Null test of the Standard Model with flavour-specific CP-asymmetries

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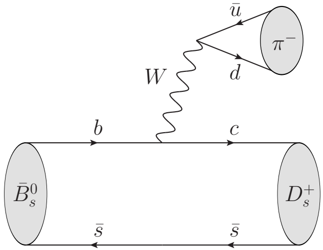
The non-leptonic decays $\bar{B}^0_{d(s)} \to D^+_{(s)} K^-(\pi^-)$



- Tree-level decays induced by $b \to c\bar{u}q$ transitions $q = d, s$
- No penguin and annihilation topologies
- "Golden" modes for the QCD factorisation (QCDF) approach

[Beneke, Buchalla, Neubert, Sachrajda (1999-2001)]

The non-leptonic decays $\bar{B}^0_{d(s)} \to D^+_{(s)} K^- (\pi^-)$

[Bordone, Gubernari, Huber, Jung, van Dyk, arXiv: 2007.10338]

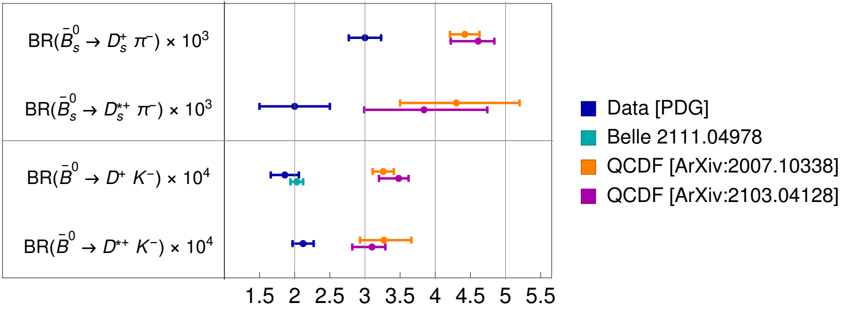
Table 2 Our fits to the available data listed in Table 4 with and without constraints from QCDF, in comparison to the PDG values [15] and our QCDF predictions. The branching fractions are given in units of 10^{-3}. Results marked with a * indicate that the distribution is non-gaussian. The two fits on the left are not using the assumption that QCDF holds. The two fits on the right are using QCDF input to varying degree, see text. Correlations for these results are available upon request from the authors

