Time dependence in $B \to V\ell\ell$

Sébastien Descotes-Genon

Laboratoire de Physique Théorique
CNRS & Université Paris-Sud, 91405 Orsay, France

Novel aspects of $b \to s$ transitions
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LPT Orsay

New observables for $b \to s\ell\ell$

Need for new $b \to s\ell\ell$ observables

- cross-check hadronic and/or NP contributions
- try different incoming and outgoing states
- more information on $B \to V\ell\ell$?

- Angular analysis of $B \to V\ell\ell$ provides interferences between transversity amplitudes, but redundancy in the information
- Add another phase/amplitude to interfere and lift the redundancy ?
- Similar to CP-violation in B-decays: interference between decay and mixing adds information compared to decay alone

Time-dependent analysis of $B \to V\ell\ell$
where V decays into a CP-eigenstate

SDG and J. Virto, JHEP 1504 (2015) 045 [1502.05509]

Decays of interest

Need V to decay into CP-eigenstate

- Not possible for flavour specific decays $B_d \to K^{*0}(\to K^- \pi^+)\ell^+\ell^-$
- Accessible via flavour non-specific decays

Three main examples in the following

$$\begin{aligned} B_d &\to K^*(\to K_S \pi^0)\ell^+\ell^- \\ B_s &\to \phi(\to K_S K_L)\ell^+\ell^- \\ B_s &\to \phi(\to K^+ K^-)\ell^+\ell^- \end{aligned}$$

Last one already studied at LHCb (time integrated) JHEP **1307**, 084 (2013)

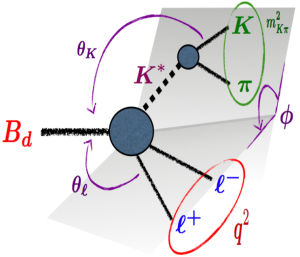
Kinematics for non-flavour specific decays

For untagged non-flavour-specific decays

- no possibility of distinguishing between B and $\bar{B}$ decays
- need for consistent kinematic conventions
- the angles cannot be defined with respect to information on the flavour of the initial B (contrary to flavour-specific decays)

$$\frac{d\Gamma[B \to V(\to M_1 M_2)\ell^+\ell^-]}{ds\, d\cos\theta_\ell\, d\cos\theta_M\, d\phi} = \sum_i J_i(s) f_i(\theta_\ell, \theta_M, \phi)$$

$$\frac{d\Gamma[\bar{B} \to \bar{V}(\to \bar{M}_1 \bar{M}_2)\ell^+\ell^-]}{ds\, d\cos\theta_\ell\, d\cos\theta_M\, d\phi} = \sum_i \zeta_i \bar{J}_i(s) f_i(\theta_\ell, \theta_M, \phi)$$



- $f_i(\theta_\ell, \theta_M, \phi)$ are kinematical functions
- J interf. of A_X and A_Y, with $X, Y \in \{L0, R0, L||, R||, L\perp, R\perp, t, S\}$
- $\bar{J}$ with $\bar{A}_X = A_X(\bar{B} \to \bar{M}_1 \bar{M}_2 \ell\ell) = A_X[\varphi_{weak} \to -\varphi_{weak}]$
- $\zeta_i = 1$ for $i = 1s, 1c, 2s, 2c, 3, 4, 7,\quad \zeta_i = -1$ for $i = 5, 6s, 6c, 8, 9$

Two CP-related amplitudes

$M_1 M_2$ CP eigenstate: two amplitudes CP-related to $A_X(B \to M_1 M_2 \ell\ell)$

- Theoretical: CP-conjugated amplitudes

$$\bar{A}_X = A_X(\bar{B} \to \bar{M}_1 \bar{M}_2 \ell\ell) = A_X[\varphi_{weak} \to -\varphi_{weak}]$$

- Phenomenological: Decay from $\bar{B}$ into the same final state

$$\widetilde{A}_X = A_X(\bar{B} \to M_1 M_2 \ell\ell)$$

From [Dunietz et al. 1991] transversity analysis for $B \to A(\to A_1 A_2) C(\to C_1 C_2)$

$$\widetilde{A}_X = \eta_X \bar{A}_X \qquad \eta_{L0,L||,R0,R||,t} = \eta \qquad \eta_{L\perp,R\perp,S} = -\eta \qquad \eta = 1$$

so that $\widetilde{J}_i = \zeta_i \bar{J}_i$, and $d\Gamma[\bar{B} \to \bar{V}(\to \bar{M}_1 \bar{M}_2)\ell^+\ell^-]$ involves $\widetilde{J}_i$

