

Measurements of CP violation in charmless 2-body B meson decays at LHCb

40th International Conference on High Energy Physics
Prague, Czech Republic

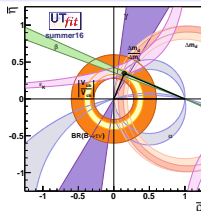
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on behalf of the LHCb collaboration

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July 28 - August 6 2020

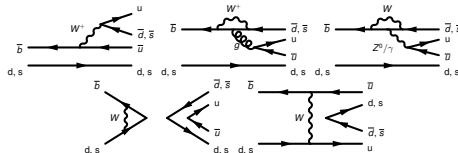
Motivations



- CPV observables are sensitive to CKM angles α/ϕ_2 , γ/ϕ_3 , β/ϕ_1 and β_s/ϕ_s
- A rich set of physics processes contributes to the $H_b \rightarrow h^+ h'^-$ decays ($h = K, \pi$)
 - tree and penguin decay topologies
 - neutral B mixing

Presence of loop diagrams:

- introduces **hadronic uncertainties** as additional parameters in the decay-amplitude
- makes the CPV observables sensitive to **New Physics** contributions



Mixing diagrams



PL B 459 (1999) 306
 PL B 621 (2005) 126
 PL B 741 (2015) 1
 PR D 94 (2016) 113014
 EPJ C 71(2011) 1532
 JHEP 03 (2017) 55
 JHEP 10 (2012) 029
 EPJ C 77 (2017) 574

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CPV observables

- Time-integrated CP asymmetry in $B^0 \rightarrow K^+ \pi^-$ and $B_s \rightarrow \pi^+ K^-$

$$A_{CP} = \frac{|\bar{A}_f|^2 - |A_f|^2}{|\bar{A}_f|^2 + |A_f|^2}$$

- Time-dependent CP asymmetry in $B^0 \rightarrow \pi^+ \pi^-$ and $B_s^0 \rightarrow K^+ K^-$ decays

$$A(t) = \frac{\Gamma_{\bar{B}^0(s) \rightarrow f}(t) - \Gamma_{B^0(s) \rightarrow f}(t)}{\Gamma_{\bar{B}^0(s) \rightarrow f}(t) + \Gamma_{B^0(s) \rightarrow f}(t)} = \frac{-\mathbf{C}_f \cos(\Delta m_{d(s)} t) + \mathbf{S}_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta \Gamma_{d(s)}}{2} t\right) + \mathbf{A}_f^{\Delta \Gamma} \sinh\left(\frac{\Delta \Gamma_{d(s)}}{2} t\right)}$$

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}$$

direct CPV

$$S_f = \frac{2 \operatorname{Im} \lambda_f}{1 + |\lambda_f|^2}$$

mixing induced CPV

$$A_f^{\Delta \Gamma} = \frac{2 \operatorname{Re} \lambda_f}{1 + |\lambda_f|^2}$$

$$|C_f|^2 + |S_f|^2 + |A_f^{\Delta \Gamma}|^2 = 1$$

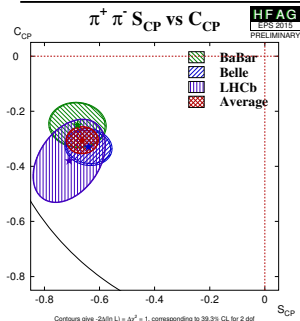
constraint not imposed

$$\lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f}$$

Status of art

- Direct CPV in $B_{(s)}^0 \rightarrow K^\pm \pi^\mp$ are dominated by LHCb ($\mathcal{L} = 1 \text{ fb}^{-1}$)
- $C_{\pi\pi}$ and $S_{\pi\pi}$ well measured by B-factories and LHCb using $B^0 \rightarrow \pi^+ \pi^-$
 - all three experiments are in good agreement