Source	PDG	Our fits (w/o QCDF)		Our fit (w/ QCDF, no f_s/f_d)		QCDF prediction
Scenario	–	No f_s/f_d	$(f_s/f_d)^{7\text{ TeV}}_{\text{LHCb,sl}}$	Ratios only	~~SU(3)~~	–
χ^2/dof	–	2.5/4	3.1/5	4.6/6	3.7/4	–
$\mathcal{B}(\bar{B}^0_s \to D^+_s \pi^-)$	3.00 ± 0.23	3.6 ± 0.7	3.11 ± 0.25	$3.11^{+0.21}_{-0.19}$	$3.20^{+0.20}_{-0.26}$ *	4.42 ± 0.21
$\mathcal{B}(\bar{B}^0 \to D^+ K^-)$	0.186 ± 0.020	0.222 ± 0.012	0.224 ± 0.012	0.227 ± 0.012	0.226 ± 0.012	0.326 ± 0.015
$\mathcal{B}(\bar{B}^0 \to D^+ \pi^-)$	2.52 ± 0.13	2.71 ± 0.12	2.73 ± 0.12	2.74 ± 0.12	$2.73^{+0.12}_{-0.11}$	–
$\mathcal{B}(\bar{B}^0_s \to D^{*+}_s \pi^-)$	2.0 ± 0.5	2.4 ± 0.7	2.1 ± 0.5	$2.46^{+0.37}_{-0.32}$	$2.43^{+0.39}_{-0.32}$	$4.3^{+0.9}_{-0.8}$
$\mathcal{B}(\bar{B}^0 \to D^{*+} K^-)$	0.212 ± 0.015	0.216 ± 0.014	0.216 ± 0.014	$0.213^{+0.014}_{-0.013}$	$0.213^{+0.014}_{-0.013}$	$0.327^{+0.039}_{-0.034}$
$\mathcal{B}(\bar{B}^0 \to D^{*+} \pi^-)$	2.74 ± 0.13	2.78 ± 0.15	2.79 ± 0.15	$2.76^{+0.15}_{-0.14}$	$2.76^{+0.15}_{-0.14}$	–
$\mathcal{R}^P_{s/d}$	16.1 ± 2.1	16.2 ± 3.3	14.0 ± 1.1	13.6 ± 0.6	$14.2^{+0.6}_{-1.1}$ *	$13.5^{+0.6}_{-0.5}$
$\mathcal{R}^V_{s/d}$	9.4 ± 2.5	11.4 ± 3.6	9.6 ± 2.5	$11.4^{+1.7}_{-1.6}$	$11.4^{+1.7}_{-1.5}$ *	$13.1^{+2.3}_{-2.0}$
$\mathcal{R}^{V/P}_s$	0.66 ± 0.16	0.66 ± 0.16	0.66 ± 0.16	$0.81^{+0.12}_{-0.11}$	$0.76^{+0.11}_{-0.10}$	$0.97^{+0.20}_{-0.17}$
$\mathcal{R}^{V/P}_d$	1.14 ± 0.15	0.97 ± 0.08	0.97 ± 0.08	0.97 ± 0.06	0.95 ± 0.07	1.01 ± 0.11
$(f_s/f_d)^{7\text{ TeV}}_{\text{LHCb}}$	–	$0.223^{+0.056}_{-0.038}$ *	0.260 ± 0.019	$0.261^{+0.018}_{-0.016}$	$0.252^{+0.023}_{-0.015}$ *	–
$(f_s/f_d)_{\text{Tev}}$	–	$0.208^{+0.056}_{-0.038}$ *	0.243 ± 0.028	$0.244^{+0.026}_{-0.023}$	$0.236^{+0.026}_{-0.022}$ *	–
Δ_P	–	–	–	$-0.164^{+0.030}_{-0.028}$	-0.167 ± 0.029	–
Δ_V	–	–	–	$-0.20^{+0.06}_{-0.05}$	$-0.20^{+0.06}_{-0.05}$	–

The non-leptonic decays $\bar{B}^0_{d(s)} \to D^+_{(s)} K^- (\pi^-)$

[Bordone, Gubernari, Huber, Jung, van Dyk, arXiv: 2007.10338]

[Cai, Deng, Li, Yang, arXiv: 2103.04138]



- Tension between QCDF predictions and data $2 - 5.5\,\sigma$!

Reasons for discrepancies ?

- Problems with QCDF? Power corrections? Form factors?
- QED corrections (incl. ultra-soft photon emission)?

  [Beneke, Böer, Finauri, Vos, arXiv: 2107.03819]

- Rescattering effects? [Endo, Iguro, Mishima, Vos, arXiv: 2109.10811]
- New physics? [Cai, Deng, Li, Yang, arXiv: 2103.04138]

  [Fleischer, Malami, arXiv: 2109.04950]

  [Fleischer, Malami, arXiv: 2110.04240]

  [Iguro, Kitahara, arXiv: 2008.01086]

  ▷ Interplay with collider constraints [Bordone, Grejio, Marzocca, arXiv: 2103.10332]

Flavour-specific CP-asymmetries in $\bar{B}^0_{d(s)} \to D^+_{(s)} K^-(\pi^-)$

- Consider a transition of the flavour eigenstate B^0_q to the final state f
- The amplitudes are denoted as

$$\mathcal{A}_f = \langle f | \mathcal{H}_{\rm eff} | B_q \rangle \qquad \bar{\mathcal{A}}_f = \langle f | \mathcal{H}_{\rm eff} | \bar{B}_q \rangle$$

$$\mathcal{A}_{\bar{f}} = \langle \bar{f} | \mathcal{H}_{\rm eff} | B_q \rangle \qquad \bar{\mathcal{A}}_{\bar{f}} = \langle \bar{f} | \mathcal{H}_{\rm eff} | \bar{B}_q \rangle$$

