CP violation in $B^0_{(s)} \to h^+ h'^-$

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Outline

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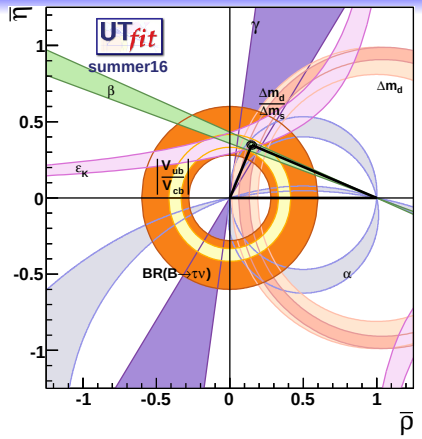
Motivations



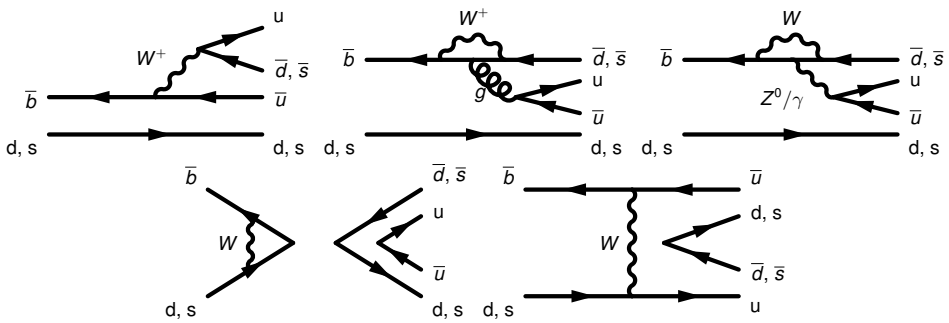
- *CPV* observables are sensitive to CKM angles α/ϕ_2, γ/ϕ_3, β/ϕ_1 and β_s/ϕ_s
- A rich set of physics processes contributes to the $H_b \to h^+ h'^-$ decays ($h = K, \pi$)
  - tree and penguin decay topologies
  - neutral B mixing

Presence of loop diagrams:

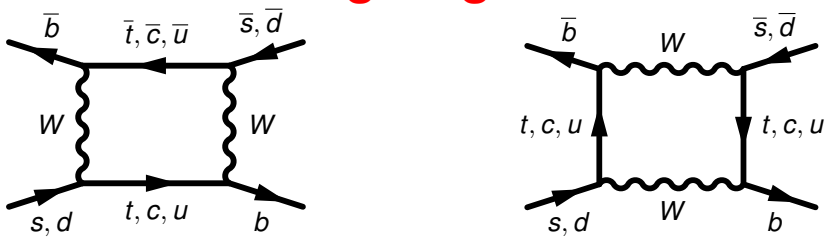
- introduces **hadronic uncertainties** as additional parameters in the decay-amplitude
- makes the *CPV* observables sensitive to **New Physics** contributions

PLB459(1999)306	PLB621(2005)126
PJC71(2011)1532	JHEP10(2012)029
PLB741(2015)1	PRD94(2016)113014
EPJ C77(2017)574	JHEP03(2017)55

Decay diagrams



Mixing diagrams



CPV observables

- Time-integrated *CPV* asymmetries in $B^0 \to K^+\pi^-$ and $B_s \to \pi^+K^-$ decays are defined as:

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

- The main *CPV* observables are the time-dependent asymmetries of $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays:

$$A(t) = \frac{\Gamma_{\overline{B}^0_{(s)} \to f}(t) - \Gamma_{B^0_{(s)} \to f}(t)}{\Gamma_{\overline{B}^0_{(s)} \to f}(t) + \Gamma_{B^0_{(s)} \to f}(t)} = \frac{-\mathbf{C_f} \cos(\Delta m_{d(s)} t) + \mathbf{S_f} \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = \frac{2Im\lambda_f}{1+|\lambda_f|^2} \qquad A_f^{\Delta\Gamma} = \frac{2Re\lambda_f}{1+|\lambda_f|^2}$$

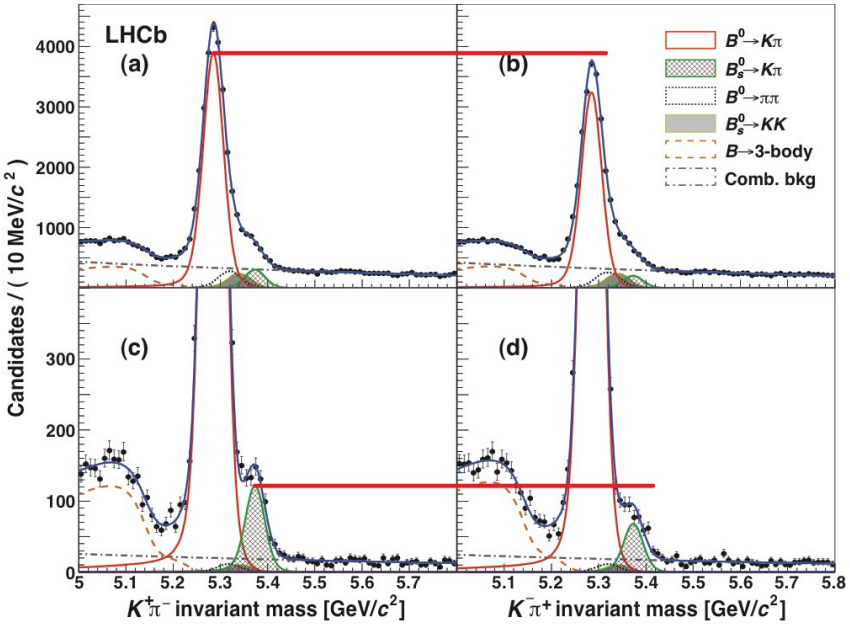
direct *CPV* — mixing induced *CPV*

$$|C_f|^2 + |S_f|^2 + |A_f^{\Delta\Gamma}|^2 = 1 \text{ (condition not imposed)}$$

