# Optimizing the basis of $B \to K^* l^+ l^-$ observables and understanding its tensions

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*Based on:* S. Descotes-Genon, T. Hurth, JM, J. Virto, JHEP 1305 (2013) 137
S. Descotes-Genon, JM, J. Virto, in preparation

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## PLAN of the TALK

- Why is so important the measurement of $B \to K^*(\to K\pi)l^+l^-$?
- The path towards an optimized basis of observables to describe this 4-body decay.
- First analysis of new data on $P_{1,2}$ and understanding of its tensions (**3**$\sigma$).
- Conclusions

$\Rightarrow$ In the short term the best paradigm to unveil **New Physics** will be an accurate analysis of Wilson coefficients.

- *UT* for CPV $\leftrightarrow$ *Wilson Coefficient* correlations for Rare Decays
- Wilson Coefficients are tested $C_i = C_i^{SM} + \delta\mathbf{C_i}$ $\left\{ \begin{array}{l} \text{different levels of accuracy} \\ \text{allow different ranges of NP} \end{array} \right.$

| Wilson coefficients | Observables | SM values |
|---|---|---|
| $\mathbf{C_7^{eff}}(\mu_\mathbf{b})$ | $\mathcal{B}(\bar{B} \to X_s\gamma), A_I(B \to K^*\gamma), S_{K^*\gamma}, A_{FB}, F_L$ | $-\ 0.292$ |
| $\mathbf{C_9}(\mu_\mathbf{b})$ | $\mathcal{B}(B \to X_s\ell\ell), A_{FB}, F_L$ | $4.075$ |
| $\mathbf{C_{10}}(\mu_\mathbf{b})$ | $\mathcal{B}(B_s \to \mu^+\mu^-), \mathcal{B}(B \to X_s\ell\ell), A_{FB}, F_L$ | $-4.308$ |
| $\mathbf{C_7'}(\mu_\mathbf{b})$ | $\mathcal{B}(\bar{B} \to X_s\gamma), A_I(B \to K^*\gamma), S_{K^*\gamma}, A_{FB}, F_L$ | $-0.006$ |
| $\mathbf{C_9'}(\mu_\mathbf{b})$ | $\mathcal{B}(B \to X_s\ell\ell), A_{FB}, F_L$ | 0 |
| $\mathbf{C_{10}'}(\mu_\mathbf{b})$ | $\mathcal{B}(B_s \to \mu^+\mu^-), A_{FB}, F_L$ | 0 |

High Precision Observables are necessary to disentangle NP and to overconstrain the deviations $\delta\mathbf{C_i}$ of Wilson Coefficients from SM in order to reduce allowed regions.

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| $\mathbf{C'_{10}}(\mu_\mathbf{b})$ | $\mathcal{B}(B_s \to \mu^+\mu^-), A_{FB}, F_L, P_1, P'_4$ | 0 |

High Precision Observables are necessary to disentangle NP and to overconstrain the deviations $\delta\mathbf{C_i}$ of Wilson Coefficients from SM in order to reduce allowed regions.

$\Rightarrow$ $B \to K^*(\to K\pi)\mu^+\mu^-$ fulfills the requirements by means of clean observables $P_{1,2,3}, P'_{4,5,6,8}$ improving the precision in not very accurately constrained coefficients like $C_9$ or $C'_{7,9,10}$ (soon).
New Physics in phases of Wilson Coefficients: $P_3, P'_{6,8}$.

All those observables come from the decay $\mathbf{\bar{B}_d} \to \mathbf{\bar{K}^{*0}}(\to \mathbf{K}^-\pi^+)\mathbf{l}^+\mathbf{l}^-$ with the $K^{*0}$ on the mass shell.
It is described by $s = q^2$ and three angles $\theta_\mathbf{l}$, $\theta_\mathbf{K}$ and $\phi$

$$\frac{d^4\Gamma(\bar{B}_d)}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_l, \theta_K, \phi)$$

The differential distribution splits in $J_i$ coefficients:

$$\begin{gathered} J(q^2, \theta_l, \theta_K, \phi) = \\ J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l + J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi \\ + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi + (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l \\ + J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi + J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\,. \end{gathered}$$

There is a corresponding $CP$- conjugate distribution for $\mathbf{B_d} \to \mathbf{K^{*0}}(\to \mathbf{K}^-\pi^+)\mathbf{l}^+\mathbf{l}^-$ function of $\bar{J}$.

The information on

- the transversity amplitudes of the $K^*$ $(A_{\perp,\|,0})$ is inside the coefficients $J_i$.
- short distance physics $C_i$ is encoded in $(A_{\perp,\|,0} = C_i \times \mathrm{form\,factors})$

$$J_{1s} = \frac{(2+\beta_\ell^2)}{4}\left[|A_\perp^L|^2 + |A_\|^L|^2 + (L\to R)\right] + \frac{4m_\ell^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R\,*} + A_\|^L A_\|^{R*}\right),$$

$$J_{1c} = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\ell^2}{q^2}\left[|A_t|^2 + 2\mathrm{Re}(A_0^L A_0^{R*})\right] + \beta_\ell^2|A_S|^2,$$

$$J_{2s} = \frac{\beta_\ell^2}{4}\left[|A_\perp^L|^2 + |A_\|^L|^2 + (L\to R)\right], \quad J_{2c} = -\beta_\ell^2\left[|A_0^L|^2 + (L\to R)\right],$$

$$J_3 = \frac{1}{2}\beta_\ell^2\left[|A_\perp^L|^2 - |A_\|^L|^2 + (L\to R)\right], \quad J_4 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Re}(A_0^L A_\|^{L\,*}) + (L\to R)\right],$$

$$J_5 = \sqrt{2}\beta_\ell\left[\mathrm{Re}(A_0^L A_\perp^{L\,*}) - (L\to R) - \frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_\|^L A_S^* + A_\|^R A_S^*)\right],$$

$$J_{6s} = 2\beta_\ell\left[\mathrm{Re}(A_\|^L A_\perp^{L\,*}) - (L\to R)\right], \quad J_{6c} = 4\beta_\ell\frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}\left[A_0^L A_S^* + (L\to R)\right],$$

$$J_7 = \sqrt{2}\beta_\ell\left[\mathrm{Im}(A_0^L A_\|^{L\,*}) - (L\to R) + \frac{m_\ell}{\sqrt{q^2}}\mathrm{Im}(A_\perp^L A_S^* + A_\perp^R A_S^*)\right],$$

$$J_8 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Im}(A_0^L A_\perp^{L\,*}) + (L\to R)\right], \quad J_9 = \beta_\ell^2\left[\mathrm{Im}(A_\|^{L\,*} A_\perp^L) + (L\to R)\right]$$

In red lepton mass terms ($\beta_\ell^2 = 1 - 4m_\ell^2/q^2$).

