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Measurements of CP violation in B→DD decays

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Motivation

- Many physics opportunities arise from the study of B mesons decays to two charm mesons
- Eg. $B^0 \longrightarrow D^- D^+$, $B_s \longrightarrow D_s^- D_s^+$ probe the mixing phases ϕ_d and ϕ_s with a complementary determination to $B^0 \longrightarrow J/\psi K^0$ and $B_s^0 \longrightarrow J/\psi \phi$ decays
  - LHCb measurements performed with Run 1 data ($B^0 \longrightarrow D^- D^+$: Phys. Rev. Lett. 117 (2016) 261801 , $B_s \longrightarrow D_s D_s$: Phys. Rev. Lett. 113 (2014) 211801), to be updated with Run 2.
- Decays are driven by tree-level and loop-level amplitudes, contributions of penguin topologies can play an important role.
- Branching fractions and CP asymmetries in different charged and neutral $B \longrightarrow DD$ decay modes can be related, employing isospin or SU(3)-flavour symmetries, and test of SM predictions can be derived (M.Jung and S.Schacht Phys.Rev.D91,034027; L.Bel,K.DeBruyn,R.Fleisher et al. JHEP 1507 (2015) 108)

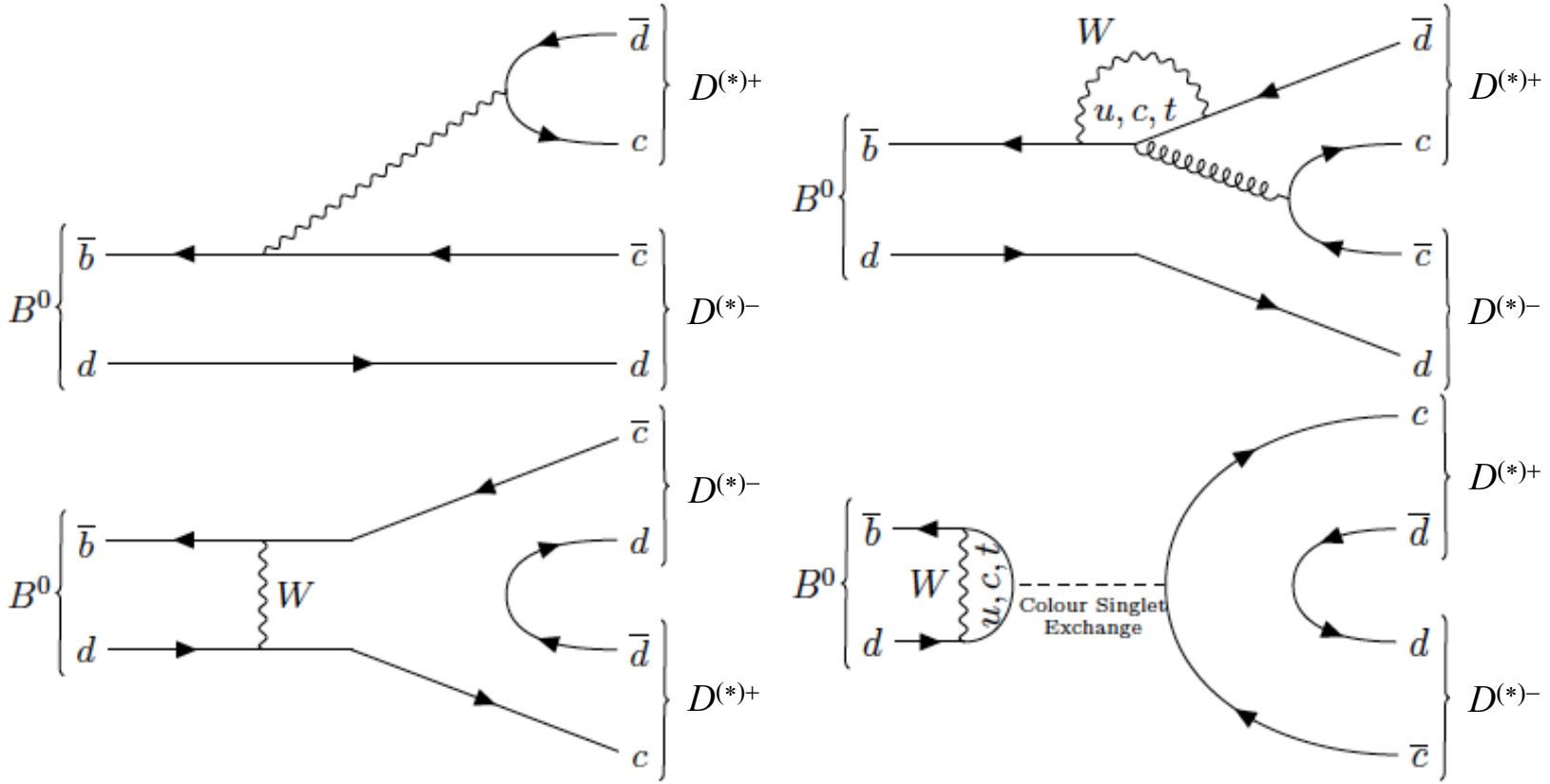
Measurement of CP violation in $B^0 \longrightarrow D^{*\pm} D^{\mp}$ decays

LHCb-PAPER-2019-036 in preparation

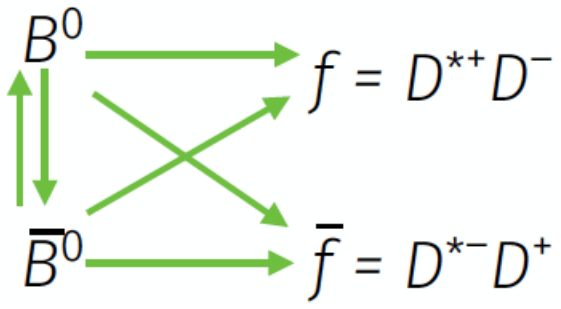
• New result and first measurement of CPV in $B^0 \longrightarrow D^{*\pm} D^{\mp}$ at LHCb

- $b \longrightarrow c\bar{c}d$ transition with tree, penguin and exchange diagrams.

- Expect mixing-induced CPV and possible direct CPV contributions.