- The knowledge of the flavour of the B candidate at production is required $\Longrightarrow$ flavour tagging tool is a key ingredient of the analysis

Status of art (TI *CPV*)

- Direct *CPV* in $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$ are dominated by LHCb measurement (L = 1 fb^{-1}) [Phys. Rev. Lett. 110 (2013) 221601]



	$A_{CP}(B^0 \to K^+\pi^-)$	$A_{CP}(B_s^0 \to \pi^+K^-)$	Reference
BaBar	$-0.107 \pm 0.016^{+0.006}_{-0.004}$	-	PRD 87 (2013) 052009
Belle	$-0.069 \pm 0.014 \pm 0.007$	-	PRD 87 (2013) 031103
CDF	$-0.083 \pm 0.013 \pm 0.004$	$0.22 \pm 0.07 \pm 0.02$	PRL 113 (2014) 242001
LHCb	$-0.080 \pm 0.007 \pm 0.003$	$0.27 \pm 0.04 \pm 0.01$	PRL 110 (2013) 221601
HFLAV average	-0.082 ± 0.006	0.26 ± 0.04	

Status of art (TD *CPV*)

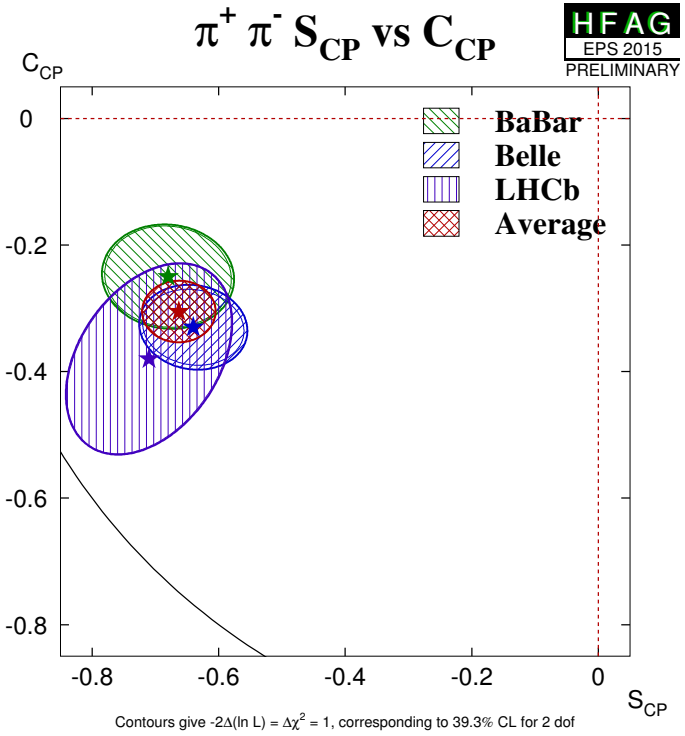
- First measurement of $C_{\pi\pi}$ and $S_{\pi\pi}$ performed by BaBar & Belle using the $B^0 \to \pi^+\pi^-$ decay

	$C_{\pi\pi}$	$S_{\pi\pi}$	Reference
BaBar	$-0.25 \pm 0.08 \pm 0.02$	$-0.68 \pm 0.10 \pm 0.03$	PRD 87 (2013) 052009
Belle	$-0.33 \pm 0.06 \pm 0.03$	$-0.64 \pm 0.08 \pm 0.03$	PRD 88 (2013) 092003

- LHCb performed a measurement using 1 fb^{-1} at 7 TeV on $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ decays

[JHEP 1310 (2013) 183]

$B^0 \to \pi^+\pi^-$
$C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02$
$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02$
$B_s \to K^+K^-$
$C_{KK} = 0.14 \pm 0.11 \pm 0.03$
$S_{KK} = 0.30 \pm 0.12 \pm 0.04$



- No measurement available for $A_{KK}^{\Delta\Gamma}$

Main ingredients of the analysis

- Analysis performed using full Run 1 data sample ($\sim 3\ fb^{-1}$)
- Main steps of TD *CPV* in $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$
  - **flavour tagging**
  - **decay-time resolution**
  - **decay-time acceptance**

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

- Main ingredients of TI *CPV* in $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$:
  - **final state detection asymmetries** (A_F)
  - **production asymmetry** (A_P)
    $\Longrightarrow$ extrapolated directly from A_{CP} by means of the time-dependent fit

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

Event selection

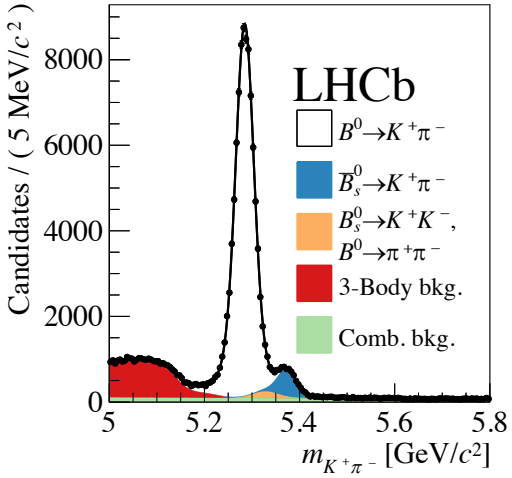
- All the *CP* parameters are determined with a multidimensional fit performed simultaneously on the $K^{\pm}\pi^{\mp}$, $\pi^+\pi^-$ and K^+K^- spectra