Untagged $d\Gamma(B \to V\ell\ell) + d\Gamma(\bar{B} \to \bar{V}\ell\ell)$ yields $J_i + \widetilde{J}_i = J_i + \zeta_i \bar{J}_i$, with both CP-conserving ($\zeta_i = 1$) and CP-violating quantities ($\zeta_i = -1$)

Time dependence

Time-dependence of decay amplitudes is straightforward,
involving decays into the same CP-eigenstate

$$\begin{aligned} A_X(t) &= A_X(B(t) \to V(\to f_{CP}) \to \ell^+\ell^-) = g_+(t)A_X + \frac{q}{p} g_-(t)\widetilde{A}_X , \\ \widetilde{A}_X(t) &= A_X(\bar{B}(t) \to V(\to f_{CP})\ell^+\ell^-) = \frac{p}{q} g_-(t)A_X + g_+(t)\widetilde{A}_X , \end{aligned}$$

where $g_\pm(t)$ are time-evolution functions and $q/p = e^{i\phi}$

Time dependence of angular coefficients is given by

$$\begin{aligned} J_i(t) + \widetilde{J}_i(t) &= e^{-\Gamma t}\Big[(J_i + \widetilde{J}_i)\cosh(y\Gamma t) - h_i \sinh(y\Gamma t)\Big] \\ J_i(t) - \widetilde{J}_i(t) &= e^{-\Gamma t}\Big[(J_i - \widetilde{J}_i)\cos(x\Gamma t) - s_i \sin(x\Gamma t)\Big] \end{aligned}$$

- $y = \Delta\Gamma/(2\Gamma)$ (small for B_d and B_s)
- $x = \Delta m/\Gamma$ ($x_d \simeq 0.77$, $x_s \simeq 27$)

Observables from time dependence

$$J_i(t) + \widetilde{J}_i(t) = e^{-\Gamma t}\Big[(J_i + \widetilde{J}_i)\cosh(y\Gamma t) - h_i \sinh(y\Gamma t)\Big] ,$$

$$J_i(t) - \widetilde{J}_i(t) = e^{-\Gamma t}\Big[(J_i - \widetilde{J}_i)\cos(x\Gamma t) - s_i \sin(x\Gamma t)\Big] ,$$

Similarly to CP-violation in interf between mixing and decay, new observables from interf between 2 decay ampli. and mixing (phase ϕ)

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

$$\widetilde{J}_8 = \frac{1}{\sqrt{2}}\beta_\ell^2 \left[\mathrm{Im}(\widetilde{A_0^L}\widetilde{A_\perp^L}^{\,*} + \widetilde{A_0^R}\widetilde{A_\perp^R}^{\,*})\right] = -\frac{1}{\sqrt{2}}\beta_\ell^2 \left[\mathrm{Im}(\bar{A}_0^L \bar{A}_\perp^{L\,*} + \bar{A}_0^R \bar{A}_\perp^{R\,*})\right] ,$$

$$h_8 = \frac{1}{\sqrt{2}}\beta_\ell^2 \mathrm{Im}[e^{i\phi}\{\widetilde{A}_0^L A_\perp^{L*} + \widetilde{A}_0^R A_\perp^{R*}\} + e^{-i\phi}\{A_0^L \widetilde{A}_\perp^{L*} + A_0^R \widetilde{A}_\perp^{R*}\}]$$

$$s_8 = -\frac{1}{\sqrt{2}}\beta_\ell^2 \mathrm{Re}[e^{i\phi}\{\widetilde{A}_0^L A_\perp^{L*} + \widetilde{A}_0^R A_\perp^{R*}\} - e^{-i\phi}\{A_0^L \widetilde{A}_\perp^{L*} + A_0^R \widetilde{A}_\perp^{R*}\}]$$

h_i's boil down to J_i's in the limit where weak phases neglected

Sorting out observables

$$J_i(t) + \widetilde{J}_i(t) = e^{-\Gamma t}\left[(J_i + \widetilde{J}_i)\cosh(y\Gamma t) - h_i \sinh(y\Gamma t)\right] ,$$

$$J_i(t) - \widetilde{J}_i(t) = e^{-\Gamma t}\left[(J_i - \widetilde{J}_i)\cos(x\Gamma t) - s_i \sin(x\Gamma t)\right] ,$$

- $y \ll 1$: h_i difficult to extract
- from $(d\Gamma + d\bar{\Gamma})/dq^2$, one gets $3(2h_{1s} + h_{1c}) - (2h_{2s} + h_{2c})$ (boils down to the corresponding J's if $\varphi_{\rm weak} \to 0$)
- s_i for $i = 1s, 1c, 2s, 2c, 3, 4, 7$: CP-asymmetries $J_i - \bar{J}_i$
- s_i for $i = 5, 6s, 6c, 8, 9$: CP-averaged angular coefficients $J_i + \bar{J}_i$.