- Not a CP eigenstate: four decay-rates for B^0 and $\overline{B^0}$ events to f and $\bar{f}$ final states. Eg.:



$$\frac{d\Gamma_{\overline{B}^0,f}(t)}{dt} = \frac{e^{-t/\tau_d}}{8\tau_d}(1 + A_{f\bar{f}})\left[1 + S_f \sin(\Delta m_d t) - C_f \cos(\Delta m_d t)\right]$$

$$S_f = \frac{2\mathcal{I}m\lambda_f}{1+|\lambda_f|^2} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad A_{f\bar{f}} = \frac{\left(|A_f|^2 + |\bar{A}_f|^2\right) - \left(|A_{\bar{f}}|^2 + |\bar{A}_{\bar{f}}|^2\right)}{\left(|A_f|^2 + |\bar{A}_f|^2\right) + \left(|A_{\bar{f}}|^2 + |\bar{A}_{\bar{f}}|^2\right)}$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$ and similar for $\bar{f}$.

- Adopt HFLAV definition, measure the 5 parameters:

$$S_{D^*D} = \frac{1}{2}(S_{D^{*+}D^-} + S_{D^{*-}D^+}) \qquad C_{D^*D} = \frac{1}{2}(C_{D^{*+}D^-} + C_{D^{*-}D^+})$$

$$\Delta S_{D^*D} = \frac{1}{2}(S_{D^{*+}D^-} - S_{D^{*-}D^+}) \qquad \Delta C_{D^*D} = \frac{1}{2}(C_{D^{*+}D^-} - C_{D^{*-}D^+}) \qquad A_{D^*D} = A_{f\bar{f}}$$

Signal sample

- Full Run1+Run2 data sample ~9 fb^{-1} collected at $\sqrt{s}$ =7, 8, 13 TeV
- $B^0 \longrightarrow D^{*+}D^-$, $D^{*+} \longrightarrow D^0\pi^+$ ($D^0 \longrightarrow K^-\pi^+$ and $D^0 \longrightarrow K^-\pi^+\pi^-\pi^+$) "Kπ","K3π"
  $D^- \longrightarrow K^-\pi^+\pi^-$

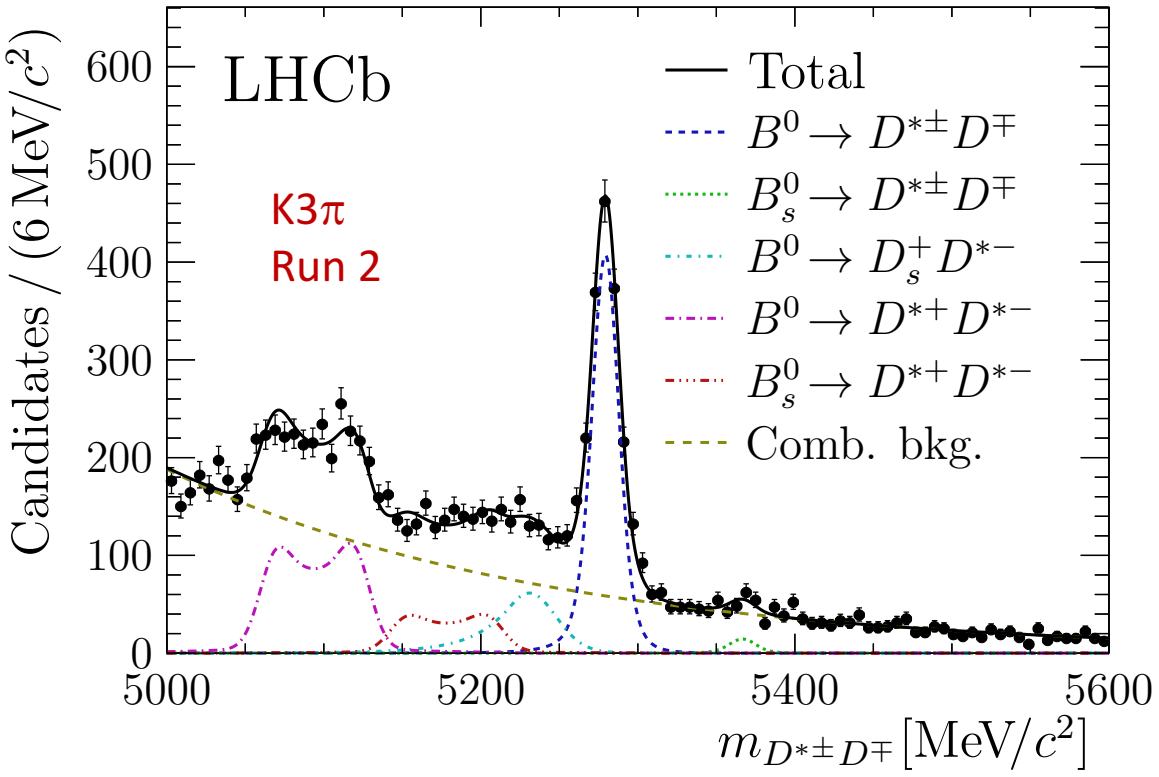
- Loose selection with kinematic, mass and particle-identification requirements to reject physics background
  - $\Lambda_b^0 \longrightarrow D^{*-}\Lambda_c^+(K^+p\pi^+)$, $B_{(s)}^0 \longrightarrow D^{*-}D_s^+(K^+K^-\pi^+)$
  - single charm $B_{(s)}^0 \longrightarrow D^{*+}h^+\pi^-\pi^-$, $h=\pi,K$