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

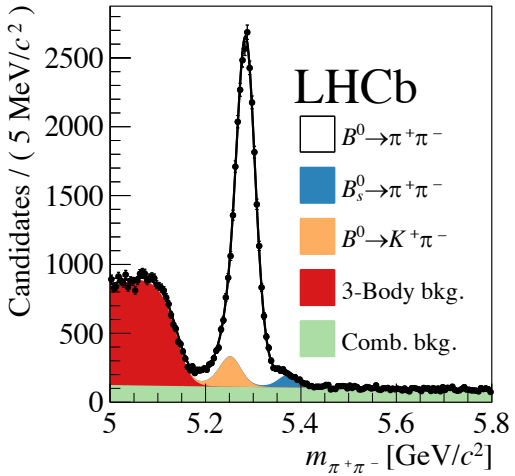
$B^0 \to \pi^+\pi^-$	$B_s \to K^+K^-$
$\sim$ 28 600	$\sim$ 36 800
$B^0 \to K^+\pi^-$	$B_s \to \pi^+K^-$
$\sim$ 94 200	$\sim$ 7 000

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

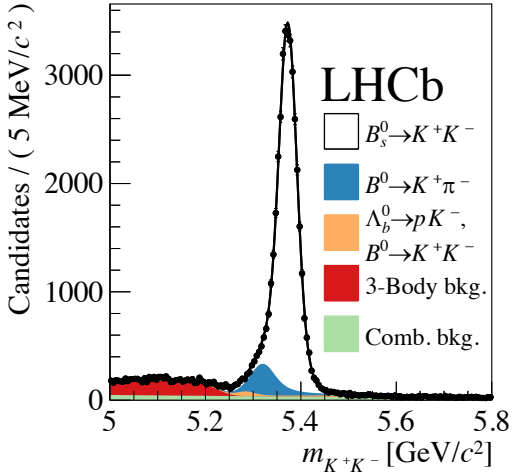
$K^{\pm}\pi^{\mp}$ spectrum



$\pi^+\pi^-$ spectrum

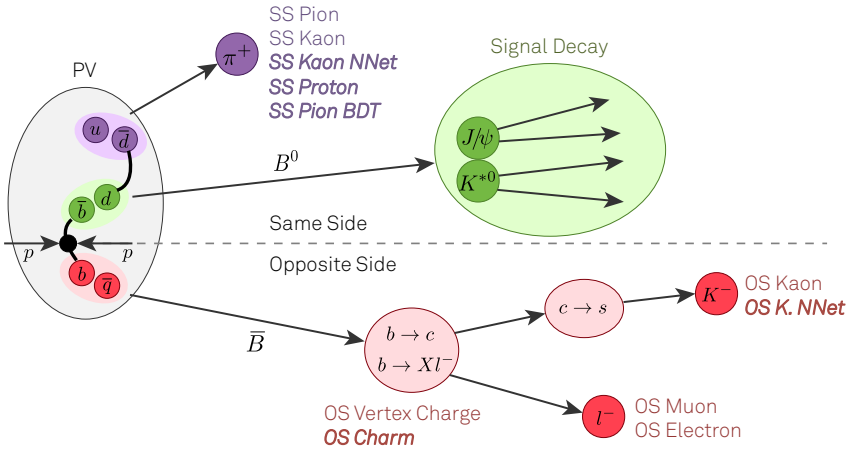


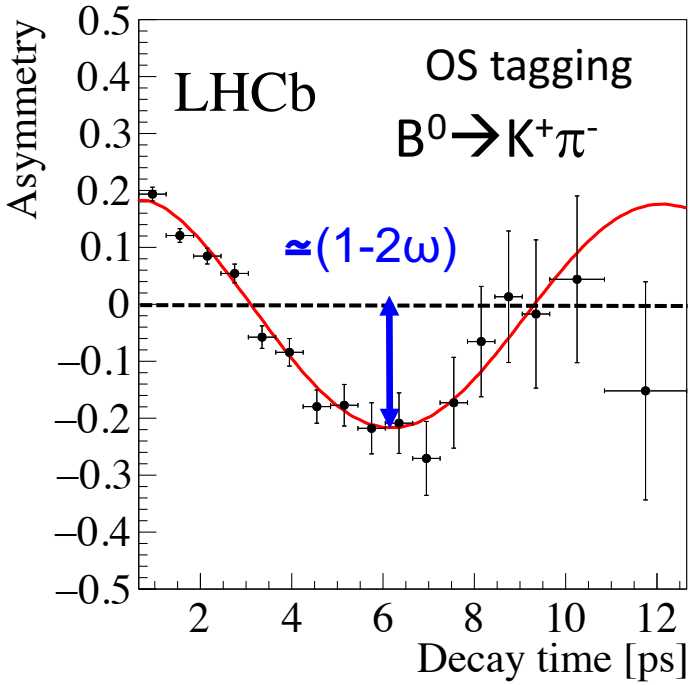
K^+K^- spectrum



Flavour tagging

- "*Same Side*" (SS) if the tagging particle comes from the signal B fragmentation:
  - SSπ & SSp for B^0
  - SSK for B_s^0
- "*Opposite Side*" (OS) if the tagger exploits the charge information of the opposite B decay