	$A_{CP}(B^0 \rightarrow K^+ \pi^-)$	$A_{CP}(B_s^0 \rightarrow \pi^+ K^-)$	$C_{\pi\pi}$	$S_{\pi\pi}$
BaBar ¹	$-0.107 \pm 0.016^{+0.006}_{-0.004}$	-	$-0.25 \pm 0.08 \pm 0.02$	$-0.68 \pm 0.10 \pm 0.03$
Belle ^{2,3}	$-0.069 \pm 0.014 \pm 0.007$	-	$-0.33 \pm 0.06 \pm 0.03$	$-0.64 \pm 0.08 \pm 0.03$
CDF ⁴	$-0.083 \pm 0.013 \pm 0.004$	$0.22 \pm 0.07 \pm 0.02$	-	-
LHCb ^{5,6}	$-0.080 \pm 0.007 \pm 0.003$	$0.27 \pm 0.04 \pm 0.01$	$-0.38 \pm 0.15 \pm 0.02$	$-0.71 \pm 0.13 \pm 0.02$
Average ⁷	-0.082 ± 0.006	0.26 ± 0.04	-0.31 ± 0.05	-0.66 ± 0.06



- C_{KK} and S_{KK} measured only by LHCb using $B_s \rightarrow K^+ K^-$, 1 fb^{-1}
- No measurement available for $A_{KK}^{\Delta\Gamma}$

$$C_{KK} = 0.14 \pm 0.11 \pm 0.03$$

$$S_{KK} = 0.30 \pm 0.12 \pm 0.04$$

1: PRD 87 (2013) 052009

2: PRD 87 (2013) 031103

3: PRD 88 (2013) 092003

4: PRL 113 (2014) 242001

5: PRL 110 (2013) 221601

6: JHEP 1310 (2013) 183

7: HFLAV average

Main ingredients of the analysis

- Analysis performed using full Run 1 data sample ($\sim 3 \text{ fb}^{-1}$)
- All the CP parameters are determined with a multidimensional fit performed simultaneously on the $K^\pm \pi^\mp$, $\pi^+ \pi^-$ and $K^+ K^-$ spectra

Time-integrated CPV

- decay modes:
 - $B^0 \rightarrow K^\pm \pi^\mp$
 - $B_s^0 \rightarrow \pi^\pm K^\pm$
- **final state detection asymmetries** (A_F)
- **production asymmetry** (A_P): extrapolated directly from A_{CP} by means of the time-dependent fit

$$A_{raw} \sim A_{CP} + A_F + A_P$$

Time-dependent CPV

- decay modes:
 - $B^0 \rightarrow \pi^+ \pi^-$
 - $B_s^0 \rightarrow K^+ K^-$
- **flavour tagging**:
$$D_{tag} = (1 - 2\omega)$$
- **decay-time resolution** (σ_t):
$$D = \exp(-\sigma_t^2 \Delta m^2 / 2)$$
- **decay-time acceptance**

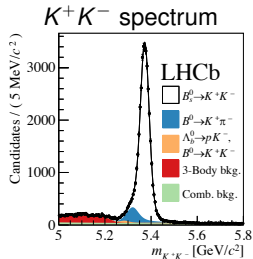
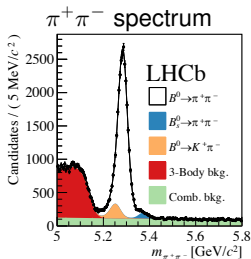
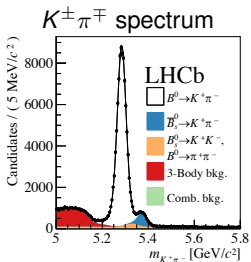
$$A_{raw}(t) \sim D_{tag} D A(t)$$

Event selection

- A **PID selection** is applied to separate the three final states and reduce the amount of cross contamination from the other $H_b \rightarrow h^+ h'^-$ to a $\sim 10\%$ of the signal
- A **MVA algorithm** based on a BDT is used to reduce the combinatorial background $\Rightarrow \text{F.O.M} = S/\sqrt{S+B}$

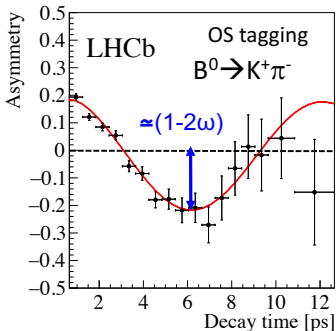
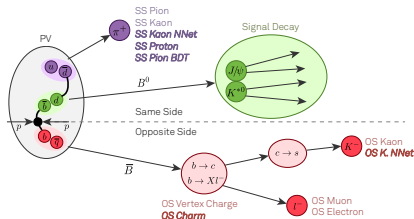
$B^0 \rightarrow \pi^+ \pi^-$	$B_s \rightarrow K^+ K^-$
$\sim 28\,600$	$\sim 36\,800$
$B^0 \rightarrow K^+ \pi^-$	$B_s \rightarrow \pi^+ K^-$
$\sim 94\,200$	$\sim 7\,000$