If vanishing phases ($\varphi_{\rm weak} \to 0$, decay amplitudes real)

- s_i for $i = 1s, 1c, 2s, 2c, 3, 4, 5, 6s, 6c$ vanish: $s_i \sim {\rm Im}(e^{i\phi}\bar{A}_X A_Y^*)$
- $s_7 = 0$ (no phases in decay amplitudes is enough)
- $(J_i - \widetilde{J}_i)_{i=8,9}$ vanish $[\rm Im]$ whereas $s_{8,9}$ expected to be large $[\rm Re]$

$\Longrightarrow s_8$ and s_9 are the most interesting coefficients

New information ?

Not all observables contain new information : there is some redundancy already in the J_i's

[Matias, Mescia, Ramon, Virto 2012]

- In the flavour-specific case (massless case without scalar contributions), unitary transformation U of

$$n_i = \begin{pmatrix} A_i^L \\ \sigma_i A_i^{R*} \end{pmatrix} \to U n_i \qquad \sigma_0 = \sigma_{||} = 1, \sigma_\perp = -1$$

  leave the angular coefficient J_i unchanged: only observables invariant under these unitarity transformations can be measured
- in the limit of vanishing weak phases, h_i do not contain genuinely new information compared to the J_i

  (but useful as independent cross-checks of J_i measurements)
- $s_{5,6c,8,9}$ contain new pieces of information

$\Longrightarrow s_8$ and s_9 are the most interesting coefficients

Time dependent vs time integrated

From time-integrated observables ? Time integration different for hadronic machines and B-factories (quantum entanglement)

$$\langle X\rangle_{\rm Hadronic} = \int_0^\infty e^{-\Gamma t}\ldots \qquad \langle X\rangle_{\rm B-factory} = \int_{-\infty}^\infty e^{-\Gamma|t|}\ldots$$

$$\begin{aligned}
\langle J_i + \widetilde{J}_i\rangle_{\rm Hadronic} &= \frac{1}{\Gamma}\left[\frac{1}{1-y^2}\times(J_i+\widetilde{J}_i) - \frac{y}{1-y^2}\times h_j\right] ,\\
\langle J_i - \widetilde{J}_i\rangle_{\rm Hadronic} &= \frac{1}{\Gamma}\left[\frac{1}{1+x^2}\times(J_i-\widetilde{J}_i) - \frac{x}{1+x^2}\times s_j\right] ,\\
\langle J_i + \widetilde{J}_i\rangle_{\rm B-fact} &= \frac{2}{\Gamma}\frac{1}{1-y^2}[J_i+\widetilde{J}_i] , \qquad \langle J_i - \widetilde{J}_i\rangle_{\rm B-fact} = \frac{2}{\Gamma}\frac{1}{1+x^2}[J_i-\widetilde{J}_i]
\end{aligned}$$

s_i and h_i from time-integrated measurements

- only at hadronic machines (but tagging needed for s_i)
- suppressed by y or in observables suppressed by $1/(1+x^2)$
- needed to analyse LHCb $B_s \to \phi\ell\ell$ in terms of transversity ampl.

Optimised observables from time dependence

s_8, s_9

- contain information that is not accessible otherwise
- come from $J_i - \widetilde{J}_i$, and thus require tagging
- but are not present in time-integrated measurement at B-factory

$\Longrightarrow$hadronic with tagging or B-factory with time-dependence

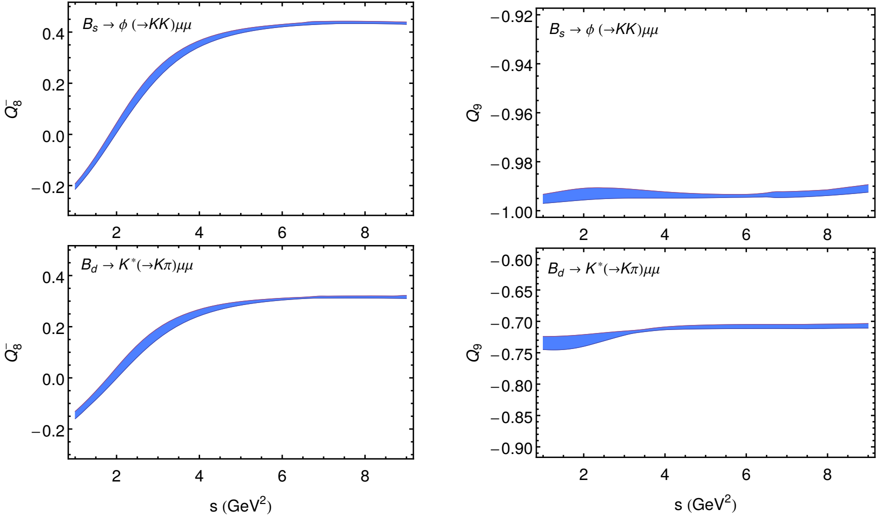
It is possible to define optimised observables at large hadronic recoil, with a limited sensitivity to form factors