[Egede, Hurth, JM, Ramon, Reece'10]

An important step forward to find a complete description of the distribution was the identification of the **symmetries** of the distribution:

*Transformation of amplitudes leaving distribution invariant.*

**Symmetries** determine the minimal # observables for each scenario:

$$n_{obs} = 2n_A - n_S$$

| Case | Coefficients | Amplitudes | Symmetries | Observables |
|---|---|---|---|---|
| $m_\ell = 0,\ A_S = 0$ | 11 | 6 | 4 | **8** $\Leftarrow$ |
| $m_\ell = 0$ | 11 | 7 | 5 | **9** |
| $m_\ell > 0,\ A_S = 0$ | 11 | 7 | 4 | **10** |
| $m_\ell > 0$ | 12 | 8 | 4 | **12** |

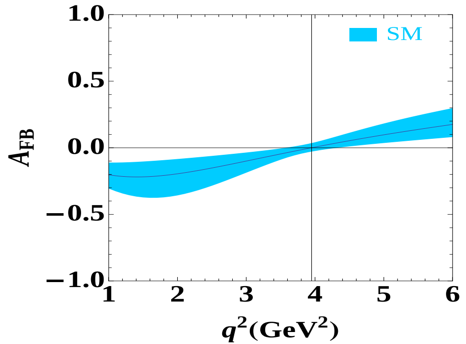
All symmetries (massive and scalars) were found explicitly later on. [JM, Mescia, Ramon, Virto'12]

**Symmetries** $\Rightarrow$ # of observables $\Rightarrow$ determine a **basis**: each angular observable constructed can be expressed in terms of this basis.

Main criteria to define this basis: **minimize the form factor sensitivity**

# The concept of clean observables

For a long time huge efforts were devoted (still now) to measure the position of the zero of the forward-backward asymmetry $A_{FB}$ of $B \to K^* \mu^+ \mu^-$.




Reason:

- At LO the soft form factor dependence $(\xi_\perp(q^2), \xi_\parallel(q^2))$ cancels exactly at the position of the zero $q_0^2$ (dependence appears at NLO).
- A relation among $\mathbf{C_9^{eff}}$ and $\mathbf{C_7^{eff}}$ arises at the zero (at LO):

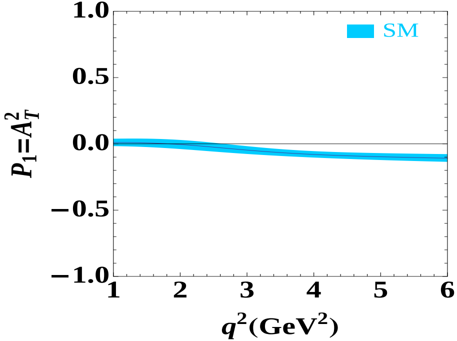
$$\mathbf{C_9^{eff}}(q_0^2) + 2\frac{m_b M_B}{q_0^2}\mathbf{C_7^{eff}} = 0$$

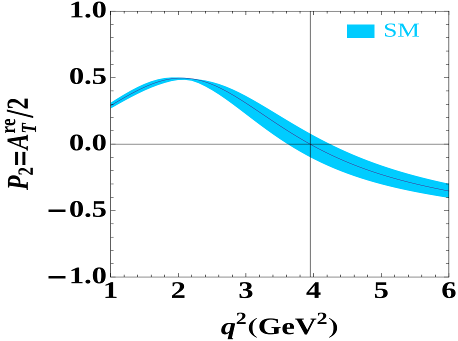
A similar idea was incorporated in the construction of the transverse asymmetry

[Kruger, J.M'05] [Becirevic et al.'12]

$$P_1 = A_T^{(2)}(q^2) = \frac{|A_\perp|^2 - |A_{||}|^2}{|A_\perp|^2 + |A_{||}|^2} \qquad P_2 = \frac{A_T^{re}}{2} = \frac{\mathrm{Re}(A_\perp^{L*} A_{||}^L - A_\perp^R A_{||}^{R*})}{|A_\perp|^2 + |A_{||}|^2}$$

where $A_{\perp,||}$ correspond to two transversity amplitudes of the $K^*$.




- Both asymmetries exhibits an exact cancellation of soft form factors **not only at a point** (like $A_{FB}$) **but in the full low-$q^2$ range** $(0.1 - 6\ \mathrm{GeV}^2)$.
- First examples of **clean** observables that could be measured.
- $A_T^{(2)}$ is constructed to detect presence of RH currents ($A_\perp \sim -A_{||}$ in the SM), $A_T^{re}$ complements (partly supersedes) $A_{FB}$ since it contains similar information, but in a theoretically better controlled way.

[Egede, Hurth, JM, Ramon, Reece'08, and '10]

- Later on a set of **transverse asymmetries** called $\mathbf{A_T^{(3,4,5)}}$ were proposed

$$\mathbf{A_T^{(3)}} = \frac{|A_0^L A_\parallel^{L*} + A_0^{R*} A_\parallel^R|}{\sqrt{|A_0|^2 |A_\perp|^2}} \quad \mathbf{A_T^{(4)}} = \frac{|A_0^L A_\perp^{L*} - A_0^{R*} A_\perp^R|}{|A_0^L A_\parallel^{L*} + A_0^{R*} A_\parallel^R|} \quad \mathbf{A_T^{(5)}} = \frac{|A_\perp^L A_\parallel^{R*} + A_\perp^{R*} A_\parallel^L|}{|A_\perp|^2 + |A_\parallel|^2}$$

[Bobeth, Hiller, Dyk,'10]

- Also at the low-recoil a set of clean observables called $\mathbf{H_T^{(1,2,3)}}$ were proposed that correspond to $P_{4,5,6}$ at large-recoil.

$$\mathbf{H_T^{(1)}} = \frac{\mathrm{Re}(A_0^L A_\parallel^{L*} + A_0^{R*} A_\parallel^R)}{\sqrt{|A_0|^2 |A_\parallel|^2}}, \quad \mathbf{H_T^{(2)}} = \frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^{R*} A_\perp^R)}{\sqrt{|A_0|^2 |A_\perp|^2}}, \quad \mathbf{H_T^{(3)}} = \frac{\mathrm{Re}(A_\parallel^L A_\perp^{L*} - A_\parallel^{R*} A_\perp^R)}{\sqrt{|A_\parallel|^2 |A_\perp|^2}}$$

[Altmannshofer, Ball, Bharucha, Buras, Straub, Wick'09]

- In parallel a set of CP-conserving and CP-violating observables $\mathbf{S_i}$ and $\mathbf{A_i}$ were constructed directly from the coefficients of the distribution, easy to measure but **not** following the criteria of **clean observables**:

$$\mathbf{S_i} = \frac{\int_{bin} dq^2 [J_i + \bar{J}_i]}{d\Gamma/dq^2 + d\bar{\Gamma}/dq^2}, \quad \mathbf{A_i} = \frac{\int_{bin} dq^2 [J_i - \bar{J}_i]}{d\Gamma/dq^2 + d\bar{\Gamma}/dq^2}.$$

Finally we arrived to an **Optimal Basis** of observables, a compromise between:

- *Excellent experimental accessibility and simplicity of the fit.*
- *Reduced FF dependence (in the large-recoil region:* $0.1 \leq q^2 \leq 8\ \mathrm{GeV}^2$).

