Mixing and CP violation in beauty and charm at LHCb

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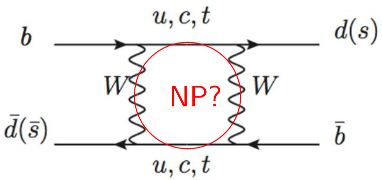
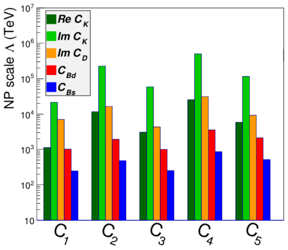
Why study flavour physics?

- Current measurements in the flavour sectors are consistent with the CKM picture to a $\sim 20\%$ level
  - SM CPV not sufficient to explain matter-antimatter asymmetry
  - However, large margin to be gain to reach EW tests precision
- Looking for SM deviations in an “indirect” way is complementary to direct production searches

M. Bona, CKM 2018





- Theoretical predictions are more difficult but processes are sensitive to far higher energy scales

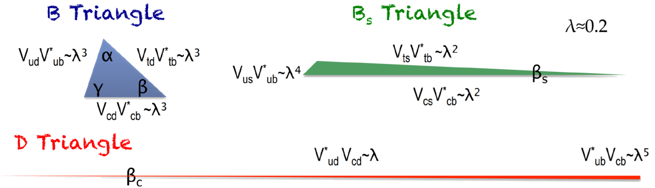
CP violation in the Standard Model

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

$$= \underbrace{\begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+A^2\lambda^5\left[1-2(\rho+i\eta)\right]/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3\left[1-(\rho+i\eta)(1-\lambda^2/2)\right] & -A\lambda^2+A\lambda^4\left[1-2(\rho+i\eta)\right]/2 & 1-A^2\lambda^4/2 \end{pmatrix}}_{\text{Wolfenstein parametrisation}} + \mathcal{O}(\lambda^6)$$

$\lambda = \sin(\theta_c) \approx 0.22, \quad \eta \approx 0.3$

- 3 quark generations allow for a CP violating phase: η is the only CPV source in the SM



$$\beta_c = \arg\left(-\frac{V_{cd}V_{ud}^*}{V_{cs}V_{us}^*}\right)$$

CP violation and mixing in neutral mesons

1. **CPV in decay**: $\left|\bar{A}_{\bar{f}}/A_f\right| \neq 1$
2. **CPV in mixing**: $|q/p| \neq 1$
3. **CPV in interference between mixing and decay**: $\phi \equiv \arg\left\{\frac{q}{p}\frac{A_f}{\bar{A}_f}\right\}$

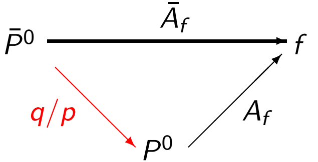
Flavour eigenstates

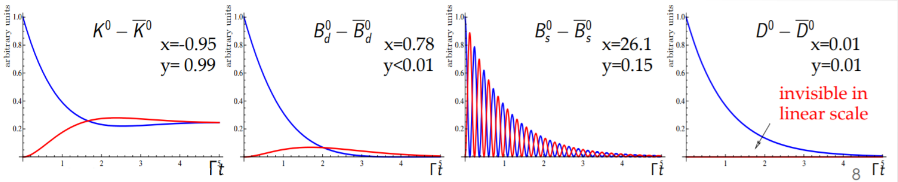
$$|P_{L,H}\rangle = p|P^0\rangle \pm q|\bar{P}^0\rangle$$

Mass eigenstates

Mixing observables

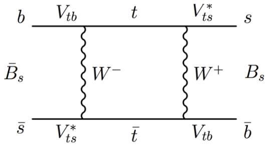
- $\Delta m \equiv (m_H - m_L), \quad x = \Delta m/\Gamma$
- $\Gamma \equiv (\Gamma_L + \Gamma_H)/2, \quad y = \Delta\Gamma/2\Gamma$
- $\Delta\Gamma \equiv \Gamma_L - \Gamma_H$



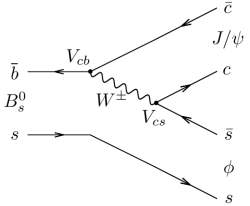


Measurement of ϕ_s in $B_s^0 \to J/\psi(\to \mu^+\mu^-)K^+K^-$ decays

Mixing $\phi_M = 2\arg(V_{tb}V_{ts}^*)$



Decay $\phi_D = \arg(V_{cb}V_{cs}^*)$



$$\phi_s = \phi_M - 2\phi_D \stackrel{SM}{=} -2\arg\left(-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right) \equiv -2\beta_s$$ (neglecting penguin contributions)