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

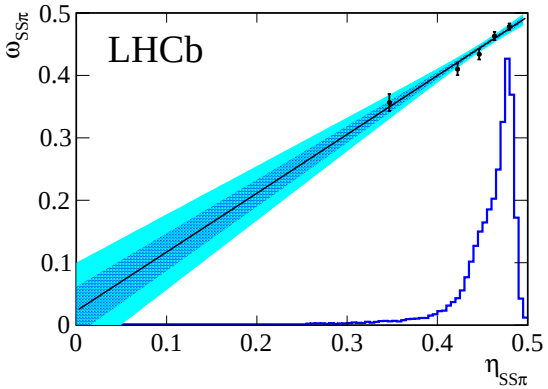
- Each tagger provides a tagging decision and a mistag rate (ω)
  $\Longrightarrow$ tagging dilution: $D_{tag} = (1 - 2\omega)$
- Tagging efficiency: ε_{tag}
- Tagging power: $\varepsilon_{eff} = \varepsilon_{tag} D_{tag}^2$

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

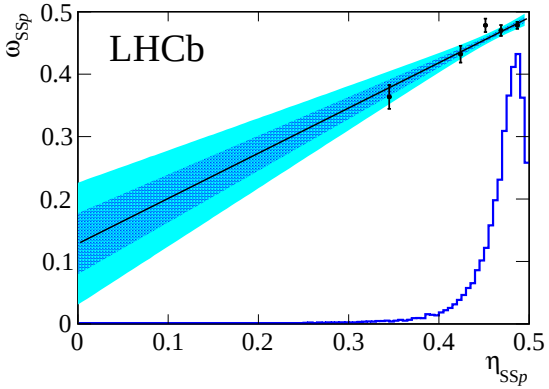
Flavour tagging calibration

- 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 $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$
- OS tagger is calibrated on the fly using $B^0 \to K^+\pi^-$: no distinction between B^0 and B_s^0
- SSπ and SSp calibrated using $B^0 \to K^+\pi^-$ and then combine into an unique tagging algorithm SScomb.
- SScomb calibrated on the fly using $B^0 \to K^+\pi^-$ (B^0 only)
- SSK calibrated using a sample of $B_s^0 \to D_s^-\pi^+$ decays (B_s^0 only) $\Longrightarrow$ yield of $B_s^0 \to \pi^+K^-$ not sufficient to obtain a reliable calibration