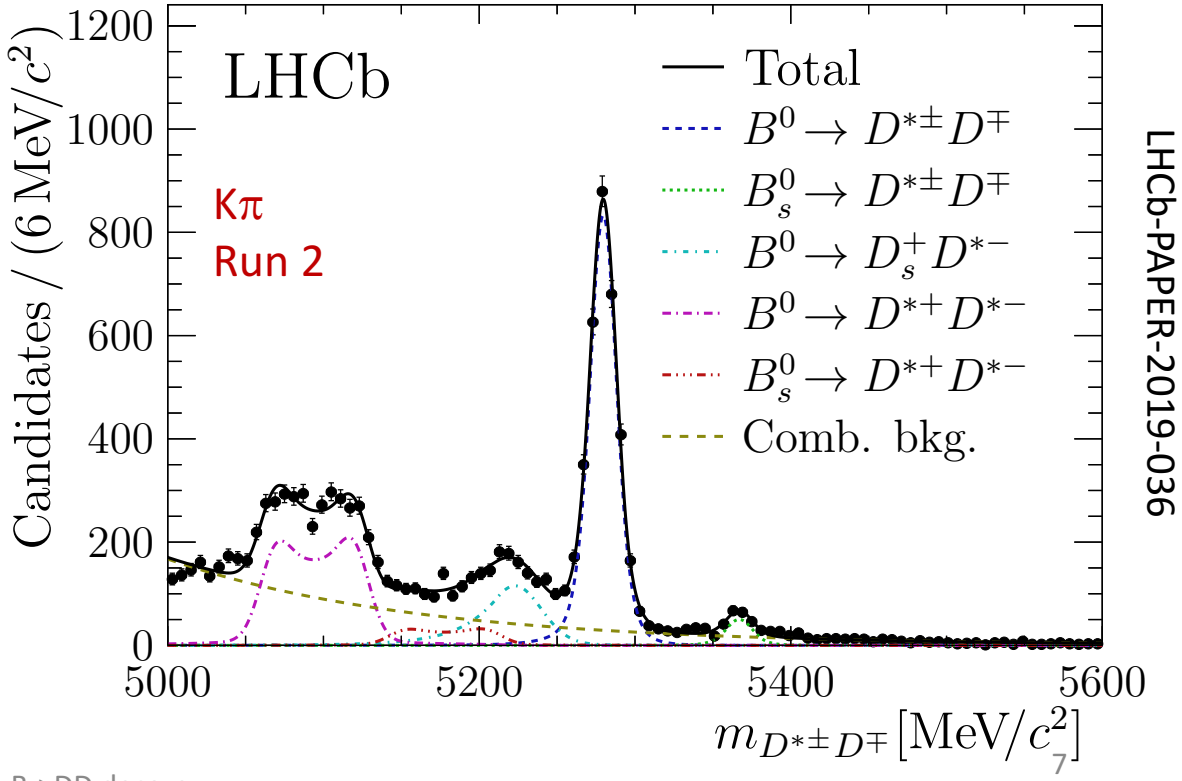
- Multivariate selection (BDT classifier) to reject combinatoric background
  - Trained with simulated signal and high B-mass side-band.
  - Inputs: kinematical, topological and PID variables
  - Maximize sensitivity to CPV

Invariant-mass fit

- Extended maximum likelihood to mass distribution
- Separate for the two D^0 samples (Kπ/K3π) and Run1/Run2

Total signal yield ~6000 candidates

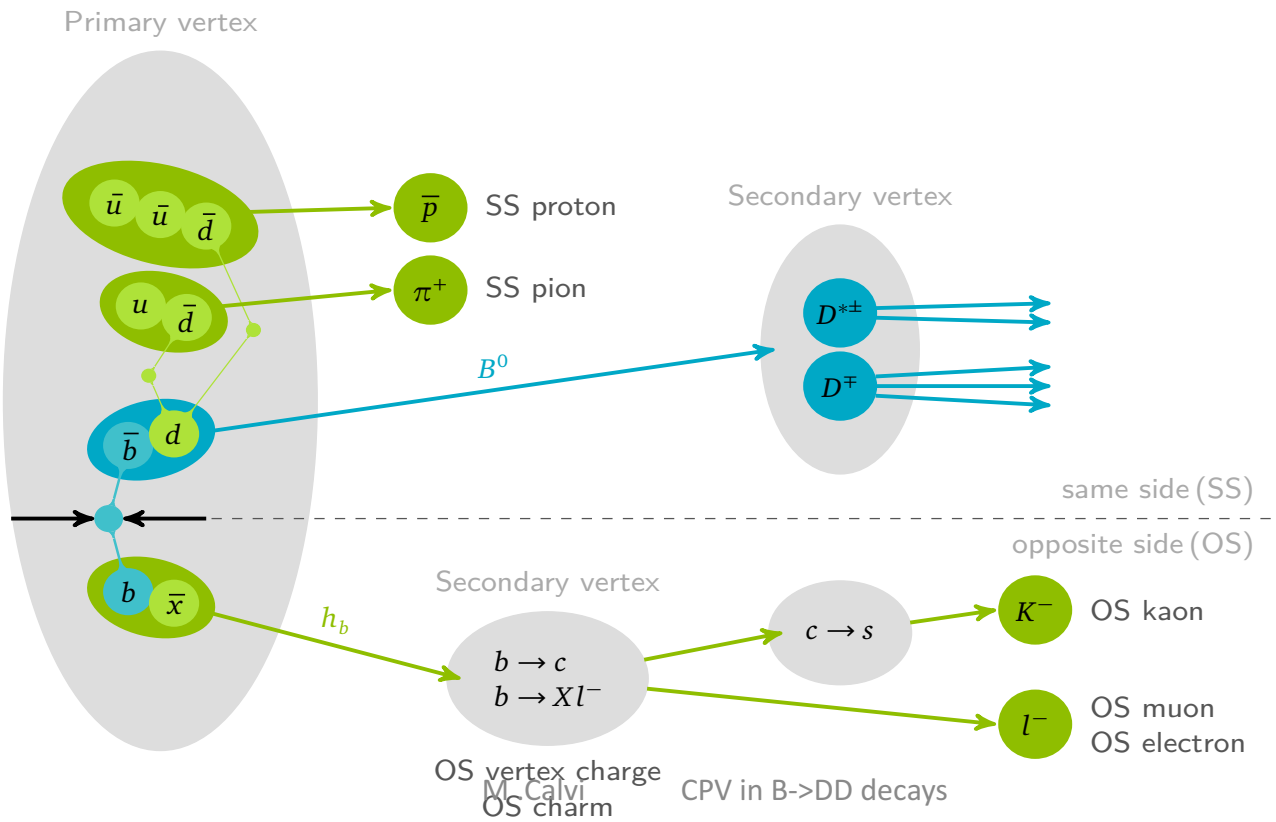




LHCb-PAPER-2019-036

Flavour Tagging

- CP measurement from time-dependent analysis of B^0 decays needs the determination of the B flavour (b or $\bar{b}$) at production
- Several tagging algorithms developed in LHCb. Here use the combination of all Opposite Side and Same Side taggers (Eur.Phys.J. C72(2012)2022, Eur.Phys.J. C77(2017)238)