Our proposal for **CP-conserving basis**:

$$\left\{ \frac{\mathbf{d\Gamma}}{\mathbf{dq^2}}, \mathbf{A_{FB}}, \mathbf{P_1}, \mathbf{P_2}, \mathbf{P_3}, \mathbf{P_4'}, \mathbf{P_5'}, \mathbf{P_6'} \right\} \text{ or } \mathbf{P_3} \leftrightarrow \mathbf{P_8'} \text{ and } \mathbf{A_{FB}} \leftrightarrow \mathbf{F_L}$$

where $P_1 = A_T^2$ [Kruger, J.M'05], $P_2 = \frac{1}{2} A_T^{\mathrm{re}}, P_3 = -\frac{1}{2} A_T^{\mathrm{im}}$ [Becirevic, Schneider'12] and $P'_{4,5,6}$ [Descotes, JM, Ramon, Virto'13]) given by

$$P_i' = \frac{1}{k_i N_i}[J_i + \bar{J}_i] \qquad N_i = \sqrt{-(J_{2s} + \bar{J}_{2s})(J_{2c} + \bar{J}_{2c})} \quad k_4 = 1, k_5 = 2, k_6 = -2$$

and the corresponding **CP-violating basis** ($J_i + \bar{J}_i \to J_i - \bar{J}_i$ in numerators):

$$\{\mathbf{A_{CP}}, \mathbf{A_{FB}^{CP}}, \mathbf{P_1^{CP}}, \mathbf{P_2^{CP}}, \mathbf{P_3^{CP}}, \mathbf{P_4'^{CP}}, \mathbf{P_5'^{CP}}, \mathbf{P_6'^{CP}}\} \text{ or } \mathbf{P_3^{CP}} \leftrightarrow \mathbf{P_8'^{CP}} \text{ and } \mathbf{A_{FB}^{CP}} \leftrightarrow \mathbf{F_L^{CP}}$$

# Computation of Primary Observables

**Large-recoil**: NLO QCDfactorization + $\mathcal{O}(\Lambda/m_b)$. Soft form factors $\xi_{\perp,\|}(q^2)$ from

$$\xi_\perp(q^2) = m_B/(m_B + m_{K^*})\mathbf{V(q^2)} \quad \xi_\|(q^2) = (m_B + m_{K^*})/(2E)\mathbf{A_1(q^2)} - (m_B - m_{K^*})/(m_B)\mathbf{A_2(q^2)}$$

- FF at $q^2 = 0$ and slope parameters are computed by [Khodjamirian et al.'10] (**KMPW**) using LCSR.

Tensor form factors $\mathcal{T}_{\perp,\|}$ are computed in QCDF following [Beneke, Feldmann, Seidel'01,'05] including factorizable and non-factorizable contributions.

**Low-recoil:** LCSR are valid up to $q^2 \leq 14$ GeV$^2$. We extend FF determination [Bobeth & Hiller & Dyk'10] till 19 Gev$^2$ and cross check the consistency with **lattice** QCD.
In HQET one expects the ratios to be near one

$$\mathbf{R_1} = \frac{\mathbf{T_1(q^2)}}{\mathbf{V(q^2)}}, \qquad \mathbf{R_2} = \frac{\mathbf{T_2(q^2)}}{\mathbf{A_1(q^2)}}, \qquad \mathbf{R_3} = \frac{q^2}{m_B^2}\frac{T_3(q^2)}{A_2(q^2)}.$$

Our approach at low-recoil: we determine $T_{1,2}$ by exploiting the ratios $R_{1,2}$ allowing for up to a 20% breaking, i.e., $R_{1,2} = 1 + \delta_{1,2}$. All other form factors extrapolated from KMPW. We find perfect agreement between our determination of $T_{1,2}$ using $R_{1,2}$ and lattice data.

Contact between theory and experiment:

Indeed the observables are measured in bins.

**Present bins: [0.1,2], [2,4.3], [4.3,8.68], [1,6], [14.18,16], [16,19]** GeV$^2$.

This requires a **redefinition** of observables in **bins**: $\langle J_i \rangle_{\rm bin} = \int_{bin} [J_i + \bar{J}_i] dq^2$

$$\left\langle A_T^{(2)} \right\rangle_{\rm bin} \equiv \langle P_1 \rangle_{\rm bin} = \frac{\langle J_3 \rangle_{\rm bin}}{2 \langle J_{2s} \rangle_{\rm bin}} \qquad \langle P_2 \rangle_{\rm bin} = \frac{\langle J_{6s} \rangle_{\rm bin}}{8 \langle J_{2s} \rangle_{\rm bin}} \qquad \langle P_3 \rangle_{\rm bin} = -\frac{\langle J_9 \rangle_{\rm bin}}{4 \langle J_{2s} \rangle_{\rm bin}}$$

$$\langle P_4' \rangle_{\rm bin} = \frac{\langle J_4 \rangle_{\rm bin}}{\sqrt{- \langle J_{2s} \rangle_{\rm bin} \langle J_{2c} \rangle_{\rm bin}}} \qquad \langle P_5' \rangle_{\rm bin} = \frac{\langle J_5 \rangle_{\rm bin}}{2\sqrt{- \langle J_{2s} \rangle_{\rm bin} \langle J_{2c} \rangle_{\rm bin}}} \qquad \langle P_6' \rangle_{\rm bin} = \frac{- \langle J_7 \rangle_{\rm bin}}{2\sqrt{- \langle J_{2s} \rangle_{\rm bin} \langle J_{2c} \rangle_{\rm bin}}}.$$

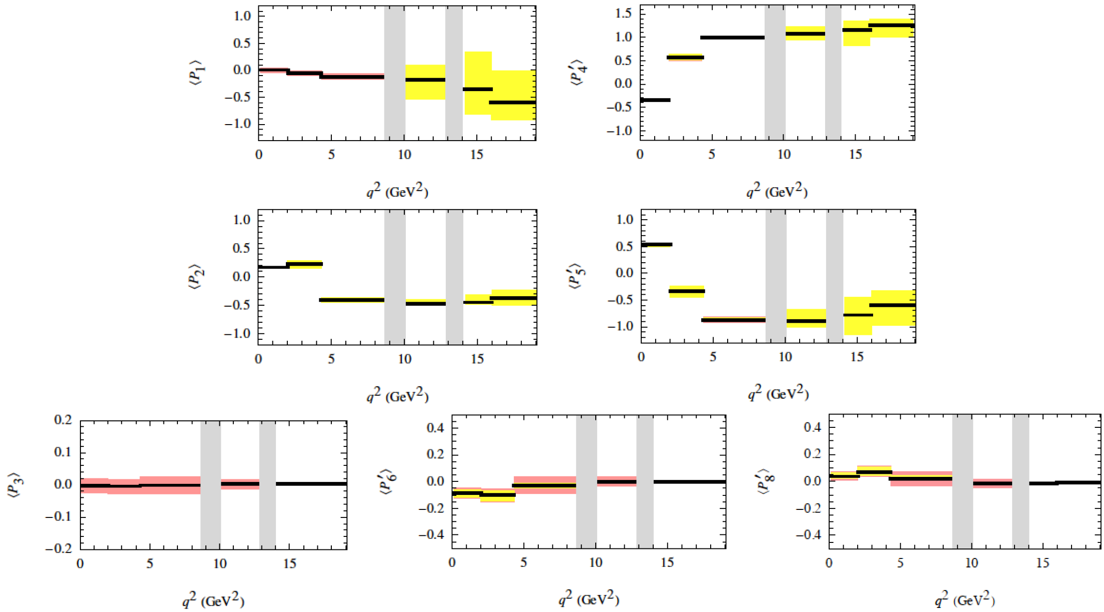
Similar definitions for $\left\langle P_i^{CP} \right\rangle_{\rm bin}$ with $J_i - \bar{J}_i$.