[Phys. Rev. D 98 (2018) 032004]



Flavour tagging

- “*Same Side*” (SS) if the tagging particle comes from the **signal B** fragmentation
- “*Opposite Side*” (OS) if the tagger exploits the charge information of the **opposite B** decay



[Phys. Rev. D 98 (2018) 032004]

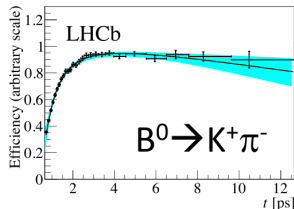
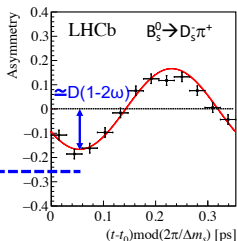
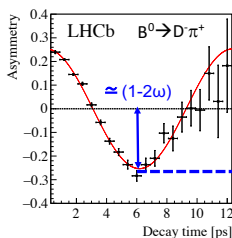
- Each tagger provides a tagging decision and a mistag rate (ω)
 \Rightarrow tagging dilution: $D_{tag} = (1 - 2\omega)$
- Tagging efficiency: ε_{tag}
- Tagging power: $\varepsilon_{eff} = \varepsilon_{tag} D_{tag}^2$

$$\sigma^{stat}(CP \text{ asym}) \propto \frac{1}{\sqrt{\varepsilon_{eff} N}}$$

- Calibration on control samples is performed for obtaining an unbiased estimation of ω

Decay-time resolution & acceptance

- Calibration is performed measuring simultaneously the time-dependent asymmetries of $B^0 \rightarrow D^- \pi^+$ and $B_s^0 \rightarrow D_s^- \pi^+$
- Raw asymmetries diluted by $D_{tag} = (1 - 2\omega)$ and $D = \exp(-\sigma_t^2 \Delta m^2 / 2)$
 \Rightarrow **dilution from σ_t negligible for B^0 due to small Δm_d**
- Reconstruction efficiency as a function of decay-time is determined using $B^0 \rightarrow K^+ \pi^-$ decays
 - Untagged decay rate of B^0 as a function of time is a pure exponential
 - Fully simulated samples are used to study the differences of the other decay modes w.r.t. $B^0 \rightarrow K^+ \pi^-$



[Phys. Rev. D 98 (2018) 032004]

Other sources of asymmetry

- The time dependent asymmetry is measured as:

$$A_{raw}(t) \approx A_{CP} + A_D + A_{PID} + A_P \cos(\Delta m_{d(s)} t)$$

- The **production asymmetry** A_P can be extracted by means of the time-dependent fit from the CP asymmetries in $B^0 \rightarrow K^+ \pi^-$ and $B_s \rightarrow \pi^+ K^-$ decays
- A correction is required taking into account:
 - asymmetry induced by the PID requirements** ($A_{PID}^{K\pi}$)
 - detection asymmetry** ($A_D^{K\pi}$)
- $A_{PID}^{K\pi}$ estimated using $D^{*+} \rightarrow D^0(\rightarrow K^- \pi^+) \pi^+$
- $A_D^{K\pi}$ measured using raw asymmetries of Cabibbo-favoured charm decays $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^+ \rightarrow K^0 \pi^+$ [JHEP 07 (2014) 041]
- Asymmetries are convoluted with the $B_{(s)}^0 \rightarrow h^+ h'^- \pi^0$ phase space

$A_{PID}^{K\pi}(B_{(s)}^0 \rightarrow K^\pm \pi^\mp)$	=	$(-0.04 \pm 0.25)\%$
$A_D^{K\pi}(B^0 \rightarrow K^+ \pi^-)$	=	$(-0.900 \pm 0.141)\%$
$A_D^{K\pi}(B_s \rightarrow \pi^+ K^-)$	=	$(-0.924 \pm 0.142)\%$

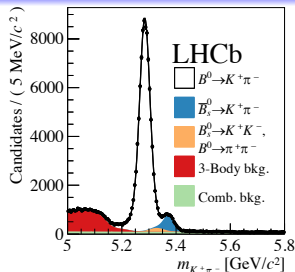
[Phys. Rev. D 98 (2018) 032004]