$$\varepsilon_{\text{tag}} = \frac{N_R + N_W}{N_R + N_W + N_U}$$

$$\omega = \frac{N_W}{N_R + N_W}$$

$$\mathcal{D} = (1 - 2\omega)$$

Flavour Tagging

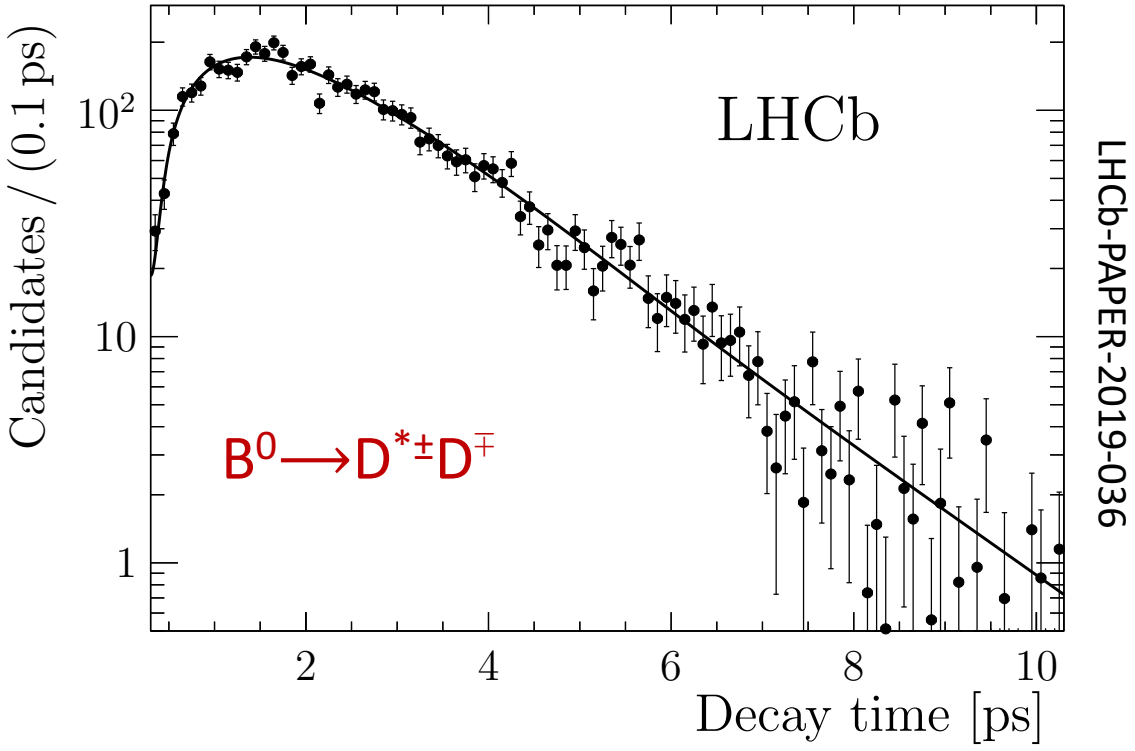
- Each tagging algorithm provides a tagging decision and the probability that it is incorrect (mistag)
  - Large data samples ($B^+ \longrightarrow J/\psi K^+$, $B^0 \longrightarrow D^- \pi^+$) are used to optimize the algorithms and calibrate the mistag probabilities.

- Data samples of $B^0 \longrightarrow D^{*+} D_s^-$ and $B^0 \longrightarrow D^+ D_s^-$ decays used to calibrate the OS and SS combinations.
  - Flavour-specific decays with high yields and similar topology and kinematics as the signal decay

- High tagging power on the signal sample (favorable signal kinematic)

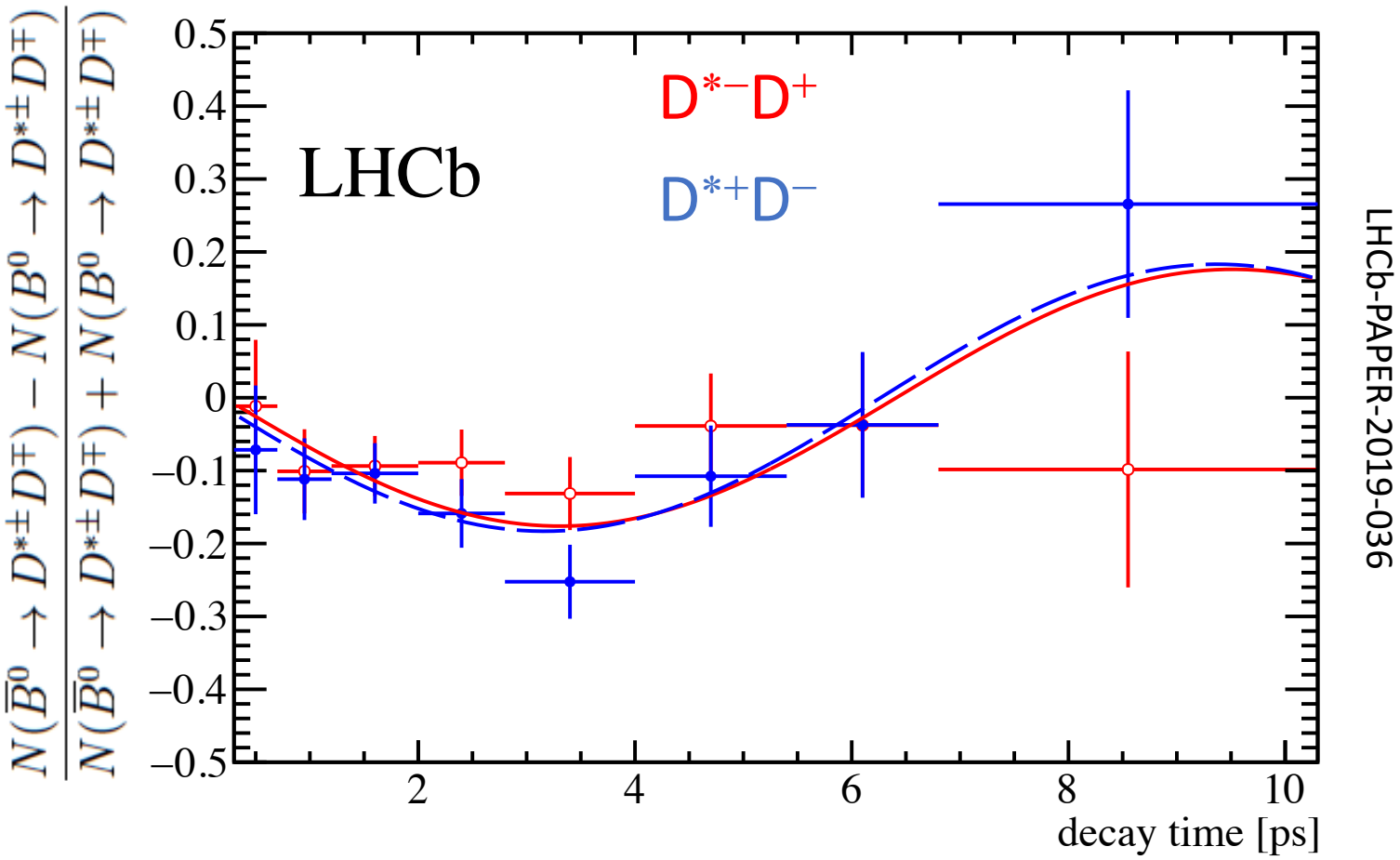
	$D^0 \rightarrow K3\pi$	$D^0 \rightarrow K\pi$
	$\varepsilon_{tag} D^2$ (%)	
Run1	6.3 ± 0.6	5.6 ± 0.4
Run2	7.1 ± 0.3	6.6 ± 0.2