- For a flavour-specific decay: $\mathcal{A}_{\bar{f}} = 0 = \bar{\mathcal{A}}_f$ [**C1**]

Examples: $\bar{B}_s \to D_s^+ \ell^- \nu_\ell$, $\bar{B}_d \to D^+ K^-$, $\bar{B}_s \to K^+ \pi^-$

- Absence of direct CP violation: $\bar{\mathcal{A}}_{\bar{f}} = \mathcal{A}_f$ [**C2**]

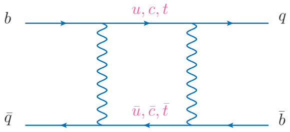
In the SM, [**C2**] applies e.g. for $\bar{B}_s \to D_s^+ \pi^-$ and $\bar{B}_d \to D^+ K^-$

$B_q - \bar{B}_q$ mixing

- The meson mass eigenstates $|B_{q,H}\rangle$ and $|B_{q,L}\rangle$

$$\begin{cases} |B_{q,L}\rangle & = p|B_q\rangle + q|\bar{B}_q\rangle \\ |B_{q,H}\rangle & = p|B_q\rangle - q|\bar{B}_q\rangle \end{cases}$$

$$|p|^2 + |q|^2 = 1$$



- The mass difference $\Delta M_q = M_H^q - M_L^q$
- The decay rate difference $\Delta\Gamma_q = \Gamma_L^q - \Gamma_H^q$

$$\Delta M_q \approx 2|M_{12}^q| \qquad \Delta\Gamma_q \approx 2|\Gamma_{12}^q| \cos\phi_{12}^q$$

$$\left|\frac{q}{p}\right| \approx 1 - \frac{a_{\rm fs}^q}{2} \qquad a_{\rm fs}^q \approx \frac{|\Gamma_{12}^q|}{|M_{12}^q|} \sin\phi_{12}^q$$

- Γ_{12}^q and M_{12}^q are the absorptive and dispersive parts of the box diagrams, $\phi_{12}^q = \arg(-M_{12}^q/\Gamma_{12}^q)$

$B_q - \bar{B}_q$ mixing

- The SM predictions

e.g. [Lenz, Tetlalmatzi-Xolocotzi, arXiv: 1912.07621] [HPQCD, arXiv:1910.00970]

$$a_{\rm fs}^d = (-4.73 \pm 0.42) \cdot 10^{-4} \qquad a_{\rm fs}^s = (2.06 \pm 0.18) \cdot 10^{-5}$$

$$\left|\frac{\Gamma_{12}^d}{M_{12}^d}\right| = (4.82 \pm 0.65) \cdot 10^{-3} \qquad \left|\frac{\Gamma_{12}^s}{M_{12}^s}\right| = (4.82 \pm 0.64) \cdot 10^{-3}$$

$$\phi_{12}^d = (-5.6 \pm 1.1)^\circ \qquad \phi_{12}^s = (0.25 \pm 0.05)^\circ$$

- Experimental measurements [HFLAV]

$$a_{\rm sl}^d = a_{\rm fs}^d = (-21 \pm 17) \cdot 10^{-4} \qquad a_{\rm sl}^s = a_{\rm fs}^s = (-60 \pm 280) \cdot 10^{-5}$$

- Expected precision of $\pm 2 \cdot 10^{-4}$ for $a_{\rm sl}^d$ and $\pm 30 \cdot 10^{-5}$ for $a_{\rm sl}^s$ by the LHCb with an integrated luminosity of $300\,{\rm fb}^{-1}$

[LHCb, arXiv: 1808.08865, 1812.07638]

- Projected sensitivity for $a_{\rm sl}^d$ by Belle II?