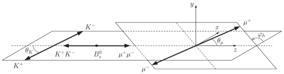
- Theoretically clean: $\phi_s \stackrel{SM}{=} -0.0370 \pm 0.0010$ rad [UTfit]
  $\phi_s \stackrel{SM}{=} -0.0368^{+0.00096}_{-0.00068}$ rad [CKMFitter]
- Accessible by measuring the time-dependent asymmetry

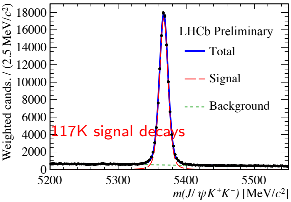
$$A_{CP}(t) = \frac{\Gamma_{B_s^0} - \Gamma_{\bar{B}_s^0}}{\Gamma_{B_s^0} + \Gamma_{\bar{B}_s^0}} = \frac{S_f \sin(\Delta m t) - C_f \cos(\Delta m t)}{\cosh(\Delta\Gamma t/2) - A_{\Delta\Gamma}\sinh(\Delta\Gamma t/2)}$$

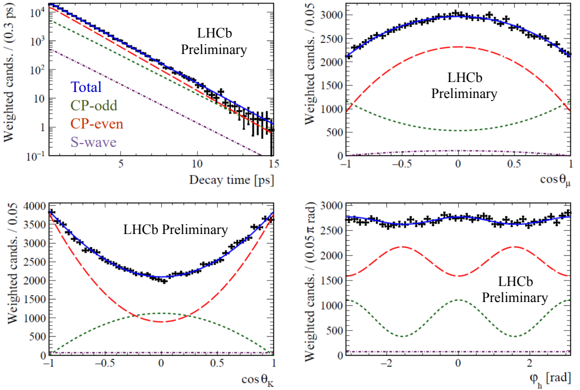
$\lambda_f = \frac{qA_f}{p\bar{A}_f}$, $\phi_s = -\arg(\lambda_f)$, $C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$, $S_f = \frac{2\mathcal{I}(\lambda_f)}{1+|\lambda_f|^2}$, $A_{\Delta\Gamma} = -\frac{2\mathcal{R}(\lambda_f)}{1+|\lambda_f|^2}$

Measurement of ϕ_s in $B_s^0 \to J/\psi(\to \mu^+\mu^-)K^+K^-$ decays

- Dominated by $\phi \to KK$. Final state is a mixture of CP even and odd
- Updated measurement with 2015 and 2016 data
- Improved tagging power at $(4.73 \pm 0.34)\%$ (3.73% in Run1)







S-wave CP-odd CP-even

Measurement of ϕ_s in $B_s^0 \to J/\psi(\to \mu^+\mu^-)K^+K^-$ decays

- Decay time efficiency taken from $B_d \to J/\psi K^*$ data, high precision on $\Gamma_s - \Gamma_d$ (important input for HQE)
- ϕ_s also measured for each polarisation state of the K^+K^- system, no evidence for polarisation dependence

Results

Parameter	Value
ϕ_s [rad]	$-0.080 \pm 0.041 \pm 0.006$
$\vert\lambda\vert$	$1.006 \pm 0.016 \pm 0.006$
$\Gamma_s - \Gamma_d$ [ps^{-1}]	$-0.0041 \pm 0.0024 \pm 0.0015$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0772 \pm 0.0077 \pm 0.0026$
Δm_s [ps^{-1}]	$17.705 \pm 0.059 \pm 0.018$
$\vert A_\perp\vert^2$	$0.2457 \pm 0.0040 \pm 0.0019$
$\vert A_0\vert^2$	$0.5186 \pm 0.0029 \pm 0.0024$
$\delta_\perp - \delta_0$	$2.64 \pm 0.13 \pm 0.10$
$\delta_\parallel - \delta_0$	$3.061^{+0.084}_{-0.073} \pm 0.037$

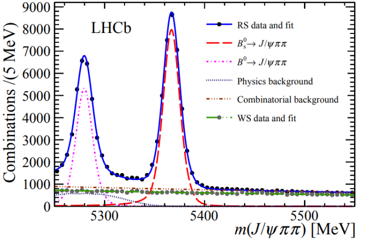
Combination with Run1

$$
\begin{aligned}
\phi_s &= -0.078 \pm 0.032\,\text{rad}\,, \\
|\lambda| &= 0.991 \pm 0.013\,, \\
\Gamma_s - \Gamma_d &= -0.0013 \pm 0.0021\,\text{ps}^{-1}\,, \\
\Delta\Gamma_s &= 0.0773 \pm 0.0062\,\text{ps}^{-1}\,, \\
\Delta m_s &= 17.695 \pm 0.042\,\text{ps}^{-1}\,, \\
|A_\perp|^2 &= 0.2491 \pm 0.0035\,, \\
|A_0|^2 &= 0.5195 \pm 0.0035\,, \\
\delta_\perp &= 2.88 \pm 0.11\,\text{rad}\,, \\
\delta_\parallel &= 3.153 \pm 0.079\,\text{rad}.
\end{aligned}
$$

