$ |
| | [0.1, 2] | $1.57^{+0.19}_{-0.26}$ | $^{+0.08}_{-0.20}$ | $^{+0.13}_{-0.13}$ | $^{+0.11}_{-0.10}$ | $\pm 0.04$ |
| | [2, 4.3] | $3.1^{+1.4}_{-1.6}$ | $^{+0.8}_{-0.8}$ | $^{+1.0}_{-1.2}$ | $^{+0.5}_{-0.7}$ | $\pm 0.0$ |
| | [1, 6] | $1.4^{+1.5}_{-1.5}$ | $^{+0.8}_{-0.7}$ | $^{+1.2}_{-1.1}$ | $^{+0.5}_{-0.6}$ | $\pm 0.0$ |
| $10^2 \times \langle P_3 \rangle$ | [0.1, 1] | $-0.1^{+1.5}_{-1.2}$ | $^{+0.0}_{-0.2}$ | $^{+0.1}_{-0.1}$ | $^{+1.5}_{-1.2}$ | $\pm 0.0$ |
| | [0.1, 2] | $-0.2^{+1.6}_{-1.3}$ | $^{+0.0}_{-0.2}$ | $^{+0.1}_{-0.1}$ | $^{+1.6}_{-1.2}$ | $\pm 0.0$ |
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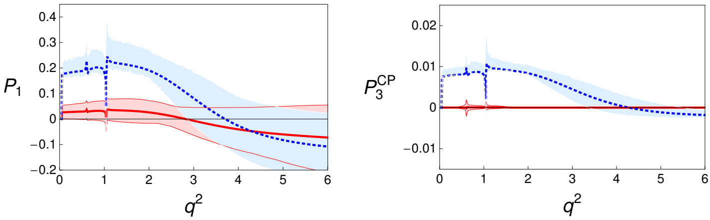
# Physics potential on constraining $C_7'$




- The observables $I_3$ and $I_9$ are proportional to

$$I_3 \propto \mathrm{Re}\left(H_+^V H_-^V\right) \propto \mathrm{Re}\left(C_7\, C_7'^*\right), \qquad I_9 \propto \mathrm{Im}\left(H_+^V H_-^V\right) \propto \mathrm{Im}\left(C_7\, C_7'^*\right),$$

  so they vanish unless $C_7' \neq 0$!!

- To study the sensitivity take the "clean" versions $P_1$ and $P_3^{CP}$ respectively
  - BSM 1: Take $C_7' = 0.1 C_7^{\mathrm{SM}}$ (left panel)
  - BSM 2: Take $C_7' = 0.01 \times i \times C_7^{\mathrm{SM}}$ (right panel)

Observables are very sensitive to BSMs contributions surfacing in $C_7'$ for $q^2 < 3$ GeV$^2$

# Conclusions

- We have re-assessed the uncertainties on $\bar{B} \to K^* \ell^+ \ell^-$ at low $q^2$
- Working in the helicity basis we have found a systematic suppression of the SM $H_+$ contributions
  - In the helicity basis the form-factors fulfill

$$\begin{aligned} T_+(q^2) &= \mathcal{O}(q^2) \times \mathcal{O}(\Lambda/m_b), \\ V_+(q^2) &= \mathcal{O}(\Lambda/m_b). \end{aligned}$$

  - This suppression extends to long-distance **charm** and **chromomagnetic penguins**
  - Implementing the experimentally-contrasted information on the $B \to VV$ **we preclude large contributions** to $H_+$ from **light resonances**
- The low-$q^2$ end-point is very well suited region for searching for BSMs ($C_7'$) $P_1$ and $P_3^{\mathrm{CP}}$ preferred observables