Flavour-specific CP-asymmetry

- Consider the flavour-specific CP asymmetry

$$A_{\rm fs}^q = \frac{\Gamma\left(\bar{B}_q(t) \to f\right) - \Gamma\left(B_q(t) \to \bar{f}\right)}{\Gamma\left(\bar{B}_q(t) \to f\right) + \Gamma\left(B_q(t) \to \bar{f}\right)}$$

- For flavour-specific decays (due to [**C1**])

$$\Gamma\left[\bar{B}_q(t) \to f\,\right] = \frac{1}{2} N_f \left|\mathcal{A}_f\right|^2 (1 + a_{\rm fs}^q)\, e^{-\Gamma_q t} \left[\cosh\left(\frac{\Delta\Gamma_q\, t}{2}\right) - \cos\left(\Delta M_q t\right)\right]$$

$$\Gamma\left[B_q(t) \to \bar{f}\,\right] = \frac{1}{2} N_f \left|\bar{\mathcal{A}}_{\bar{f}}\right|^2 (1 - a_{\rm fs}^q)\, e^{-\Gamma_q t} \left[\cosh\left(\frac{\Delta\Gamma_q\, t}{2}\right) - \cos\left(\Delta M_q t\right)\right]$$

- In the SM (due to [**C2**]) $\quad A_{\rm fs}^q = a_{fs}^q$

A^q_{fs} beyond the SM

- Under the presence of general New Physics

$$\mathcal{A}_f = \left|\mathcal{A}_f^{\rm SM}\right| e^{i\phi^{\rm SM}} e^{i\varphi^{\rm SM}} + \left|\mathcal{A}_f^{\rm BSM}\right| e^{i\phi^{\rm BSM}} e^{i\varphi^{\rm BSM}}$$
$$=: \left|\mathcal{A}_f^{\rm SM}\right| e^{i\phi^{\rm SM}} e^{i\varphi^{\rm SM}} \left(1 + r e^{i\phi} e^{i\varphi}\right)$$

$\phi = \phi^{\rm BSM} - \phi^{\rm SM}$ – relative strong phase
$\varphi = \varphi^{\rm BSM} - \varphi^{\rm SM}$ – relative weak phase
$r = |\mathcal{A}_f^{\rm BSM}|/|\mathcal{A}_f^{\rm SM}|$ $\qquad r \sim (10 - 20)\%$

- $$A^q_{\rm fs} = \frac{a^q_{\rm fs} - 2r\sin\phi\sin\varphi + 2a^q_{\rm fs} r\cos\phi\cos\varphi + a^q_{\rm fs} r^2}{1 + 2r\cos\phi\cos\varphi + r^2 - 2a^q_{\rm fs} r\sin\phi\sin\varphi} \approx a^q_{\rm fs} - A^q_{\rm dir}$$

  with the direct CP asymmetry $A^q_{\rm dir} \approx 2r\sin\phi\sin\varphi$

- Enhancement from $a^q_{fs} \sim 10^{-5}$ (in the SM) up to 40% possible !

Untagged CP-asymmetry

- Time-dependent untagged CP-asymmetry

$$A^q_{\rm untagged} = \frac{\left[\Gamma(\bar{B}_q(t) \to \bar{f}) + \Gamma(B_q(t) \to \bar{f})\right] - \left[\Gamma(\bar{B}_q(t) \to f) + \Gamma(B_q(t) \to f)\right]}{\left[\Gamma(\bar{B}_q(t) \to \bar{f}) + \Gamma(B_q(t) \to \bar{f})\right] + \left[\Gamma(\bar{B}_q(t) \to f) + \Gamma(B_q(t) \to f)\right]}$$

- $$\boxed{A^q_{\rm untagged} = \frac{2r \sin\phi \sin\varphi - a^q_{\rm fs}\left(1 + 2r\cos\phi\cos\varphi + r^2\right) Y(t)}{1 + 2r\cos\phi\cos\varphi + r^2 - 2a^q_{\rm fs}\, r\sin\phi\sin\varphi\, Y(t)}}$$

where $Y(t) = \frac{1}{2}\left[1 - \cos\left(\Delta M_q t\right) / \cosh\left(\frac{\Delta\Gamma_q t}{2}\right)\right]$

- Expanding in small r and $a^q_{\rm fs}$

$$A^q_{\rm untagged} \approx A^q_{\rm dir} - a^q_{\rm fs}\, Y(t)$$

- Used to measure $a^d_{\rm sl}$ (assuming no CP violation)