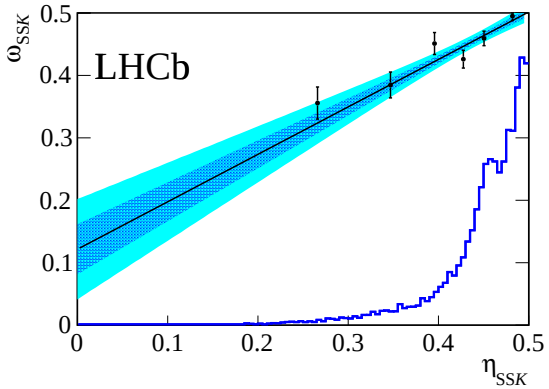
SSπ



SSp



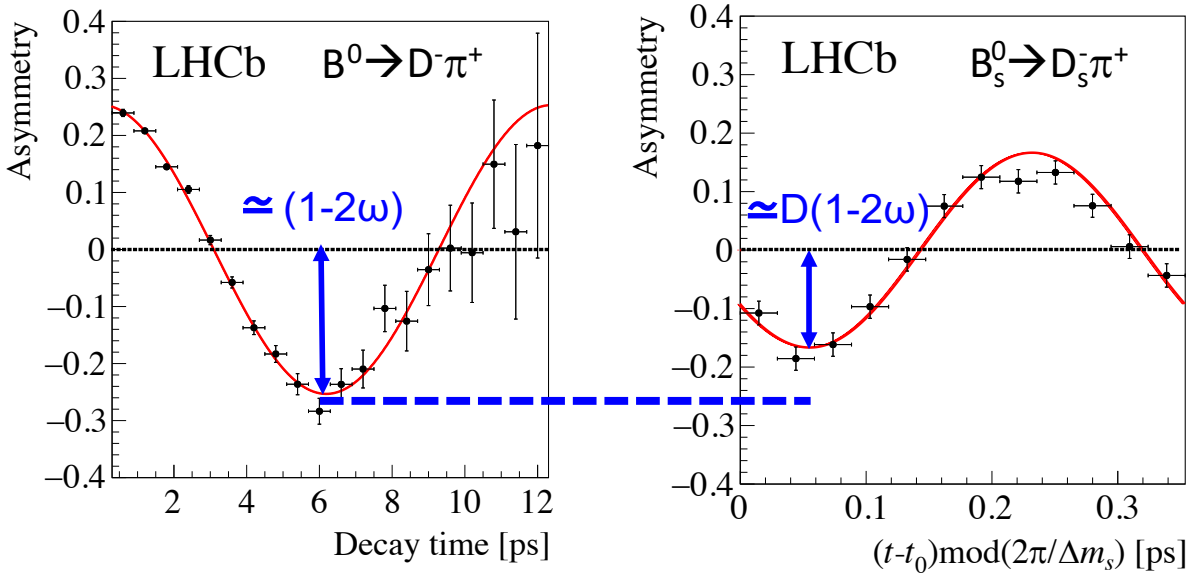
SSK



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

Decay-time resolution

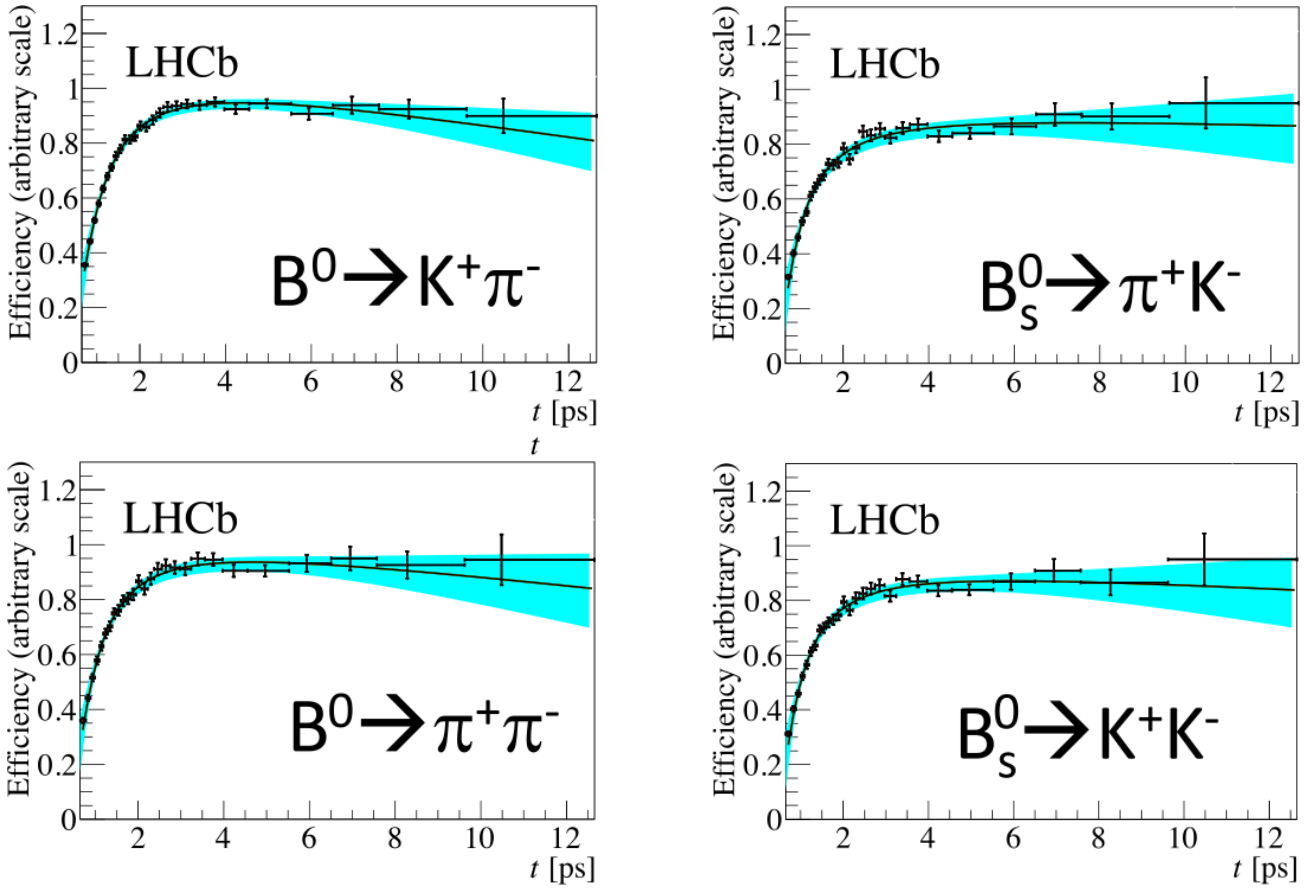
- Calibration is performed measuring simultaneously the time-dependent asymmetries of $B^0 \to D^- \pi^+$ and $B_s^0 \to D_s^- \pi^+$
- Raw asymmetries diluted by:
  - **flavour tagging**: $D_{tag} = (1 - 2\omega)$
  - **decay-time resolution** $\Rightarrow D = \exp(-\sigma_t^2 \Delta m^2/2)$
- $B^0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



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

Decay-time acceptance

- Reconstruction efficiency as a function of decay-time is determined using $B^0 \to K^+\pi^-$ 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. $B^0 \to K^+\pi^-$



[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 $B^0 \to K^+\pi^-$ and $B_s \to \pi^+ K^-$ 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 $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$
- $A_D^{K\pi}$ measured using raw asymmetries of Cabibbo-favoured charm decays $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K^0\pi^+$ [JHEP 07 (2014) 041]
- Asymmetries are convoluted with the $B_{(s)}^0 \to h^+h'^-$ phase space

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

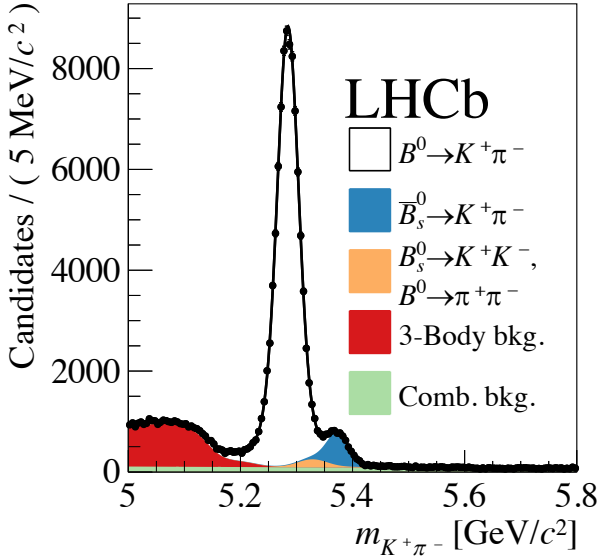
[Phys. Rev. D 98 (2018) 032004]