$P_{1,2,3}$ were first indirectly measured via $S_3, A_{im}, A_{FB}, F_L$

(**and already provide constraints**).

**First results on $P_{1,2}$ available since Beauty 2013.**
**BUT it is urgent to get experimental measurements of $P_i'$**

# Binned SM predictions for $\langle P_{1,2,3}\rangle$ and $\langle P'_{4,5,6,8}\rangle$ JHEP 1305 (2013) 137

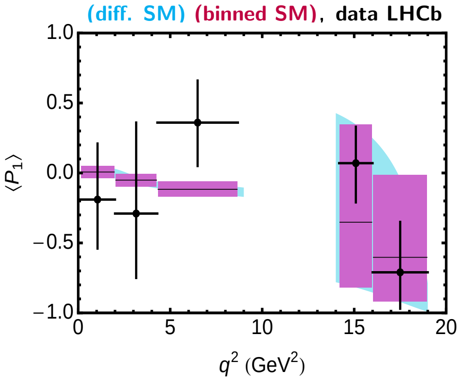


# First measurement and analysis of $P_1$, $P_2$

R. Aaij et al. LHCb, 1304.6325 [hep-ex]

At Beauty $P_{1,2}$ were presented. Conclusion: Results consistent with SM predictions. BUT ...

Regarding measurement of $P_1$ at LHCb:




- Three first bins same 'shape' as CDF.
- Why error bars so large?
- **Too early to draw any definite conclusion on existence or not of right-handed currents.**

We suggest a new folding to measure uniquely $P_1$.

$$d\Gamma(\hat\phi,\hat\theta_\ell,\hat\theta_K)+d\Gamma(\hat\phi,\hat\theta_\ell,\pi-\hat\theta_K)+d\Gamma(-\hat\phi,\pi-\hat\theta_\ell,\hat\theta_K)+d\Gamma(-\hat\phi,\pi-\hat\theta_\ell,\pi-\hat\theta_K)=f(P_1,F_L)+g(A_S^5,A_S^8)$$

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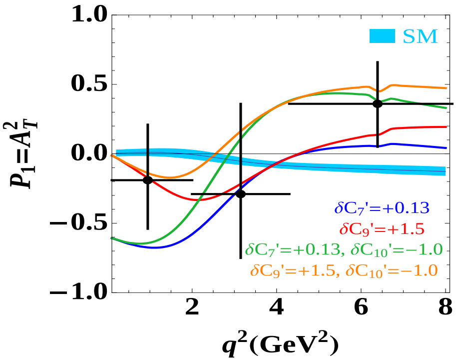


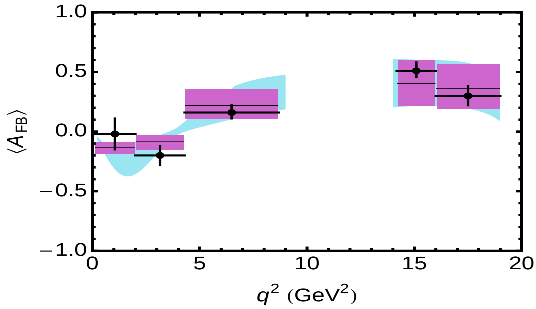

- Three first bins same 'shape' as CDF.
- Why error bars so large?
- **Too early to draw any definite conclusion on existence or not of right-handed currents.**
- $P_1$ can discriminate clearly **at large recoil** on the presence of $\delta C_7'$, $\delta C_9'$ and $\delta C_{10}'$ if error bars reduced:
  - $\delta C_7' > 0$ (a bit large) **BLUE**
  - $\delta C_9' > 0$ also can generate it. RED
  - $\delta C_{10}' < 0$ together with ($\delta C_7' > 0$ GREEN or $\delta C_9' > 0$ ORANGE) can reproduce the shape easily.

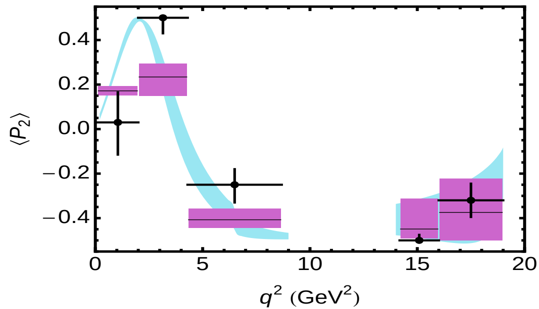
We suggest a new folding to measure uniquely $P_1$.

$$d\Gamma(\hat\phi,\hat\theta_\ell,\hat\theta_K)+d\Gamma(\hat\phi,\hat\theta_\ell,\pi-\hat\theta_K)+d\Gamma(-\hat\phi,\pi-\hat\theta_\ell,\hat\theta_K)+d\Gamma(-\hat\phi,\pi-\hat\theta_\ell,\pi-\hat\theta_K)=f(P_1,F_L)+g(A_S^5,A_S^8)$$

# First measurement and analysis of $P_1$, $P_2$

Concerning the forward-back asymmetry ($A_{FB}$) and $P_2$:




- $P_2$ is the evolved version of $A_{FB}$, but, they play a complementary role.
- It magnifies a tiny tension in the second bin of $A_{FB}$.
- Both zeroes prefer a higher value $q_0^{2exp} = 4.9 \pm 0.9$ GeV$^2$ compared to $q_0^{2SM} = 3.95 \pm 0.38$ GeV$^2$.

At LO how to move the position of the zero to the right?