Results of the $K^\pm \pi^\mp$ final state [Phys. Rev. D 98 (2018) 032004]

- Most precise measurement from a single experiment

$$A_{CP}^{B^0} = (-8.4 \pm 0.4 \pm 0.3)\%$$

$$A_{CP}^{B_s^0} = (21.3 \pm 1.5 \pm 0.3)\%$$



- Production asymmetry is subtracted by means of the time-dependent fit

$$A_P(B^0) = (0.19 \pm 0.60)\%$$

$$A_P(B_s^0) = (2.4 \pm 2.1)\%$$

(compatible with expectation from Phys. Lett. B 774 (2017) 139)

- SM test assuming U-spin validity [PLB 621 (2005) 126]

$$\Delta = \frac{A_{CP}^{B^0}}{A_{CP}^{B_s^0}} + \frac{\mathcal{B}(B_s^0 \rightarrow \pi^+ K^-)}{\mathcal{B}(B^0 \rightarrow K^+ \pi^-)} \frac{\tau_d}{\tau_s} = -0.11 \pm 0.03 \pm 0.04 \text{ (from } A_{CP} \text{)}$$

Results of the $\pi^+\pi^-/K^+K^-$ final states [Phys. Rev. D 98 (2018) 032004]

- Most precise measurement from a single experiment
- Uncertainties halved wrt previous LHCb results

$$C_{\pi\pi} = -0.34 \pm 0.06 \pm 0.01$$

$$S_{\pi\pi} = -0.63 \pm 0.05 \pm 0.01$$

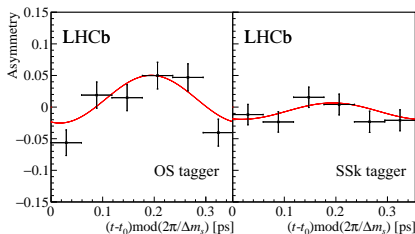
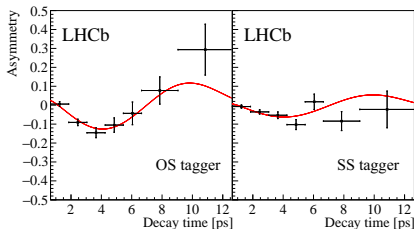
$$\rho(C_{\pi\pi}, S_{\pi\pi}) = 0.448$$

- Very first measurement of $A_{KK}^{\Delta\Gamma}$
- Strongest evidence of CPV in B_s^0 sector: confirmed at 4σ

$$C_{KK} = 0.20 \pm 0.06 \pm 0.02$$

$$S_{KK} = 0.18 \pm 0.06 \pm 0.02$$

$$A_{KK}^{\Delta\Gamma} = -0.79 \pm 0.07 \pm 0.10$$



Conclusions

- The latest measurements of CPV in B meson decays to charmless charged 2-body final states at LHCb have been presented [Phys. Rev. D 98 (2018) 032004]
- Analysis is based on the full Run 1 sample corresponding to an integrated luminosity of 1 fb^{-1} at 7 TeV and 2 fb^{-1} at 8 TeV
- **Significant improvement with respect to previous measurements**
 - best measurement of $C_{\pi\pi}$ and $S_{\pi\pi}$ from a single experiment
 - best measurement of $A_{CP}^{B^0}$ and $A_{CP}^{B_s^0}$ from a single experiment
 - strongest evidence of CPV in $B_s^0 \rightarrow K^+ K^-$ decay at 4σ
- Analysis update based on Run 2 data sample is close to be published
- Run1+Run2 combination expected to exceed 5σ for CPV in $B_s^0 \rightarrow K^+ K^-$
- Analysis targets are summer conferences, so please stay tuned!



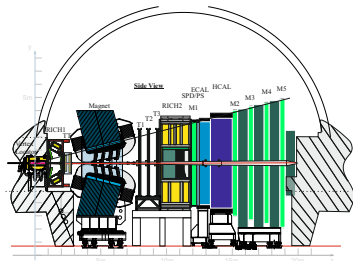
Thank you for your attention!