Results of the $K^{\pm}\pi^{\mp}$ final state

- Most precise measurement from a single experiment

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

$$A_{CP}^{B^0} = (-8.4 \pm 0.4 \pm 0.3)\%$$
$$A_{CP}^{B_s^0} = (21.3 \pm 1.5 \pm 0.3)\%$$



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

$$A_P(B^0) = (0.19 \pm 0.60)\% \qquad A_P(B_s^0) = (2.4 \pm 2.1)\%$$

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

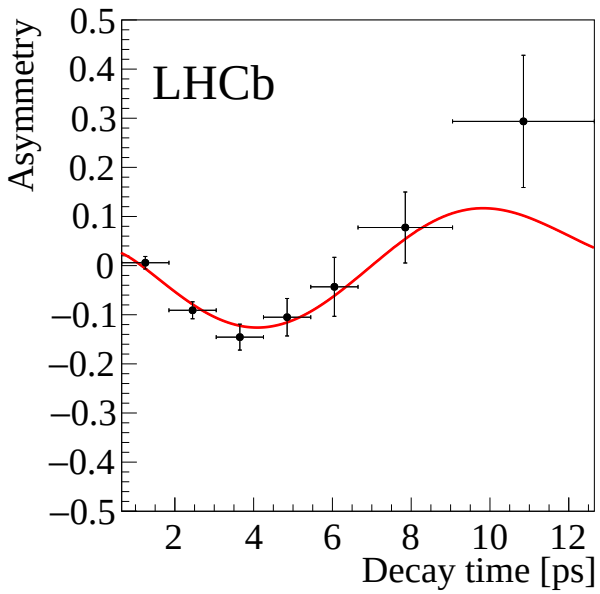
- SM test assuming U-spin validity [PLB 621 (2005) 126]

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

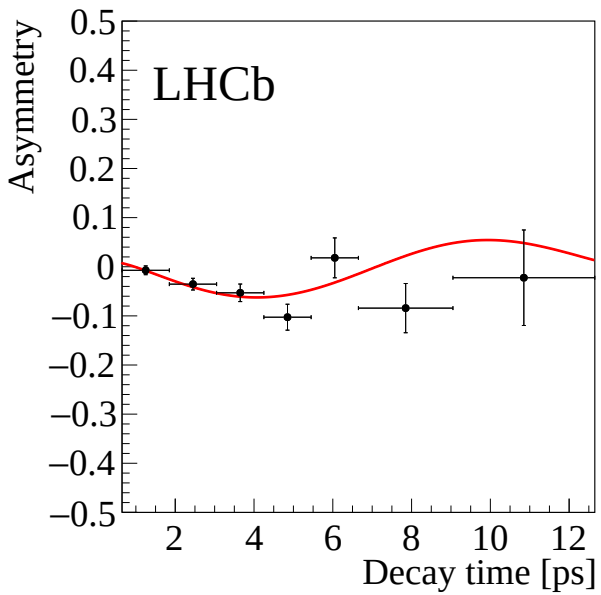
Results of the $\pi^+\pi^-$ final state

- Most precise measurement from a single experiment [Phys. Rev. D 98 (2018) 032004]
- Uncertainties halved with respect to previous LHCb results

OS **tagging**



$SS(\pi + p)$ **tagging**

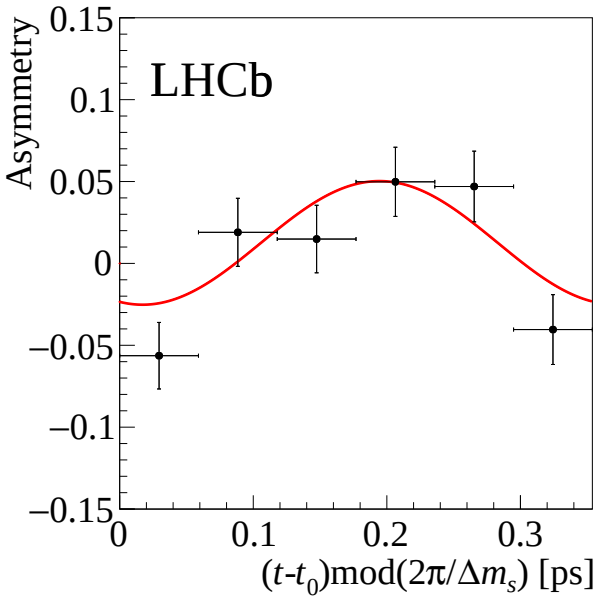


$$\mathbf{C}_{\pi\pi} = -0.34 \pm 0.06 \pm 0.01$$
$$\mathbf{S}_{\pi\pi} = -0.63 \pm 0.05 \pm 0.01$$
$$\rho(C_{\pi\pi}, S_{\pi\pi}) = 0.448$$

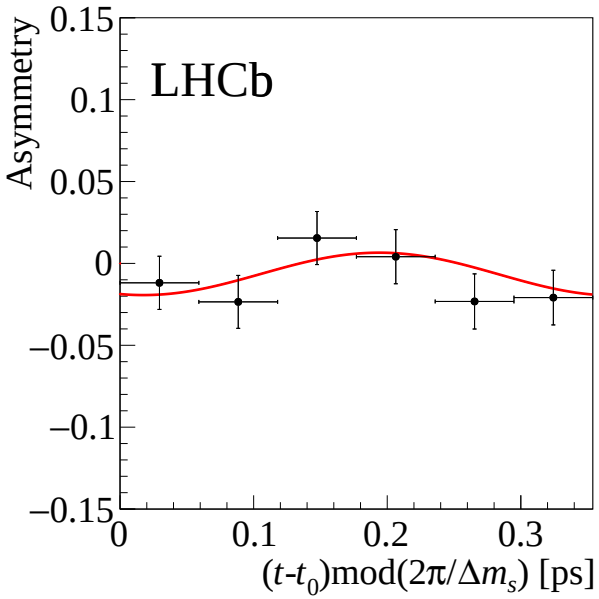
Results for the K^*K^- final state

- **Very first measurement of $\mathbf{A_{KK}^{\Delta\Gamma}}$** [Phys. Rev. D 98 (2018) 032004]
- Strongest evidence of *CPV* in B_s^0 sector: confirmed at 4σ