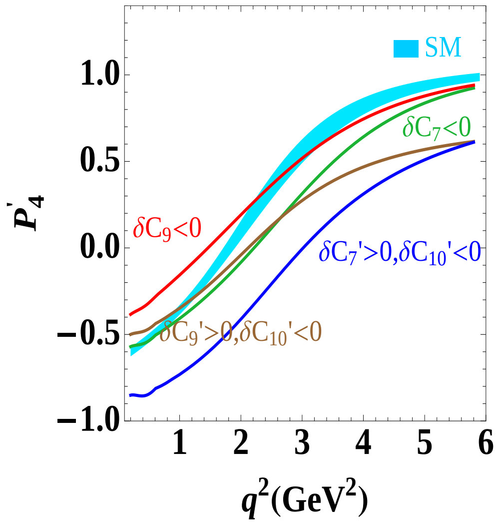
$$q_0^{2LO} = -2 m_b M_B \frac{C_7^{eff} C_{10} - C_7' C_{10}'}{C_9^{eff}(q_0^2) C_{10} - C_9' C_{10}'} \qquad \text{where} \qquad C_i = C_i^{SM} + \delta C_i$$

Four main possibilities on how to test them:

| Mechanism | Constraint: $A_{FB}$ in 3 bins | Constraint: $P_2$ in 3 bins | Constraint: $P_1$ in 3 bins |
|---|---|---|---|
| I. $\delta \mathbf{C_7} < \mathbf{0}$ | OK | OK | $\sim$ |
| II. $\delta \mathbf{C_9} < \mathbf{0}$ | OK | OK | $\sim$ |
| III. $(\delta \mathbf{C_7'} > \mathbf{0}, \delta \mathbf{C_{10}'} < \mathbf{0})$ | OK | $\sim$ | OK |
| IV. $(\delta C_7' < 0, \delta C_{10}' > 0)$ | NO | $\sim$ | NO |
| V. $(\delta \mathbf{C_9'} > \mathbf{0}, \delta \mathbf{C_{10}'} < \mathbf{0})$ | OK | $\sim$ | OK |
| VI. $(\delta C_9' < 0,\ \delta C_{10}' > 0)$ | NO | $\sim$ | NO |

**Mechanism I, II, III and V preferred.**

- $\delta \mathbf{C_7} < \mathbf{0}$ preferred by radiative constraints.
- $\delta \mathbf{C_9} < \mathbf{0}$, mechanism mainly tested with $P_5'$
- Mec. III-VI sign of $\delta C_{10}'$ tested by $P_4'$ and $P_1$.
- Mec. III-IV sign of $\delta C_7'$ tested by $P_1$
- Mec. V, $\delta C_9'$ can be tested by $P_1$.



At LO how to move the position of the zero to the right?

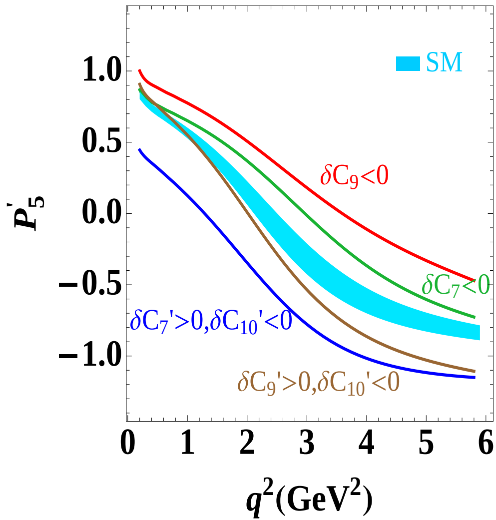
$$q_0^{2LO} = -2m_b M_B \frac{C_7^{eff} C_{10} - C_7' C_{10}'}{C_9^{eff}(q_0^2) C_{10} - C_9' C_{10}'} \qquad \text{where} \qquad C_i = C_i^{SM} + \delta C_i$$

Six main possibilities and how to test them:

| Mechanism | Constraint: $A_{FB}$ in 3 bins | Constraint: $P_2$ in 3 bins | Constraint: $P_1$ in 3 bins |
|---|---|---|---|
| I. $\delta \mathbf{C_7} < \mathbf{0}$ | OK | OK | $\sim$ |
| II. $\delta \mathbf{C_9} < \mathbf{0}$ | OK | OK | $\sim$ |
| III. $(\delta \mathbf{C_7'} > \mathbf{0}, \delta \mathbf{C_{10}'} < \mathbf{0})$ | OK | $\sim$ | OK |
| IV. $(\delta C_7' < 0, \delta C_{10}' > 0)$ | NO | $\sim$ | NO |
| V. $(\delta \mathbf{C_9'} > \mathbf{0}, \delta \mathbf{C_{10}'} < \mathbf{0})$ | OK | $\sim$ | OK |
| VI. $(\delta C_9' < 0,\ \delta C_{10}' > 0)$ | NO | $\sim$ | NO |

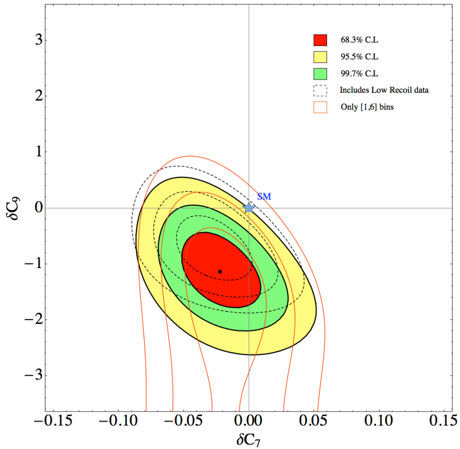
**Mechanism I, II, III and V preferred.**

- $\delta \mathbf{C_7} < \mathbf{0}$ preferred by radiative constraints.
- $\delta \mathbf{C_9} < \mathbf{0}$, mechanism mainly tested with $P_5'$
- Mec. III-VI sign of $\delta C_{10}'$ tested by $P_4'$ and $P_1$.
- Mec. III-IV sign of $\delta C_7'$ tested by $P_1$
- Mec. V, $\delta C_9'$ can be tested by $P_1$.



After analyzing different scenarios we have perform a frequentist analysis with asymmetric errors and NP error bars to an scenario with $\delta C_7$ and $\delta C_9$ including: I. $\mathcal{B}(B \to X_s\gamma)$, $A_I(B \to K^*\gamma)$, $S_{K^*\gamma}$, $\mathcal{B}(B \to X_s\mu^+\mu^-)$ and $\mathcal{B}(B_s \to \mu^+\mu^-)$ together with $P_1$, $P_2$, $A_{FB}$ of $B \to K^*\mu^+\mu^-$.

**Result in $\delta \mathbf{C_7} - \delta \mathbf{C_9}$:**



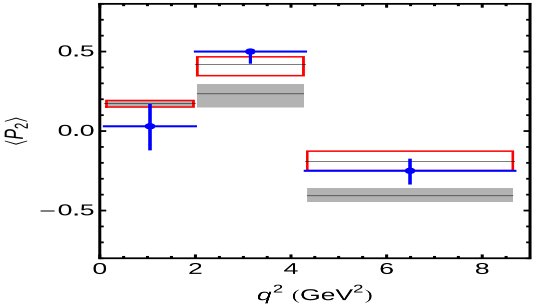

**We find 3$\sigma$ deviation from SM prediction for $C_9$ (check the rest of basis $P_i'$!)**

- 3 large-recoil bins (colored) $\mathbf{C_7 \in (-0.332, -0.287)}$ **and** $\mathbf{C_9 \in (2.58, 3.38)}$
- ONLY 1-6 bin at large recoil (orange)
- 3 large-recoil and 2 low-recoil bins (dashed)

Robustness tests:

- We have check using naive factorization that the effect on $C_9$ is confirmed.
- Also the bin 1-6 confirms the deviation.
- We have analyzed two types of charm effects:
  - $m_c$ value: Increasing $m_c$ up to 1.4 GeV reduces significance to 2.3 $\sigma$.
  - non-perturbative $c - \bar{c}$ contribution (KMPW) increases slightly the significance above 3 $\sigma$.