Backup

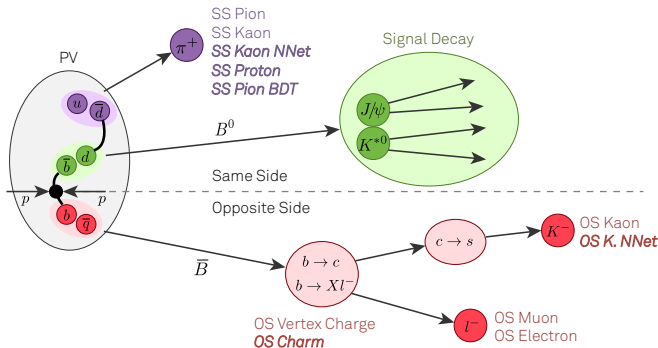
The Large Hadron Collider beauty (LHCb) Experiment

- LHCb detector is a single-arm forward spectrometer optimised for b and c hadron physics
 - pseudorapidity range: $[2,5] \Rightarrow \sim 25\% \, b\bar{b}$ pairs in LHCb acceptance
- **High precision measurements** in flavour physics (e.g. CKM, beyond SM)
- Collected data:
 - Run1 (2010-2012) $\Rightarrow \approx 3 \, \text{fb}^{-1}$
 - Run2 (2015-2018) $\Rightarrow \approx 4$ (already taken) + 2 (expected) fb^{-1}
- Excellent performances
[Int. J. Mod. Phys. A 30, 1520022 (2015)]:
 - **Momentum resolution:**
 $\frac{\sigma_p}{p} \approx 0.5 - 0.8\% \, (p < 100 \, \text{GeV}/c)$
 - **Impact Parameter (IP) resolution:**
 $\sigma_{IP} \approx 20 \, \mu\text{m}$ (at high p_T)
 - **Decay time resolution:**
 $\sigma_t \approx 50 \, \text{fs}$
 - **Particle Identification (PID):**
 $\varepsilon(K) \approx 95\%, \pi \text{ mis-ID} \approx 5\% \, (p < 100 \, \text{GeV}/c)$
 $\varepsilon(\mu) \approx 97\%, \pi \text{ mis-ID} \approx 1\text{-}3\%$



Flavour Tagging algorithms

- “*Same Side*” (SS): exploit the charge of the particle (π , p , K) produced in the fragmentation of the **signal b-hadron** to infer its flavour at production
- “*Opposite Side*” (OS): exploit the charge of the particle (l , K , c -decays) or of the reconstructed secondary vertex produced from the **opposite b-hadron** to infer the **signal b-hadron** flavour at production



Tagging performance

- **Tagging Efficiency:** fraction of tagged events

$$\varepsilon_{tag} = \frac{N_{wrong} + N_{right}}{N_{wrong} + N_{right} + N_{untag}}$$

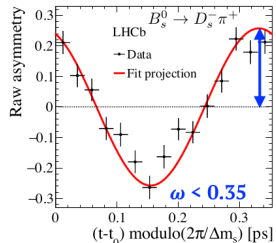
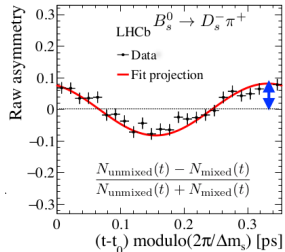
- correlated with the transverse momentum of the signal B
- **Mistag probability:** fraction of the events with wrong tag decision, defined in range [0, 0.5].

$$\omega = \frac{N_{wrong}}{N_{right} + N_{wrong}}$$

- **Dilution:** $D = (1 - 2\omega)$ of asymmetries and decay rates.
 - Predicted mistag probability η computed by taggers needs calibration $\omega(\eta)$ to provide unbiased estimate of the mistag probability ω
- **Tagging power:** statistical degradation of CP asymmetries

$$\varepsilon_{eff} = \varepsilon_{tag} D^2 = \varepsilon_{tag} \langle (1 - 2\omega)^2 \rangle$$

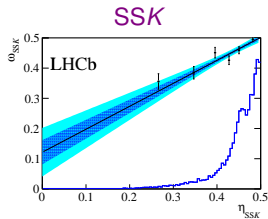
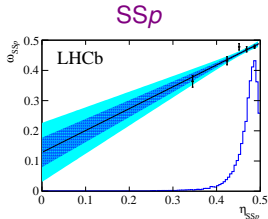
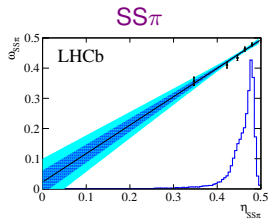
$$\sigma^{stat}(CP \text{ asym}) \propto \frac{1}{\sqrt{\varepsilon_{eff} N}}$$