Results compatible with the SM at 1.3σ and different from 0 at 2.4σ

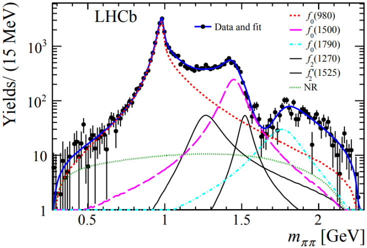
Measurement of ϕ_s in $B_s^0 \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$ decays

- Update of previous of Run1 result [PLB(2014)06079] with 2015 and 2016 data



Results

- $\phi_s = -0.057 \pm 0.060(stat) \pm 0.011(syst)$ rad
- $|\lambda| = 1.01^{+0.08}_{-0.06}(stat) \pm 0.03(syst)$
- $\Gamma_H - \Gamma_d = -0.050 \pm 0.004(stat) \pm 0.004(syst)/\text{ps}$



Combination with Run1 measurement

- $\phi_s = 0.002 \pm 0.044(stat) \pm 0.012(syst)$ rad
- $|\lambda| = 0.949 \pm 0.036(stat) \pm 0.019(syst)$

ϕ_s, combined results

$$\phi_s = -0.040 \pm 0.025\,\text{rad}$$

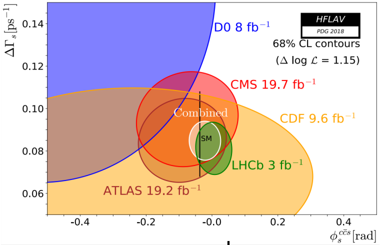
$$|\lambda| = -0.991 \pm 0.010$$

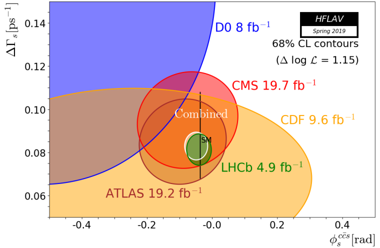
$$\Delta\Gamma_s = 0.0813 \pm 0.0048\,\mathrm{ps}^{-1}$$

$$\Gamma_s - \Gamma_{B^0} = -0.0024 \pm 0.0018\,\mathrm{ps}^{-1}$$

ϕ_s is 1.6σ from 0 (0.1σ from SM)
$\Gamma_s - \Gamma_{B^0}$ consistent with HQE

Stay tuned for future updates with the full dataset!

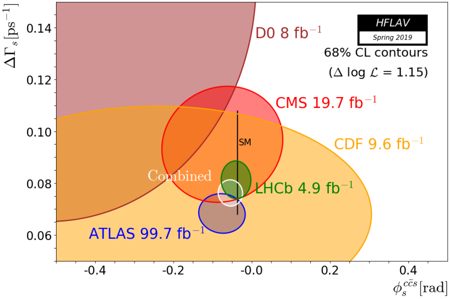




Including latest ATLAS results [ATLAS-CONF-2019-009]

Combination of ATLAS results ($\sqrt{s}$ =7, 8 and 13 TeV):

$$\phi_s = -0.076 \pm 0.034(stat) \pm 0.019(syst) \text{ rad}$$
$$\Delta\Gamma_s = 0.068 \pm 0.004(stat) \pm 0.003(syst)\,\mathrm{ps}^{-1}$$



New HFLAV average

$$\phi_s = -0.0544 \pm 0.0205$$
$$\Delta\Gamma_s = 0.0762 \pm 0.0033\,\mathrm{ps}^{-1}$$

Thanks to the HFLAV team!