Decay-time Fit



- Unbinned likelihood fit to the decay-time distribution of background-subtracted candidates
  - Simultaneous fit to the 4 data samples (Run1,Run2) x (Kπ,K3π) of tagged and untagged candidates.
- Physics decay-rate include terms dependent on flavour tagging parameters (efficiencies and mistag for B^0 and $\bar{B}^0$) and B^0 production asymmetry
  - Gaussian-constrained to the measurement performed in the $B^0 \longrightarrow D^{(*)+} D_s^-$ control-channels

CP asymmetry



LHCb-PAPER-2019-036

Corrections for A_{D^*D}

- The raw charge asymmetry measured in the decay-time fit has to be corrected for the detection asymmetry (including reconstruction and PID)

$$-A_{D^*D} = A_{\rm raw} - A_{\rm det}$$

$$A_{\rm det}^{D^{*-}D^+} = A_{\rm det}^{D^{*-}} - A_{\rm det}^{D^-} \qquad A_{\rm det}^{D^{(*)-}} = \frac{\epsilon(D^{(*)-}) - \epsilon(D^{(*)+})}{\epsilon(D^{(*)-}) + \epsilon(D^{(*)+})}$$

- Each detection asymmetry measured from samples of prompt $D^- \longrightarrow K^-\pi^+\pi^-$ decays, after weighting the D^- final state particles to match the spectra of signal kaons and pions.

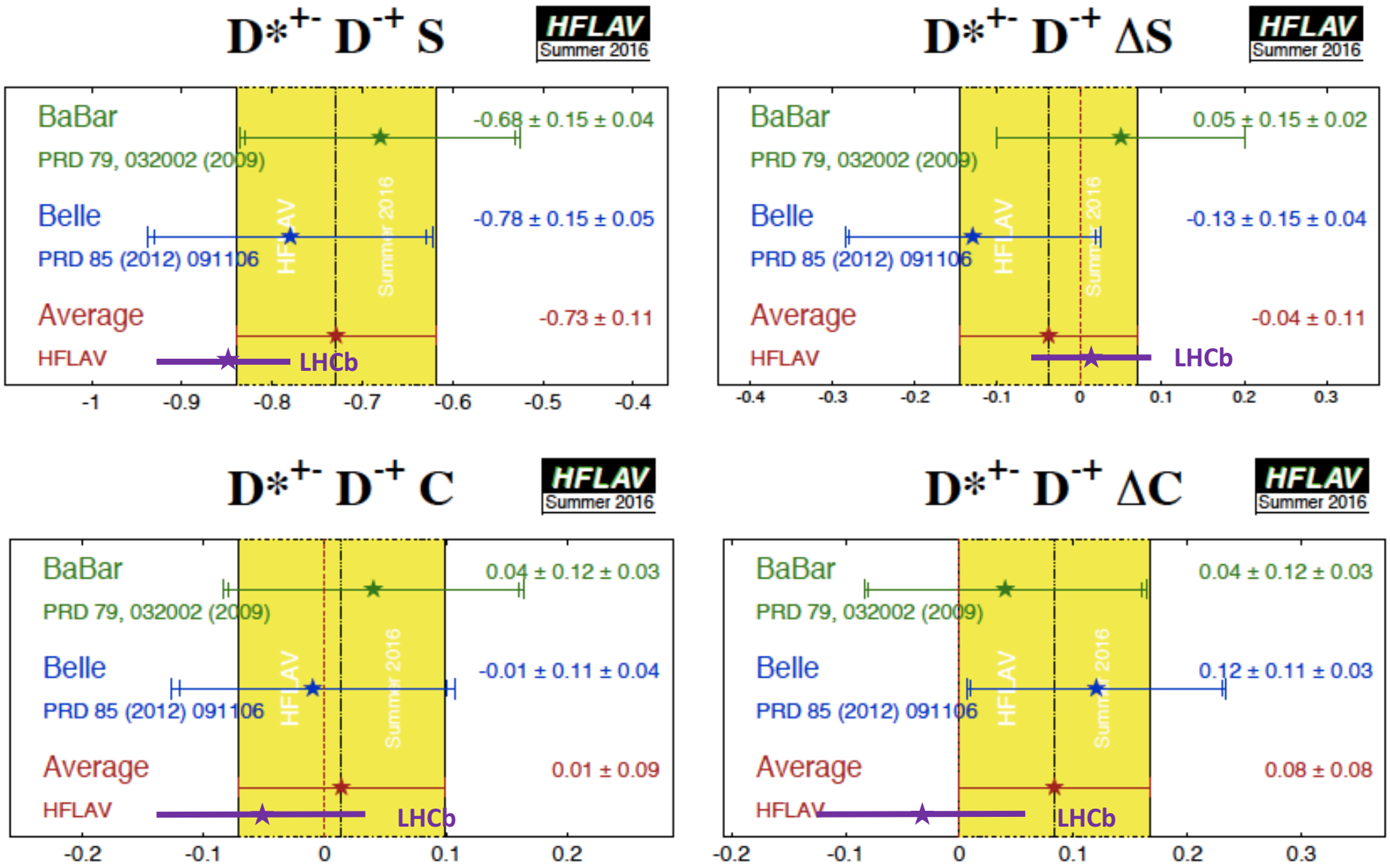
Final state	$A_{\rm det}^{D^{*-}}$	$A_{\rm det}^{D^-}$	$A_{\rm det}^{D^{*-}D^+}$
$D^0 \to K^-\pi^+$	0.0169 ± 0.0036	0.0158 ± 0.0018	$0.0011 \pm 0.0040 \pm 0.020$
$D^0 \to K^-\pi^-\pi^+\pi^+$	0.0146 ± 0.0022	0.0138 ± 0.0015	$0.0009 \pm 0.0026 \pm 0.049$