[JINST 11 (2016) P05010]

Flavour tagging calibration

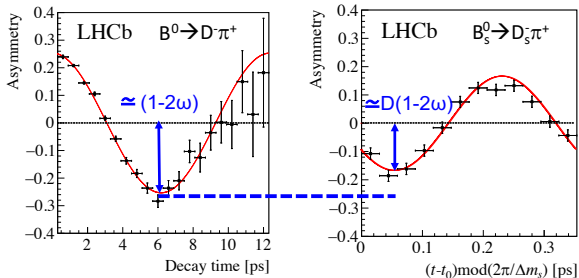
- Calibration of the predicted mistag rate η is crucial step in order to obtain an unbiased estimation of the mistag probability ω
- Natural control samples are $B^0 \rightarrow K^+ \pi^-$ and $B_s^0 \rightarrow \pi^+ K^-$
- **OS** tagger is calibrated on the fly using $B^0 \rightarrow K^+ \pi^-$: no distinction between B^0 and B_s^0
- **SS π** and **SS p** calibrated using $B^0 \rightarrow K^+ \pi^-$ and then combine into a unique tagging algorithm **SScomb**.
- **SScomb** calibrated on the fly using $B^0 \rightarrow K^+ \pi^-$ (B^0 only)
- **SSK** calibrated using a sample of $B_s^0 \rightarrow D_s^- \pi^+$ decays (B_s^0 only)
 \Rightarrow yield of $B_s^0 \rightarrow \pi^+ K^-$ not sufficient to obtain a reliable calibration



[Phys. Rev. D 98 (2018) 032004]

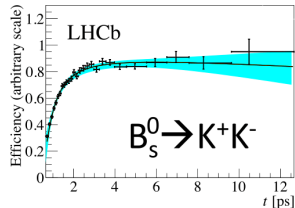
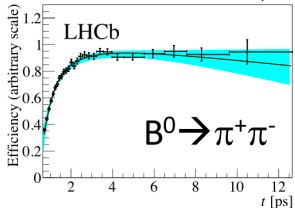
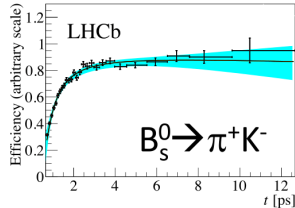
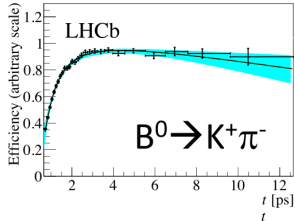
Decay-time resolution

- Calibration is performed measuring simultaneously the time-dependent asymmetries of $B^0 \rightarrow D^- \pi^+$ and $B_s^0 \rightarrow D_s^- \pi^+$
- Raw asymmetries diluted by:
 - **flavour tagging**: $D_{tag} = (1 - 2\omega)$
 - **decay-time resolution** $\Rightarrow D = \exp(-\sigma_t^2 \Delta m^2 / 2)$
- $B^0 \rightarrow D^- \pi^+$ decay used to calibrate tagging dilution
- $B_s^0 \rightarrow D_s^- \pi^+$ decay used to calibrate the decay-time resolution
 \Rightarrow **dilution from σ_t negligible for B^0 due to small Δm_d**
- Portability from $B_{(s)}^0 \rightarrow D_{(s)}^- \pi^+$ to $B_{(s)}^0 \rightarrow h^+ h'^-$ studied using fully simulated events



Decay-time acceptance

- Reconstruction efficiency as a function of decay-time is determined using $B^0 \rightarrow K^+ \pi^-$ decays
 - Untagged decay rate of B^0 as a function of time is a pure exponential
 - Fully simulated samples are used to study the differences of the other decay modes w.r.t. $B^0 \rightarrow K^+ \pi^-$



[Phys. Rev. D 98 (2018) 032004]

Fixed parameters

Parameter	Value
Δm_d	$0.5065 \pm 0.0019 \text{ ps}^{-1}$
Γ_d	$0.6579 \pm 0.0017 \text{ ps}^{-1}$
$\Delta \Gamma_d$	0
Δm_s	$17.757 \pm 0.021 \text{ ps}^{-1}$
Γ_s	$0.6654 \pm 0.0022 \text{ ps}^{-1}$
$\Delta \Gamma_s$	$0.083 \pm 0.007 \text{ ps}^{-1}$
$\rho(\Gamma_s, \Delta \Gamma_s)$	-0.292