$$Q_8^- = \frac{s_8}{\sqrt{-2(J_{2c} + \widetilde{J}_{2c})[2(J_{2s} + \widetilde{J}_{2s}) - (J_3 + \widetilde{J}_3)]}} ,$$

$$Q_9 = \frac{s_9}{2(J_{2s} + \widetilde{J}_{2s})} .$$

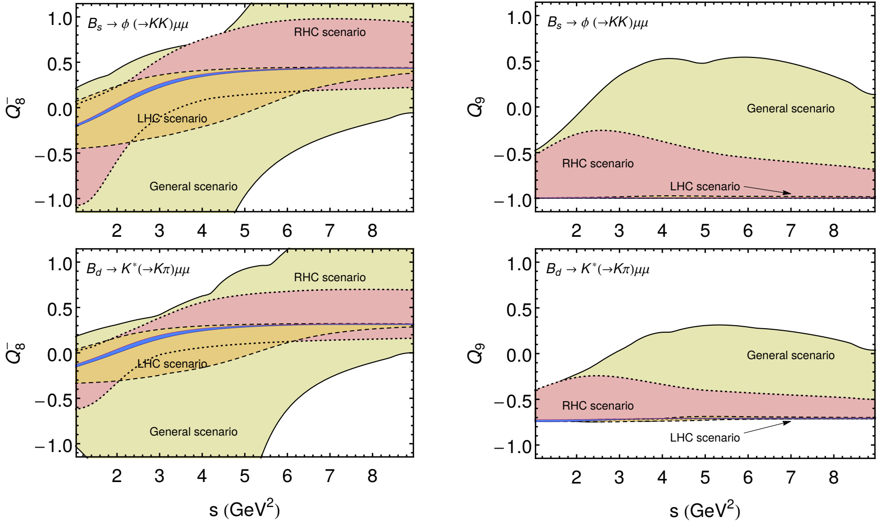
similarly to what is done to translate J_i into P_i

Q_8, Q_9: SM predictions



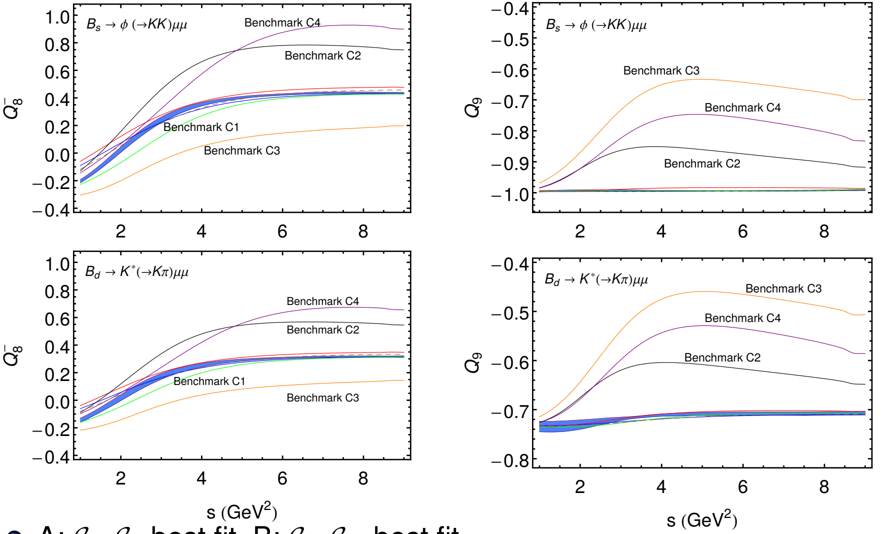
- In SM, $Q_9 \simeq -\cos(\phi - 2\beta_s)$, modified in presence of RHC
- In SM, zero of Q_8 given at LO by: $\frac{s_0}{m_B^2} \simeq \frac{-2\mathcal{C}_7(2\mathcal{C}_7+\mathcal{C}_9)}{\mathcal{C}_{10}^2+(2\mathcal{C}_7+\mathcal{C}_9)\mathcal{C}_9}$