Results

$$
\begin{aligned}
S_{D^*D} &= -0.861 \pm 0.077\,(\text{stat}) \pm 0.019\,(\text{syst}) \\
\Delta S_{D^*D} &= 0.019 \pm 0.075\,(\text{stat}) \pm 0.012\,(\text{syst}) \\
C_{D^*D} &= -0.059 \pm 0.092\,(\text{stat}) \pm 0.020\,(\text{syst}) \\
\Delta C_{D^*D} &= -0.031 \pm 0.092\,(\text{stat}) \pm 0.016\,(\text{syst}) \\
A_{D^*D} &= 0.008 \pm 0.014\,(\text{stat}) \pm 0.005\,(\text{syst})
\end{aligned}
$$

- Main correlations: $\rho(S_{D^*D}, C_{D^*D}) = 0.44$ $\rho(\Delta S_{D^*D}, \Delta C_{D^*D}) = 0.46$

- Systematic uncertainties come from
  - Variation of mass-model (signal and backgrounds)
  - Variation of flavour tagging calibration model
  - Decay-time acceptance and resolution
  - Main systematic on A_{D^*D} from the uncertainty on the instrumental asymmetries



- All results are compatible with, and more precise than previous measurements

Effective mixing phase

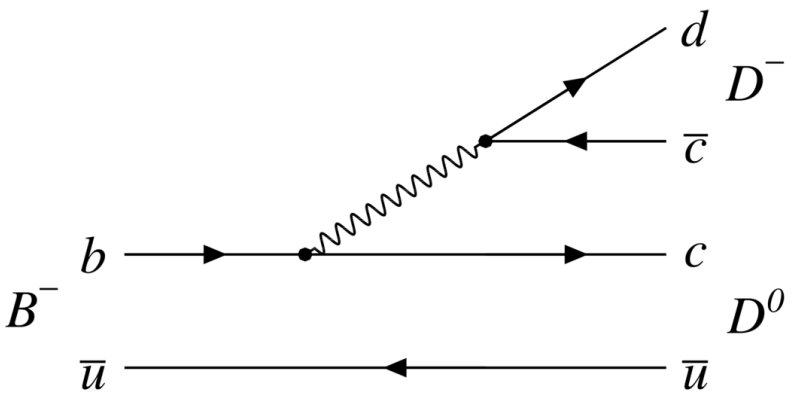
- The results are consistent with sizeable mixing-induced CP violation, negligible contribution of penguin diagrams, zero hadronic phase between $B^0 \longrightarrow D^{*+}D^-$ and $B^0 \longrightarrow D^{*-}D^+$ amplitudes and same magnitudes ($A_{D^*D} = 0$, $C_{D^*D} = 0$, $\Delta S_{D^*D} = 0$, $\Delta C_{D^*D} = 0$).
- In this picture $S_{D^*D} = -\sin(2\beta)$.

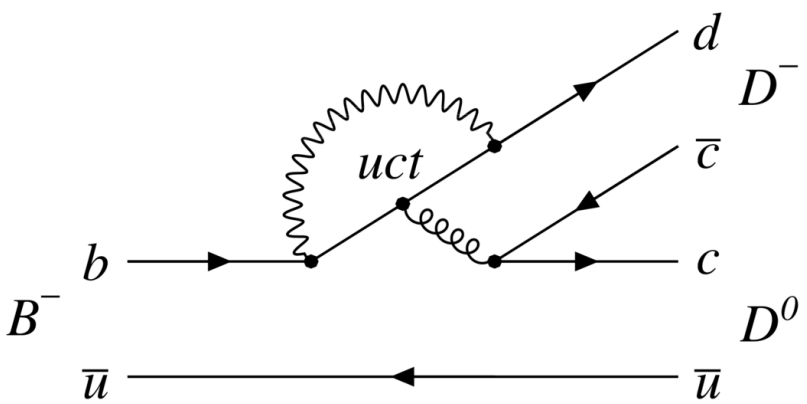
- The result $\sin(2\beta)_{D^*D} = 0.861 \pm 0.070 \pm 0.019$ is compatible at 1.9 σ with the w.a. from $b \longrightarrow c\bar{c}s$ transitions $\sin(2\beta)_{ccs} = 0.699 \pm 0.017$ (HFLAV) and at 1.5 σ with the SM prediction $\sin(2\beta)_{SM} = 0.740+0020-0.025$ (Eur. Phys. J. C41 (2005) 1)

Measurement of the CP asymmetry in $B^- \longrightarrow D_s^- D^0$ and $B^- \longrightarrow D^- D^0$ decays

LHCb Collaboration, JHEP05(2018)160

- First measurement of CP asymmetry in $B^- \longrightarrow D_{(s)}^- D^0$ at LHCb.





- Non-zero CP asymmetry expected due to interference of contributions from tree and loop amplitudes, $O(10^{-2})$ in SM.

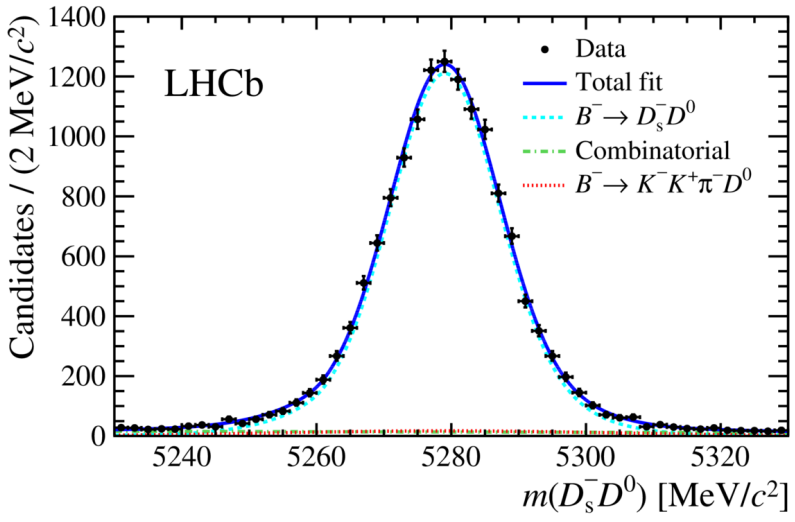
$$\mathcal{A}^{CP}(B^- \to D_{(s)}^- D^0) \equiv \frac{\Gamma(B^- \to D_{(s)}^- D^0) - \Gamma(B^+ \to D_{(s)}^+ \overline{D}^0)}{\Gamma(B^- \to D_{(s)}^- D^0) + \Gamma(B^+ \to D_{(s)}^+ \overline{D}^0)}$$