***OS* tagging**



***SSK* tagging**



$$\mathbf{C_{KK}} = 0.20 \pm 0.06 \pm 0.02$$
$$\mathbf{S_{KK}} = 0.18 \pm 0.06 \pm 0.02$$
$$\mathbf{A_{KK}^{\Delta\Gamma}} = -0.79 \pm 0.07 \pm 0.10$$

Systematic uncertainties

- Summary of the systematic uncertainties taken into account
- Main contribution highlighted in red

Parameters	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$C_{K^+K^-}$	$S_{K^+K^-}$	$A^{\Delta\Gamma}_{K^+K^-}$	$A_{CP}(B^0 \to K^+\pi^-)$	$A_{CP}(B_s \to \pi^+K^-)$
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

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

Conclusions

- The latest measurements of *CPV* in $B^0_{(s)} \to h^+h'^-$ decays at LHCb have been shown [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 $A_{CP}^{B^0_s}$ from a single experiment
  - Strongest evidence of *CPV* in $B^0_s \to K^+K^-$ decay at 4σ

$C_{\pi^+\pi^-}$	=	$-0.34 \pm 0.06 \pm 0.01$
$S_{\pi^+\pi^-}$	=	$-0.63 \pm 0.05 \pm 0.01$
$C_{K^+K^-}$	=	$0.20 \pm 0.06 \pm 0.02$
$S_{K^+K^-}$	=	$0.18 \pm 0.06 \pm 0.02$
$A^{\Delta\Gamma}_{K^+K^-}$	=	$-0.79 \pm 0.07 \pm 0.10$
$A_{CP}^{B^0}$	=	$(-8.4 \pm 0.4 \pm 0.3)\%$
$A_{CP}^{B^0_s}$	=	$(21.3 \pm 1.5 \pm 0.3)\%$

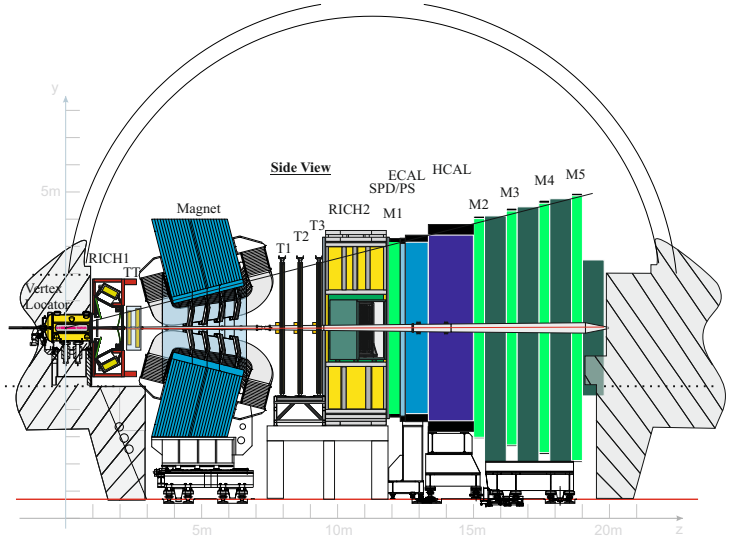
Thank you for your attention!