**$P_2$** for **New Physics** $\delta C_9 = -1.5$ (**red box**)
SM binned prediction in **gray** $\Rightarrow$
LHCb data crosses in **blue**




For completeness we show also the result of full fit to all:

- $\delta C_{10}, \delta C'_{7,9,10}$ are already consistent with SM at $1\sigma$
- $\delta C_7$ at $2\sigma$
- $\delta C_9$ at $3\sigma$

| Coefficient | $1\,\sigma$ | $2\,\sigma$ | $3\,\sigma$ |
|---|---|---|---|
| $\delta C_7$ | $[-0.04, -0.01]$ | $[-0.06, 0.01]$ | $[-0.08, 0.03]$ |
| $\delta C_9$ | $[-1.2, -0.5]$ | $[-1.5, -0.1]$ | $[-1.8, 0.4]$ |
| $\delta C_{10}$ | $[0, +1.8]$ | $[-0.8, 2.4]$ | $[-1.8, 3.4]$ |
| $\delta C'_7$ | $[-0.05, 0.03]$ | $[-0.1, 0.08]$ | $[-0.14, 0.13]$ |
| $\delta C'_9$ | $[-0.2, 1]$ | $[-0.8, 1.4]$ | $[-1.4, 1.8]$ |
| $\delta C'_{10}$ | $[-0.8, 0.2]$ | $[-1.4, 0.6]$ | $[-2.0, 1.0]$ |

Table : 68.3% ($1\,\sigma$), 95.5% ($2\,\sigma$) and 99.7% ($3\,\sigma$) confidence intervals for the NP contributions to Wilson coefficients resulting from the global analysis.

# Conclusions

- We have combined recent LHCb measurements on the first two theoretically clean observables $P_{1,2}$ of the optimal basis together with $A_{FB}$, other radiative modes and $B_s \to \mu^+\mu^-$. We work in the framework of NLO QCDF at large-recoil and HQET at low-recoil.

- **We have found a strong indication for a negative possible New Physics contribution to the coefficient $\mathcal{C}_9$ at $3\sigma$ using large-recoil data and $2.6\sigma$ using both large and low-recoil data.** This result corresponds to a range for $C_9$ inside a 68% CL of $2.6 \leq C_9 \leq 3.4$ to be compared with the SM value for $C_9^{SM} = 4.075$ at same $\mu_b$ scale. Different robustness tests have been included.

- A too large error bars on $P_1$ does not allow **yet** to draw any definite conclusion on the existence or not of right-handed currents. Still in our global fit we do not see clear indications of the need to introduce them.

**Prospects:** A measurement of the rest of the basis $P_i'$ is essential to disprove or confirm this result

# BACK-UP SLIDES

# Computation of Primary Observables

**Large-recoil**: NLO QCDfactorization + $\mathcal{O}(\Lambda/m_b)$. Soft form factors $\xi_{\perp,\|}(q^2)$ from

$$\xi_\perp(q^2) = m_B/(m_B+m_{K^*})\mathbf{V(q^2)} \quad \xi_\|(q^2) = (m_B+m_{K^*})/(2E)\mathbf{A_1(q^2)} - (m_B-m_{K^*})/(m_B)\mathbf{A_2(q^2)}$$

- FF at $q^2=0$ and slope parameters are computed by [Khodjamirian et al.'10] (**KMPW**) using LCSR.

Tensor form factors $\mathcal{T}_{\perp,\|}$ are computed in QCDF following [Beneke, Feldmann, Seidel'01,'05] including factorizable and non-factorizable contributions.

The wide spread of different errors in literature associated to FF:

$V(0) = 0.31 \pm 0.04$ and $A(0) = 0.33 \pm 0.03$ [W. Altmannshofer et al.'09]

$V(0) = 0.36 \pm 0.17$ and $A(0) = 0.29 \pm 0.10$ [A. Khodjamirian et al. '10].

Even central values have shifted significantly $V(0) = 0.41 \pm 0.05$ [P. Ball and R. Zwicky,'05] (**BZ**).

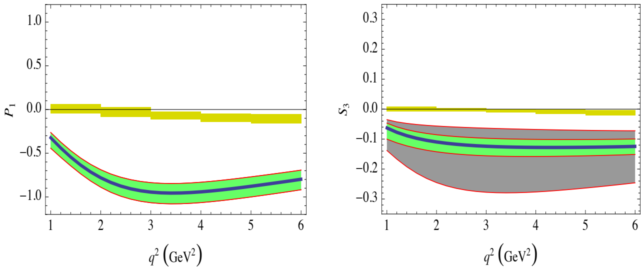


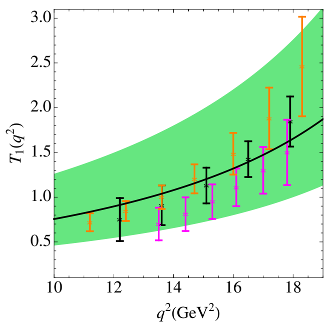

Figure : Predictions in SM and for one benchmark point of NP for $P_1$ (left) and $S_3$ (right). The yellow boxes are the SM predictions integrated in five 1 GeV$^2$ bins. The blue curve corresponds to the central values for the NP scenario. The green/grey band is the total uncertainty considering two different FF determinations (BZ/KMPW).

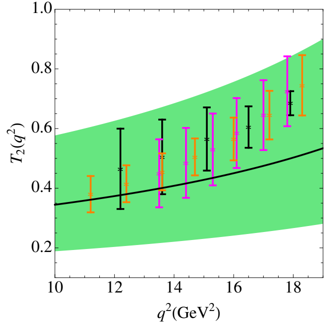
**Low-recoil:** LCSR are valid up to $q \leq 14$ GeV$^2$. We extend FF determination [Bobeth & Hiller & Dyk'10] till 19 Gev$^2$ and cross check the consistency with **lattice** QCD.
In HQET one expects the ratios to be near one

$$\mathbf{R_1} = \frac{\mathbf{T_1(q^2)}}{\mathbf{V(q^2)}}\,, \qquad \mathbf{R_2} = \frac{\mathbf{T_2(q^2)}}{\mathbf{A_1(q^2)}}\,, \qquad \mathbf{R_3} = \frac{q^2}{m_B^2}\frac{T_3(q^2)}{A_2(q^2)}\,.$$

- BZ was problematic with $R_3$.