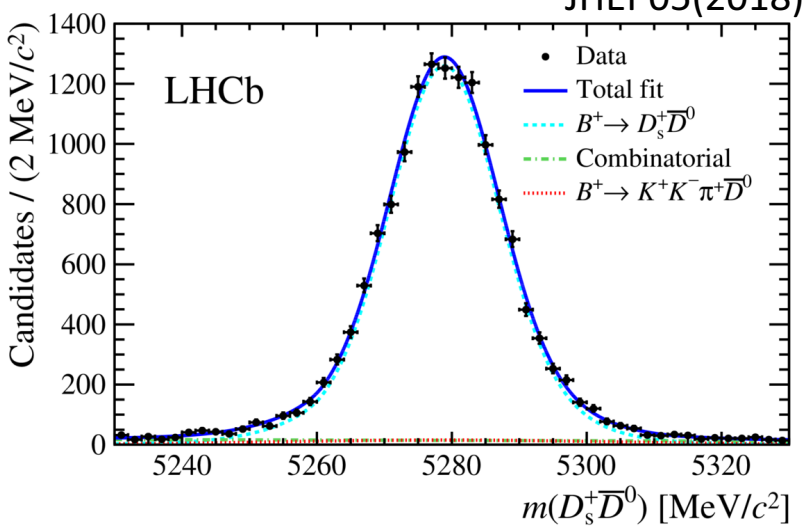
- Asymmetries from the time-integrated measurement, from yield of selected signal candidates. Run 1 data sample, 3 fb^{-1} at $\sqrt{s}$ =7, 8 TeV.
  - $D^- \longrightarrow K^+\pi^-\pi^-$, $D_s^- \longrightarrow K^-K^+\pi^-$, $D^0 \longrightarrow K^-\pi^+$ and $D^0 \longrightarrow K^-\pi^+\pi^-\pi^+$

JHEP05(2018)160

$B^- \longrightarrow D_s^- D^0$

$D^0 \longrightarrow K^-\pi^+$



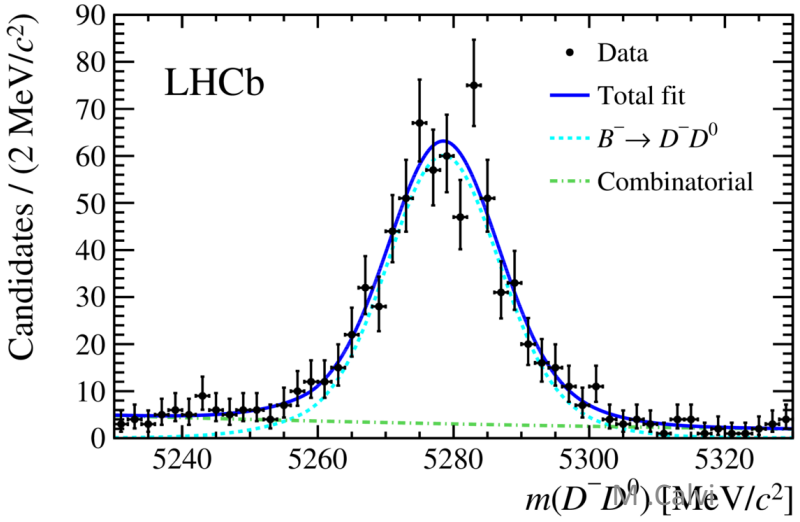


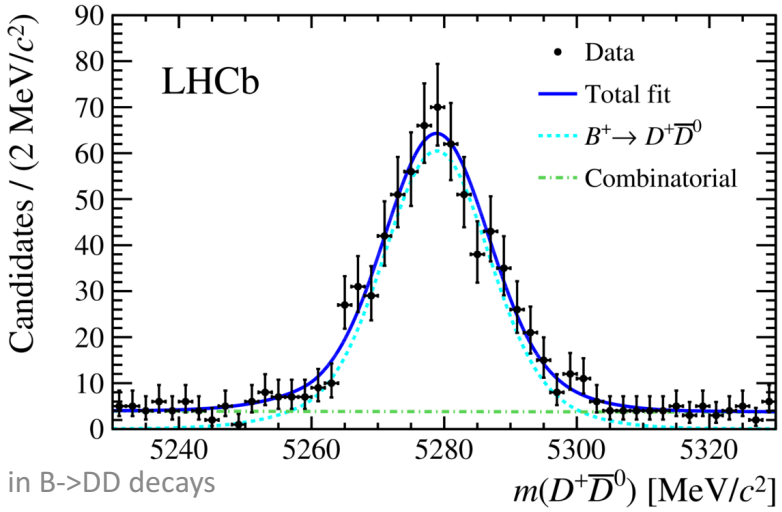
$B^+ \longrightarrow D_s^+ \overline{D}^0$

$\overline{D}^0 \longrightarrow K^+\pi^-$

$B^- \longrightarrow D^- D^0$

$D^0 \longrightarrow K^-\pi^+$





$B^+ \longrightarrow D^+ \overline{D}^0$

$\overline{D}^0 \longrightarrow K^+\pi^-$

- Raw asymmetry to be corrected for production and detection asymmetries

$$\mathcal{A}^{CP} = A_{\rm raw} - A_P - A_D$$

$$A_P \equiv \frac{\sigma(B^-) - \sigma(B^+)}{\sigma(B^-) + \sigma(B^+)}$$

B^- production asymmetry measured in $B^- \longrightarrow D^0\pi^-$ decays (Phys.Rev. D95 (2017) 052005)

$$A_D \equiv \frac{\varepsilon(B^- \to D^-_{(s)} D^0) - \varepsilon(B^+ \to D^+_{(s)} \overline{D}^0)}{\varepsilon(B^- \to D^-_{(s)} D^0) + \varepsilon(B^+ \to D^+_{(s)} \overline{D}^0)}$$

Detection asymmetries measured in data control samples of D^{*+} and D^+ decays

Channel	$N(B^-)$	$N(B^+)$	$A_{\rm raw}$	$A_P + A_D$
$B^- \to D_s^- D^0$, $D^0 \to K^-\pi^+$	13659 ± 129	14209 ± 132	$(-2.0 \pm 0.7)\%$	
$B^- \to D_s^- D^0$, $D^0 \to K^-\pi^+\pi^-\pi^+$	7717 ± 103	7945 ± 104	$(-1.5 \pm 0.9)\%$	$(-1.4 \pm 0.5)\%$
$B^- \to D_s^- D^0$, combined	21375 ± 165	22153 ± 168	$(-1.8 \pm 0.5)\%$	
$B^- \to D^- D^0$, $D^0 \to K^-\pi^+$	678 ± 32	660 ± 31	$(1.3 \pm 3.3)\%$	
$B^- \to D^- D^0$, $D^0 \to K^-\pi^+\pi^-\pi^+$	369 ± 24	345 ± 24	$(3.4 \pm 4.7)\%$	$(-0.3 \pm 0.4)\%$
$B^- \to D^- D^0$, combined	1047 ± 40	1005 ± 39	$(2.0 \pm 2.7)\%$	