Backup

The Large Hadron Collider beauty (LHCb) Experiment

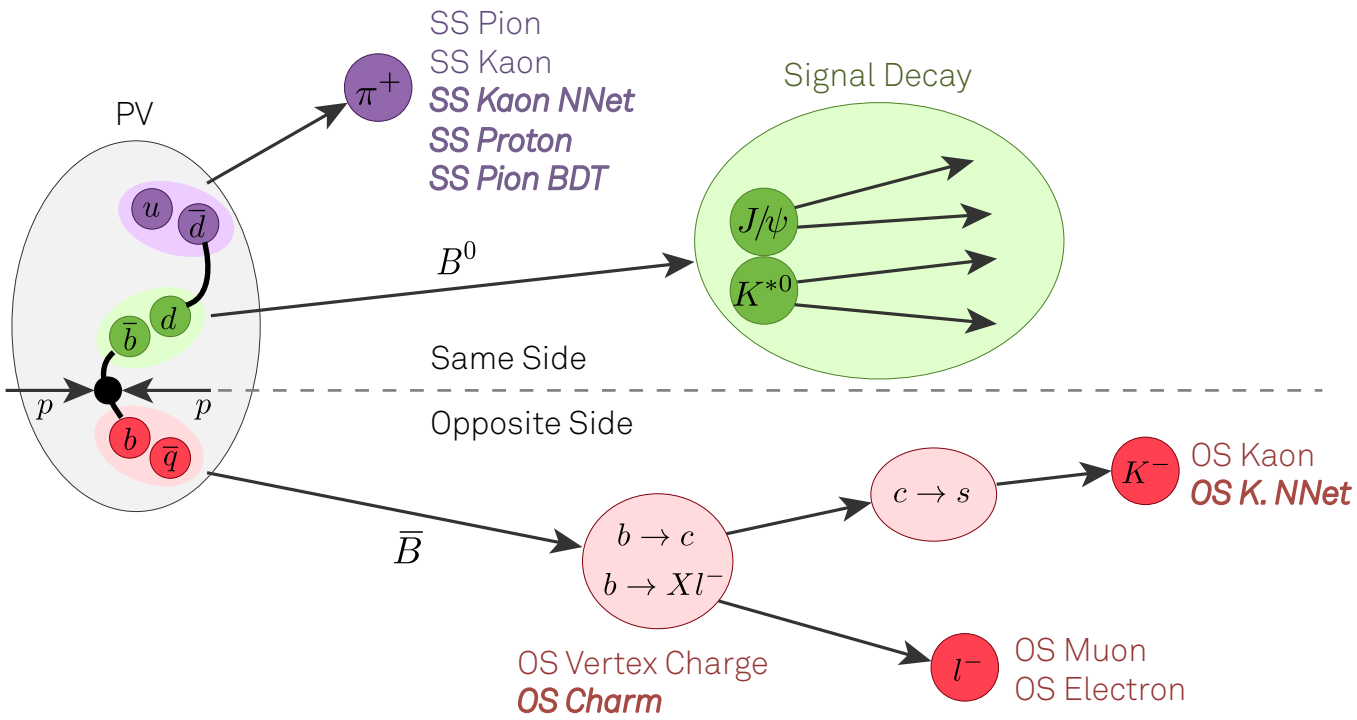
- LHCb detector is a single-arm forward spectrometer optimised for b and c hadron physics
  - pseudorapidity range: [2,5] $\Longrightarrow \sim 25\%$ $b\bar{b}$ pairs in LHCb acceptance
- **High precision measurements** in flavour physics (e.g. CKM, beyond SM)
- Collected data:
  - Run1 (2010-2012) $\Longrightarrow \approx 3$ fb^{-1}
  - Run2 (2015-2018) $\Longrightarrow \approx 4$ (already taken) $+$ 2 (expected) fb^{-1}

- Excellent performances [Int. J. Mod. Phys. A 30, 1520022 (2015)]:
  - **Momentum resolution**: $\frac{\sigma_p}{p} \approx 0.5 - 0.8\%$ ($p < 100\ GeV/c$)
  - **Impact Parameter (IP) resolution**: $\sigma_{IP} \approx 20\ \mu m$ (at high p_T)
  - **Decay time resolution**: $\sigma_t \approx 50\ fs$
  - **Particle Identification (PID)**: $\varepsilon(K) \approx 95\%, \pi$ mis-ID $\approx 5\%$ ($p < 100\ GeV/c$) $\varepsilon(\mu) \approx 97\%, \pi$ mis-ID $\approx$ 1-3%



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].

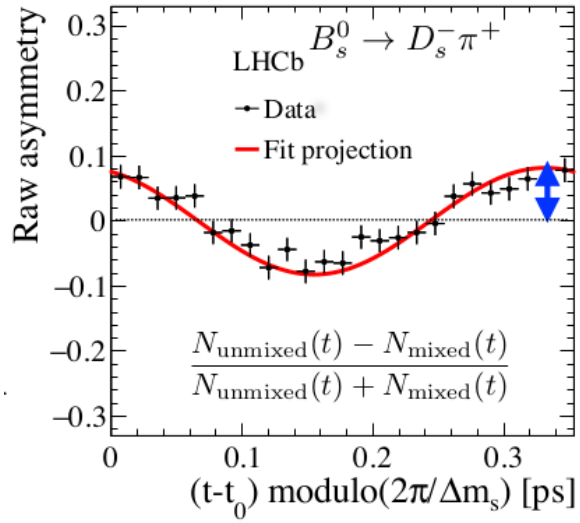
$$\omega = \frac{N_{wrong}}{N_{right}+N_{wrong}}$$

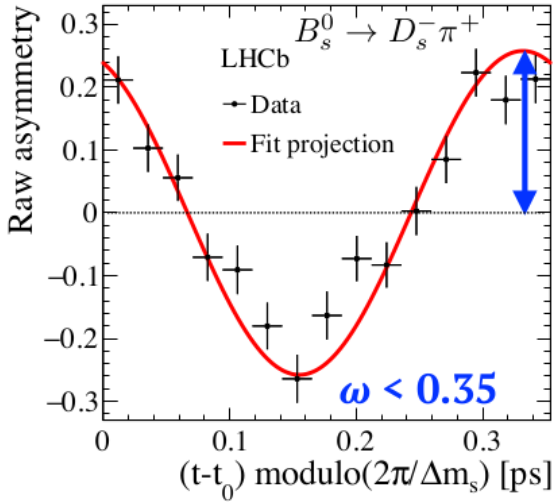
  - **Dilution**: $D = (1 - 2\omega)$ of asymmetries and decay rates.
  - Predicted mistag probability η computed by taggers needs calibration $\omega(\eta)$ to provide unbiased estimate of the mistag probability ω

- **Tagging power**: statistical degradation of CP asymmetries

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

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





[JINST 11 (2016) P05010]

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

- CP asymmetries of $B^0 \to \pi^+\pi^-$ decays
  - fundamental input to the isospin analysis to determine the CKM angle α/ϕ_2
- First proposal to include also $B_s^0 \to K^+K^-$ 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 $B^0 \to K^+\pi^-$ and $B_s \to \pi^+K^-$ provide a test of the SM assuming U-spin symmetry:

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

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

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	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$C_{K^+K^-}$	$S_{K^+K^-}$	$A^{\Delta\Gamma}_{K^+K^-}$	$A_{CP}(B^0 \to K^+\pi^-)$	$A_{CP}(B_s \to \pi^+K^-)$
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

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