**Our approach**: we determine $T_{1,2}$ by exploiting the ratios $R_{1,2}$ allowing for up to a 20% breaking, i.e., $R_{1,2} = 1 + \delta_{1,2}$. All other form factors extrapolated from KMPW.




- We find excellent agreement between our determination of $T_{1,2}$ using $R_{1,2}$ and lattice data.

# Integrated observables

Contact between theory and experiment:

Indeed the observables are measured in bins.

**Present bins: [0.1,2], [2,4.3], [4.3,8.68], [1,6], [14.18,16], [16,19]** GeV$^2$.

Comments on the bins:

- Ultralow bin region **[0.1,1]** including light-resonances analyzed in [S. Jager, JM Camalich]'12. Binning tends to wash out the resonances.
- The region $q^2 \sim 6 - 8.68$ GeV$^2$ can be affected by charm-loop effects. [Khodjamirian, Mannel, Pivovarov, Wang'10]
- The middle bin $[\mathbf{10.09}, \mathbf{12.89}]$ GeV$^2$ between $J/\Psi$ and $\Psi(2s)$ . Charm-loop effects lead to a destructive interference (raw estimate).
  We treat it as a simple interpolation.
- Suggestion to experimentalists on binning: **[1,2], [2,4.3], [4.3,6]**

# S-wave pollution

[S. Descotes, T. Hurth, JM, J. Virto'13], [J.M'12]

- Another possible source of uncertainty is the **S-wave contribution** coming from $B \to K_0^* l^+ l^-$ decay. [Becirevic, Tayduganov '13], [Blake et al.'13]
- We will assume that both P and S waves are described by $q^2$-dependent FF times a Breit-Wigner function.
- The **distinct** angular dependence of the S-wave terms in **folded** distributions allow to disentangle the signal of the P-wave from the S-wave: $P_i^{(\prime)}$ *can be* **disentangled** *from S-wave pollution* [JM'12].

**Problem**: Changing the normalization used for the distribution from

$$\frac{d\Gamma_K^*}{dq^2} \equiv \Gamma'_{K^*} \to \Gamma'_{full}$$

introduces a $(1 - \mathbf{F_S})$ in front of the P-wave.

$$\Gamma'_{full} = \Gamma'_{K^*} + \Gamma'_S$$

and the longitudinal polarization fraction associated to $\Gamma'_S$ is

$$\mathbf{F_S} = \frac{\Gamma'_S}{\Gamma'_{full}} \qquad \text{and} \qquad 1 - \mathbf{F_S} = \frac{\Gamma'_{K^*}}{\Gamma'_{full}}$$

The modified distribution including the **S-wave** and new normalization $\Gamma'_{full}$:

$$\frac{1}{\Gamma'_{full}}\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}\mathbf{F_T}\sin^2\theta_K + \mathbf{F_L}\cos^2\theta_K$$

$$+(\frac{1}{4}\mathbf{F_T}\sin^2\theta_K - F_L\cos^2\theta_K)\cos 2\theta_l + \frac{1}{2}\mathbf{P_1}\mathbf{F_T}\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$

$$+\sqrt{\mathbf{F_T}\mathbf{F_L}}\left(\frac{1}{2}\mathbf{P'_4}\sin 2\theta_K\sin 2\theta_l\cos\phi + \mathbf{P'_5}\sin 2\theta_K\sin\theta_l\cos\phi\right)$$

$$-\sqrt{\mathbf{F_T}\mathbf{F_L}}\left(\mathbf{P'_6}\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}\mathbf{Q'}\sin 2\theta_K\sin 2\theta_l\sin\phi\right)$$

$$+2\mathbf{P_2}\mathbf{F_T}\sin^2\theta_K\cos\theta_l - \mathbf{P_3}\mathbf{F_T}\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big](1-\mathbf{F_S}) + \frac{1}{\Gamma'_{full}}\mathbf{W_S}$$

in the massless case and where the polluting terms are

$$\frac{\mathbf{W_S}}{\Gamma'_{full}} = \frac{3}{16\pi}\Big[\mathbf{F_S}\sin^2\theta_\ell + \mathbf{A_S}\sin^2\theta_\ell\cos\theta_K + \mathbf{A_S^4}\sin\theta_K\sin 2\theta_\ell\cos\phi$$

$$+\mathbf{A_S^5}\sin\theta_K\sin\theta_\ell\cos\phi + \mathbf{A_S^7}\sin\theta_K\sin\theta_\ell\sin\phi + \mathbf{A_S^8}\sin\theta_K\sin 2\theta_\ell\sin\phi\Big]$$

We can get **bounds** on the size of the S-wave polluting terms.
Let's take for instance $A_S$

$$\mathbf{A_S} = 2\sqrt{3}\frac{1}{\Gamma'_{full}}\int \mathrm{Re}\left[({A'_0}^L A_0^{L*} + {A'_0}^R A_0^{R*}) BW_{K_0^*}(m_{K\pi}^2) BW_{K^*}^\dagger(m_{K\pi}^2)\right] dm_{K\pi}^2$$

where

$$\mathbf{F_S} = \frac{8}{3}\frac{\tilde{J}_{1a}^c}{\Gamma'_{full}} = \frac{|{A'_0}^L|^2 + |{A'_0}^R|^2}{\Gamma'_{full}}\mathbf{Y} \qquad \mathbf{Y} = \int dm_{K\pi}^2 |BW_{K_0^*}(m_{K\pi}^2)|^2$$

**Y** factor included to take into account the width of scalar resonance $K_0^*$

A bound is obtained once we define the $S-P$ interference integral

$$\mathbf{Z} = \int \left| BW_{K_0^*}(m_{K\pi}^2) BW_{K^*}^\dagger(m_{K\pi}^2)\right| dm_{K\pi}^2$$

and use the bound from the Cauchy-Schwartz inequality

$$\left|\int (\mathrm{Re}, \mathrm{Im}) \left[({A'_0}^L A_j^{L*} \pm {A'_0}^R A_j^{R*}) BW_{K_0^*}(m_{K\pi}^2) BW_{K^*}^\dagger(m_{K\pi}^2)\right] dm_{K\pi}^2\right|$$
$$\leq \mathbf{Z} \times \sqrt{[|{A'_0}^L|^2 + |{A'_0}^R|^2][|A_j^L|^2 + |A_j^R|^2]}$$

From the definitions of $\mathbf{F_S}$ and $\mathbf{F_L}$ and $\mathbf{P_1}$ one gets the following bound:

$$|\mathbf{A_S}| \leq 2\sqrt{3}\sqrt{\mathbf{F_S(1-F_S)F_L}}\,\frac{\mathbf{Z}}{\sqrt{\mathbf{XY}}}$$

the factor $(1-F_S)$ in the bound arises due to the fact that $\mathbf{F_L}$ is defined with respect to $\Gamma'_{K^*}$ rather than $\Gamma'_{full}$.