Results

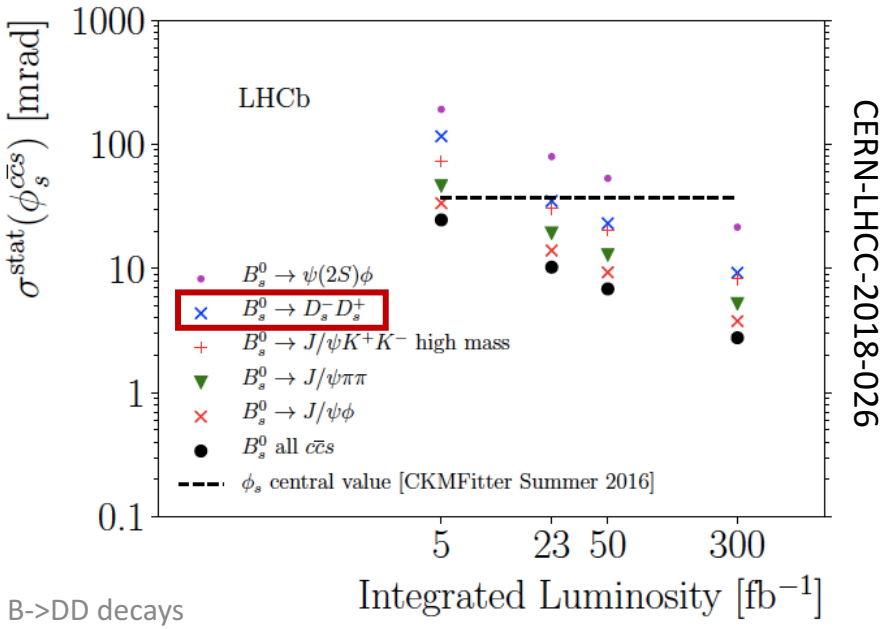
$$\mathcal{A}^{CP}(B^- \to D_s^- D^0) = (-0.4 \pm 0.5 \pm 0.5)\%$$
$$\mathcal{A}^{CP}(B^- \to D^- D^0) = (\ \ 2.3 \pm 2.7 \pm 0.4)\%$$

- No evidence of CP violation in $B^- \longrightarrow D_{(s)}^- D^0$ decays.
- $B^- \longrightarrow D_s^- D^0$ asymmetry measured for the first time.
- Uncertainty on $B^- \longrightarrow D^- D^0$ reduced by more than a factor two with respect to the previous measurements from Babar A^{CP}=(-13±14±2)% Phys.Rev. D73(2006)112004 and Belle A^{CP}=(0±8±2)% Phys.Rev.D77(2008)091101

Conclusions and prospects

- Beauty to double-charm decays have been successfully studied at LHCb.
- CPV observed in $B^0 \longrightarrow D^{*\pm} D^{\mp}$ decays, while no CPV measured in $B^- \longrightarrow D_{(s)}^- D^0$.
- Full exploitation of Run2 data sample for double-charm decays not completed yet.
- Importance of these channels will increase in Run3, with LHCb-Upgrade, due to removal of hardware trigger.

- Future LHCb-Upgrade-2 will allow to further reduce all statistical uncertainties.



CERN-LHCC-2018-026

Backup

Flavour Tagging

Sample	Tagger	Run 1		Run 2	
		ε_{tag} [%]	$\varepsilon_{\text{tag}} D^2$ [%]	ε_{tag} [%]	$\varepsilon_{\text{tag}} D^2$ [%]
$D^0 \to K^-\pi^-\pi^+\pi^+$	OS only	8.3 ± 1.6	0.64 ± 0.18	3.9 ± 0.6	0.36 ± 0.08
	SS only	43.0 ± 2.9	1.17 ± 0.16	47.4 ± 1.5	1.57 ± 0.11
	OS&SS both	37.5 ± 2.9	4.44 ± 0.57	41.5 ± 1.5	5.11 ± 0.30
	total	88.8 ± 1.9	6.25 ± 0.55	92.7 ± 0.8	7.05 ± 0.29
$D^0 \to K^-\pi^+$	OS only	12.2 ± 1.2	1.14 ± 0.19	4.2 ± 0.4	0.42 ± 0.06
	SS only	40.3 ± 1.8	1.43 ± 0.18	51.4 ± 0.9	1.61 ± 0.07
	OS&SS both	27.7 ± 1.7	3.05 ± 0.30	37.9 ± 0.9	4.57 ± 0.19
	total	80.2 ± 1.4	5.61 ± 0.36	93.5 ± 0.5	6.61 ± 0.19

Systematics

Origin	$\sigma_\Delta C_{D^*D}$	σ_{CD^*D}	$\sigma_\Delta S_{D^*D}$	σ_{SD^*D}	$\sigma_{A_{\rm raw}^{K\pi\pi\pi,\rm Run1}}$	$\sigma_{A_{\rm raw}^{K\pi\pi\pi,\rm Run2}}$	$\sigma_{A_{\rm raw}^{K\pi,\rm Run1}}$	$\sigma_{A_{\rm raw}^{K\pi,\rm Run2}}$
Fit bias	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Mass model	0.006	0.014	0.003	0.011	0.0025	0.0024	0.0021	0.0016
$\Delta m_d, \tau_d, \Delta\Gamma_d$	0.001	0.003	0.001	0.001	0.0003	0.0002	0.0002	0.0001
Decay time resolution	–	–	–	–	0.0002	0.0001	0.0001	0.0001
Decay time acceptance	–	–	–	–	0.0003	0.0001	0.0002	0.0001
Flavour Tagging	0.015	0.014	0.012	0.015	0.0001	0.0001	0.0001	0.0001
Quadratic sum of syst.	0.016	0.020	0.012	0.019	0.0027	0.0026	0.0023	0.0019

- Additional (dominant) systematic on A_{D^*D} coming from the subtraction of A_{det}
- No significant variation of parameters observed when the analysis is repeated on data sub-samples (D^0 decay mode, FT algorithm etc.)

B^0 production asymmetry

Parameter	Run 1	Run 2
$A_{\rm prod}$	$-0.011 \pm 0.008 \pm 0.003$	$0.004 \pm 0.005 \pm 0.002$