Q_8, Q_9: General NP scenarios



- LHC: $\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}$ only, RHC: $\mathcal{C}_{7'}, \mathcal{C}_{9'}, \mathcal{C}_{10'}$ only, General NP: All
- varying in $3\,\sigma$ ranges of [SDG, Matias, Virto 2013] (see backup)

Q_8, Q_9: Benchmark points



- A: $\mathcal{C}_7, \mathcal{C}_9$ best fit, B: $\mathcal{C}_9, \mathcal{C}_{9'}$ best fit
- C: $\mathcal{C}_{9(')}, \mathcal{C}_{10(')}$ scenarios, D: general best fit

(see backup)

Conclusion

Time-dependent analysis of $B \to V\ell\ell$ with V into CP eigenstate

- Mixing allowing richer pattern of interferences
- Concerns both $B_d \to K^*(\to K_S\pi^0)\ell^+\ell^-$ and $B_s \to \phi(\to K_SK_L)\ell^+\ell^-$, $B_s \to \phi(\to K^+K^-)\ell^+\ell^-$
- Two interesting new observables s_8 and s_9
- Hadronic colliders with tagging or B-factory with time dep.

Optimised versions Q_8 and Q_9

- Accurate predictions in the SM
- $Q_9 + \cos(\phi - \beta_s) = 0$ test of right-handed currents
- Good sensitivity to NP scenarios

How realistic to get them measured ?

Backup

General NP scenarios (Fig p13)

$$\mathcal{C}_i = \mathcal{C}_i^{\rm SM} + \mathcal{C}_i^{\rm NP} \ ,$$

taking 3 σ ranges fro fit to $b \to s\gamma$ and $b \to s\ell\ell$ in [SDG, Matias, Virto 2013]

$$\mathcal{C}_7^{\rm NP} \in (-0.08, 0.03) \ , \quad \mathcal{C}_9^{\rm NP} \in (-2.1, -0.2) \ , \quad \mathcal{C}_{10}^{\rm NP} \in (-2.0, 3.0) \ ,$$
$$\mathcal{C}_{7'}^{\rm NP} \in (-0.14, 0.10) \ , \quad \mathcal{C}_{9'}^{\rm NP} \in (-1.2, 1.8) \ , \quad \mathcal{C}_{10'}^{\rm NP} \in (-1.4, 1.2) \ .$$

- LHC (Left-Handed Currents) scenario (orange, dashed): NP contributions to $\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}$ only.
- RHC (Right-Handed Currents) scenario (red dotted): NP contributions to $\mathcal{C}_{7'}, \mathcal{C}_{9'}, \mathcal{C}_{10'}$ only.
- General NP scenario (green solid): NP contributions to all six coefficients $\mathcal{C}_{7^{(\prime)}}, \mathcal{C}_{9^{(\prime)}}, \mathcal{C}_{10^{(\prime)}}$

NP Benchmarks (Fig p14)

A. Best fit point in the $\mathcal{C}_7 - \mathcal{C}_9$ scenario of [1307.5683]

$$\mathcal{C}_7^{\rm NP} = -0.02, \quad \mathcal{C}_9^{\rm NP} = -1.6 \,.$$

B. Best fit point in the $\mathcal{C}_9 - \mathcal{C}_{9'}$ scenario of [1411.3161]

$$\mathcal{C}_9^{\rm NP} = -1.28, \quad \mathcal{C}_{9'}^{\rm NP} = 0.47 \,.$$

C. Z'-motivated $\mathcal{C}_{9^{(\prime)}}, \mathcal{C}_{10^{(\prime)}}$ scenarios [1211.1896,1309.2466]

- C1: $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP} = -1$
- C2: $\mathcal{C}_{9'}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP} = 1$
- C3: $\mathcal{C}_9^{\rm NP} = \mathcal{C}_{9'}^{\rm NP} = -\mathcal{C}_{10}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP} = -1$
- C4: $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP} = -\mathcal{C}_{10}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP} = -1$

C1 and C2 in singlet/triplet and doublet leptoquark models [1408.1627]

D. Best fit point in the general fit of [1307.5683]

$$\begin{aligned}\mathcal{C}_7^{\rm NP} &= -0.02 \,,\ \mathcal{C}_9^{\rm NP} = -1.3 \,,\ \mathcal{C}_{10}^{\rm NP} = 0.3 \,,\\ \mathcal{C}_{7'}^{\rm NP} &= -0.01 \,,\ \mathcal{C}_{9'}^{\rm NP} = 0.3 \,,\ \mathcal{C}_{10'}^{\rm NP} = 0 \,.\end{aligned}$$