$$\begin{aligned}
|\mathbf{A_S^4}| &\leq \sqrt{\frac{3}{2}}\sqrt{\mathbf{F_S(1-F_S)}(1-\mathbf{F_L})\left(\frac{1-\mathbf{P_1}}{2}\right)}\,\frac{\mathbf{Z}}{\sqrt{\mathbf{XY}}} \\
|\mathbf{A_S^5}| &\leq 2\sqrt{\frac{3}{2}}\sqrt{\mathbf{F_S(1-F_S)}(1-\mathbf{F_L})\left(\frac{1+\mathbf{P_1}}{2}\right)}\,\frac{\mathbf{Z}}{\sqrt{\mathbf{XY}}} \\
|\mathbf{A_S^7}| &\leq 2\sqrt{\frac{3}{2}}\sqrt{\mathbf{F_S(1-F_S)}(1-\mathbf{F_L})\left(\frac{1-\mathbf{P_1}}{2}\right)}\,\frac{\mathbf{Z}}{\sqrt{\mathbf{XY}}} \\
|\mathbf{A_S^8}| &\leq \sqrt{\frac{3}{2}}\sqrt{\mathbf{F_S(1-F_S)}(1-\mathbf{F_L})\left(\frac{1+\mathbf{P_1}}{2}\right)}\,\frac{\mathbf{Z}}{\sqrt{\mathbf{XY}}}
\end{aligned}$$

| Coefficient | Large recoil $\infty$ Range | Low recoil $\infty$ Range | Large Recoil Finite Range | Low Recoil Finite Range |
|---|---|---|---|---|
| $\|A_S\|$ | 0.33 | 0.25 | 0.67 | 0.49 |
| $\|A_S^4\|$ | 0.05 | 0.10 | 0.11 | 0.19 |
| $\|A_S^5\|$ | 0.11 | 0.11 | 0.22 | 0.23 |
| $\|A_S^7\|$ | 0.11 | 0.19 | 0.22 | 0.38 |
| $\|A_S^8\|$ | 0.05 | 0.06 | 0.11 | 0.11 |

Table : Illustrative values of the size of the bounds for the choices of $F_S, F_L, P_1$ and $\mathbf{F} = \mathbf{Z}/\sqrt{\mathbf{XY}}$

- **Large-recoil**: $F_S \sim 7\%$ (like $B^0 \to J/\psi K^+\pi^-$), $F_L \sim 0.7$ and $P_1 \sim 0$
- **Low-recoil**: $F_S \sim 7\%$, $F_L \sim 0.38$ and $P_1 \sim -0.48$.

We take the maximal value for $Z/\sqrt{XY}$ factor in two cases:

"infinite range" $\to$ integrals in the whole $m_{K\pi}$ range

"finite range" $\to$ integrals around $m_{K^*} \pm 0.1$ GeV.

This may help in estimating the **systematics** associated to S-wave.

There is a correspondence between $\mathbf{P_i^{(\prime)}}$ and $\mathbf{J_k}$ ($\beta_\ell^2$ absorbed here in $F_{L,T}$)

$$(\mathbf{J_{2s}} + \mathbf{\bar{J}_{2s}}) = \frac{1}{4}\mathbf{F_T}\frac{\mathbf{d\Gamma + d\bar{\Gamma}}}{\mathbf{dq^2}} \qquad (\mathbf{J_{2c}} + \mathbf{\bar{J}_{2c}}) = -\mathbf{F_L}\frac{\mathbf{d\Gamma + d\bar{\Gamma}}}{\mathbf{dq^2}}$$

$$\mathbf{J_3} + \mathbf{\bar{J}_3} = \frac{1}{2}\mathbf{P_1}\mathbf{F_T}\frac{\mathbf{d\Gamma + d\bar{\Gamma}}}{\mathbf{dq^2}} \qquad \mathbf{J_3} - \mathbf{\bar{J}_3} = \frac{1}{2}\mathbf{P_1^{CP}}\mathbf{F_T}\frac{\mathbf{d\Gamma + d\bar{\Gamma}}}{\mathbf{dq^2}}$$

$$\mathbf{J_{6s}} + \mathbf{\bar{J}_{6s}} = 2\mathbf{P_2}\mathbf{F_T}\frac{\mathbf{d\Gamma + d\bar{\Gamma}}}{\mathbf{dq^2}} \qquad \mathbf{J_{6s}} - \mathbf{\bar{J}_{6s}} = 2\mathbf{P_2^{CP}}\mathbf{F_T}\frac{\mathbf{d\Gamma + d\bar{\Gamma}}}{\mathbf{dq^2}}$$

$$\mathbf{J_9} + \mathbf{\bar{J}_9} = -\mathbf{P_3}\mathbf{F_T}\frac{\mathbf{d\Gamma + d\bar{\Gamma}}}{\mathbf{dq^2}} \qquad \mathbf{J_9} - \mathbf{\bar{J}_9} = -\mathbf{P_3^{CP}}\mathbf{F_T}\frac{\mathbf{d\Gamma + d\bar{\Gamma}}}{\mathbf{dq^2}}$$

$$\mathbf{J_4} + \mathbf{\bar{J}_4} = \frac{1}{2}\mathbf{P_4'}\sqrt{\mathbf{F_T F_L}}\,\frac{\mathbf{d\Gamma + d\bar{\Gamma}}}{\mathbf{dq^2}} \qquad \mathbf{J_4} - \mathbf{\bar{J}_4} = \frac{1}{2}\mathbf{P_4'^{CP}}\sqrt{\mathbf{F_T F_L}}\,\frac{\mathbf{d\Gamma + d\bar{\Gamma}}}{\mathbf{dq^2}}$$

$$\mathbf{J_5} + \mathbf{\bar{J}_5} = \mathbf{P_5'}\sqrt{\mathbf{F_T F_L}}\frac{\mathbf{d\Gamma + d\bar{\Gamma}}}{\mathbf{dq^2}} \qquad \mathbf{J_5} - \mathbf{\bar{J}_5} = \mathbf{P_5'^{CP}}\sqrt{\mathbf{F_T F_L}}\frac{\mathbf{d\Gamma + d\bar{\Gamma}}}{\mathbf{dq^2}}$$

$$\mathbf{J_7} + \mathbf{\bar{J}_7} = -\mathbf{P_6'}\sqrt{\mathbf{F_T F_L}}\frac{\mathbf{d\Gamma + d\bar{\Gamma}}}{\mathbf{dq^2}} \qquad \mathbf{J_7} - \mathbf{\bar{J}_7} = -\mathbf{P_6'^{CP}}\sqrt{\mathbf{F_T F_L}}\frac{\mathbf{d\Gamma + d\bar{\Gamma}}}{\mathbf{dq^2}}$$

where each $\mathbf{P_i^{(\prime)}}$ and $\mathbf{P_i^{(\prime)CP}}$ encodes the information that can be extracted *cleanly* at large-recoil inside each $\mathbf{J_k}$ and define the simplest possible fit besides $S_i, A_i$. The **brown** and **blue** pieces are strongly FF-dependent pieces.