Systematic uncertainties

- Two main strategies:
 - Fixed parameters** → repeat the fit to data 100 times changing the parameter values according to their uncertainties and correlations with the other parameters
 - Models**: generating pseudo-experiments with the default model, then repeating the fit both with the default and the modified models
- The squared sum of the mean and the RMS of the variation is taken as systematic uncertainties

Parameters	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$C_{K^+K^-}$	$S_{K^+K^-}$	$A_{K^+K^-}^{\Delta\Gamma}$	$A_{CP}(B^0 \rightarrow K^+\pi^-)$	$A_{CP}(B_s \rightarrow \pi^+K^-)$
Time-dependent efficiency	0.0011	0.0004	0.0020	0.0017	0.0778	0.0004	0.0002
Time-resolution calibration	0.0014	0.0013	0.0108	0.0119	0.0051	0.0001	0.0001
Time-resolution model	0.0001	0.0005	0.0002	0.0002	0.0003	negligible	negligible
Input parameters	0.0025	0.0024	0.0092	0.0107	0.0480	negligible	0.0001
OS tagger calibration	0.0018	0.0021	0.0018	0.0019	0.0001	negligible	negligible
SSK tagger calibration	n/a	n/a	0.0061	0.0086	0.0004	n/a	n/a
SS tagger calibration	0.0015	0.0017	n/a	n/a	n/a	negligible	negligible
Cross-feed time model	0.0075	0.0059	0.0022	0.0024	0.0003	0.0001	0.0001
Three-body bkg.	0.0070	0.0056	0.0044	0.0043	0.0304	0.0008	0.0043
Comb. bkg. time model	0.0016	0.0016	0.0004	0.0002	0.0019	0.0001	0.0005
Signal mass model (reso)	0.0027	0.0025	0.0015	0.0015	0.0023	0.0001	0.0041
Signal mass model (tails)	0.0007	0.0008	0.0013	0.0013	0.0016	negligible	0.0003
Comb. bkg. mass model	0.0001	0.0003	0.0002	0.0002	0.0016	negligible	0.0001
PID asymmetry	n/a	n/a	n/a	n/a	n/a	0.0025	0.0025
Detection asymmetry	n/a	n/a	n/a	n/a	n/a	0.0014	0.0014
Total	0.0115	0.0095	0.0165	0.0191	0.0966	0.0030	0.0066

How to exploit $H_b \rightarrow h^+ h'^-$ decays

- CP asymmetries of $B^0 \rightarrow \pi^+ \pi^-$ decays
 - fundamental input to the isospin analysis to determine the CKM angle α/ϕ_2
- First proposal to include also $B_s^0 \rightarrow K^+ K^-$ decays dates back to 1999
 - exploiting U-spin symmetry to constraint QCD uncertainties and determine γ/ϕ_3 and $-2\beta_s/\phi_s$
- A_{CP} of $B^0 \rightarrow K^+ \pi^-$ and $B_s \rightarrow \pi^+ K^-$ provide a test of the SM assuming U-spin symmetry:

$$\Delta = \frac{A_{CP}^{B^0}}{A_{CP}^{B_s^0}} + \frac{\mathcal{B}(B_s^0 \rightarrow \pi^+ K^-)}{\mathcal{B}(B^0 \rightarrow K^+ \pi^-)} \frac{\tau_d}{\tau_s} = 0 \quad [\text{PLB 621 (2005) 128}]$$

- More recent studies aimed to reduce the impact of the uncertainty due to U-spin breaking:
 - combined analysis of $B^{0,\pm} \rightarrow \pi^{0,\pm} \pi^{0,\mp}$ and $B_s^0 \rightarrow K^+ K^-$
- Combining CP asymmetries of $B^0 \rightarrow \pi^+ \pi^-$ and $B_s^0 \rightarrow K^+ K^-$ with information from semileptonic $B^0 \rightarrow \pi l \nu$ and $B_s \rightarrow K l \nu$ allow to reduce the usage of U-spin symmetry [arXiv:1608.00901, arXiv:1612.07342]