Untagged CP-asymmetry

- Time-integrated untagged CP-asymmetry

$$\langle A^q_{\rm untagged}\rangle = \frac{\int_0^\infty dt\,\left[\Gamma(\bar{B}_q(t)\to\bar{f})+\Gamma(B_q(t)\to\bar{f})\right]-\int_0^\infty dt\,\left[\Gamma(\bar{B}_q(t)\to f)+\Gamma(B_q(t)\to f)\right]}{\int_0^\infty dt\,\left[\Gamma(\bar{B}_q(t)\to\bar{f})+\Gamma(B_q(t)\to\bar{f})\right]+\int_0^\infty dt\,\left[\Gamma(\bar{B}_q(t)\to f)+\Gamma(B_q(t)\to f)\right]}$$

- $$\boxed{\langle A^q_{\rm untagged}\rangle = \frac{4r\sin\phi\sin\varphi - a^q_{\rm fs}(1-\rho_q)\left(1+2r\cos\phi\cos\varphi+r^2\right)}{2\left(1+2r\cos\phi\cos\varphi+r^2-a^q_{\rm fs}(1-\rho_q)r\sin\phi\sin\varphi\right)}}$$

$$\rho_q = \frac{\Gamma_q^2-\Delta\Gamma_q^2/4}{\Gamma_q^2+\Delta M_q^2} \qquad (\rho_d\approx 0.63 \text{ and } \rho_s\approx 0.001)$$

- Expanding in small r and $a^q_{\rm fs}$

$$\langle A^q_{\rm untagged}\rangle \approx A^q_{\rm dir} - \frac{a^q_{\rm fs}}{2}(1-\rho_q)$$

- $\langle A^s_{\rm untagged}\rangle$ is convenient for experimental determination

Experimental prospects

- Experimentally, one measures

$$A_{\rm raw} = \frac{N(D_s^+\pi^-) - N(D_s^-\pi^+)}{N(D_s^+\pi^-) + N(D_s^-\pi^+)}$$

- This is related to $\langle A^s_{\rm untagged}\rangle$ by

$$\langle A^s_{\rm untagged}\rangle = A_{\rm raw} - A_{\rm det} - A_{\rm prod}\frac{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cos(\Delta M_s t)\epsilon(t)dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cosh(\frac{\Delta\Gamma_s t}{2})\epsilon(t)dt} - \sum_i f^i_{\rm bkg}\cdot A^i_{\rm bkg}$$

- ▷ A significant gain in the statistics by not tagging the initial state flavour
- ▷ $A_{\rm det}$ will be reduced by reconstructing $D_s^\pm \to \phi\pi$
- ▷ B_s decays are fully reconstructed in the symmetric $K^\pm K^\mp\pi^\pm\pi^\mp$ final states
- ▷ Due to fast $B_s^0 - \bar{B}_s^0$ oscillations, the impact of $A_{\rm prod}$ is significantly diluted
- ▷ The sources of background are well-understood [LHCb, arXiv: 2104.04412]
- ▷ An expected sensitivity to $\langle A^s_{\rm untagged}\rangle$ is $\mathcal{O}(10^{-3})$ based on Run 1 and Run 2 data (9 $\rm fb^{-1}$) and anticipated Run 3 data ($\approx$ 15 $\rm fb^{-1}$) by LHCb

Conclusion

- There are current tension between QCDF predictions and data on the tree-level non-leptonic $B_{(s)}$-meson decays
- May be caused by unaccounted-for QCD effects or New Physics
- We propose to investigate flavour-specific CP asymmetries in non-leptonic $\bar{B}_d^0 \to D^+ K^-$ and $\bar{B}_s^0 \to D_s^+ \pi^-$ decays

	SM	Exp. sensitivity (Run 3 LHCb)	NP
$\langle A^s_{\rm untagged} \rangle$	$\sim 10^{-5}$	10^{-3}	up to 0.4

- Prospects to study also $\langle A^d_{\rm untagged} \rangle$ by LHCb and Belle II