CP asymmetries in four-body Λ_b^0 and Ξ_b^0 decays

- Only CPV in decay is accessible. Theory for charmless decays predicts about 20% CPV [PRD91,116007(2015]. Not observed so far
- LHCb has the ideal environment to study CPV in baryons
- $\Delta A_{CP} = A_{CP}^{signal} - A_{CP}^{control}$ measured in the full phase space and in specific regions
- Results from Run1

Full phasespace

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (+1.1 \pm 2.5 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (+3.2 \pm 1.1 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) = (-6.9 \pm 4.9 \pm 0.8)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+K^-) = (+0.2 \pm 1.8 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Xi_b^0 \to pK^-\pi^+\pi^-) = (-17 \pm 11 \pm 1)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Xi_b^0 \to pK^-\pi^+K^-) = (-6.8 \pm 8.0 \pm 0.8)\,\%$$

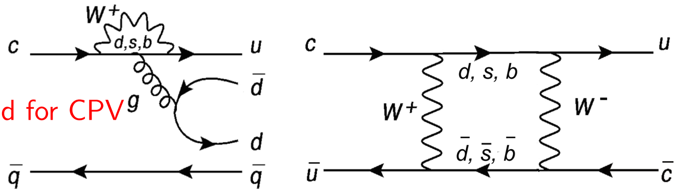
Decay mode	Signal yields X_b^0	Signal yields $\overline{X}_b^0$
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	2335 ± 56	2264 ± 55
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	6807 ± 92	6232 ± 89
$\Lambda_b^0 \to pK^-K^+\pi^-$	555 ± 38	630 ± 38
$\Lambda_b^0 \to pK^-K^+K^-$	2312 ± 54	2248 ± 54
$\Xi_b^0 \to pK^-\pi^+\pi^-$	180 ± 28	252 ± 29
$\Xi_b^0 \to pK^-\pi^+K^-$	265 ± 25	305 ± 26
$\Lambda_b^0 \to (\Lambda_c^+ \to p\pi^-\pi^+)\pi^-$	1607 ± 40	1586 ± 40
$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$	24687 ± 159	24052 ± 157
$\Xi_b^0 \to (\Xi_c^+ \to pK^-\pi^+)\pi^-$	259 ± 18	260 ± 18

18 CP asymmetry measurements (backups), no significant CPV observed

Why study charm physics?

- Up-type quark: unique probe of NP in the flavour sector, complementary to studies in K and B systems
- Precision CKM physics in the B sectors needs input from charm
- Rare processes are very suppressed in the SM

Needed for CPV

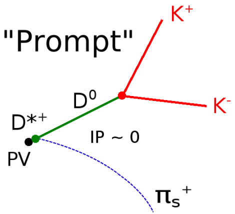


- New Physics may be hidden in the loops
- Long-distance contributions are non-negligible and precise theoretical predictions are difficult

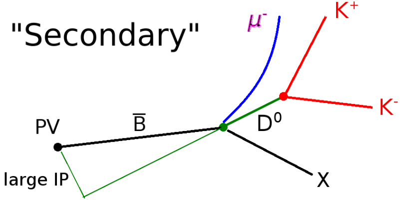
How to get the D flavour at production?

- Whether the decaying D meson is produced as D^0 or $\bar{D}^0$ needs to be determined to perform mixing and CPV measurements
- There are two possible tagging methods

$D^{*\pm}$-tag



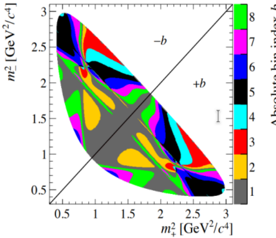
Semileptonic-tag



- Both samples used by LHCb, independent and complementary in lifetime coverage

Mass difference between neutral charm-meson eigenstates

- $D^0 \to K_s^0 \pi^+ \pi^-$ has a rich resonant structure
- Time dependent, Dalitz analysis performed with the model independent "bin-flip" approach, it does not need accurate efficiency modeling [PRD99(2019)012007]
- Binning chosen to have $\sim$constant strong-phase difference



Observables

Measure yield ratio, R, between b and -b bins as a function of decay time, this is a function of:

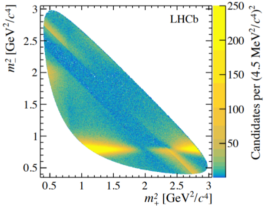
$z_{CP} \pm \Delta z = -(q/p)^{\pm 1}(y + ix)$

$x_{CP} = -\mathrm{Im}(z_{CP}),\ y_{CP} = -\mathrm{Re}(z_{CP})$

$\Delta x = -\mathrm{Im}(\Delta z),\ \Delta y = -\mathrm{Re}(\Delta z)$

Δy often referred to as A_Γ

$$m_\pm^2 \equiv \begin{cases} m^2(K_S^0\pi^\pm) & \text{for } D^0 \to K_S^0\pi^+\pi^- \\ m^2(K_S^0\pi^\mp) & \text{for } \overline{D}^0 \to K_S^0\pi^+\pi^- \end{cases}$$



- Run1 data, both prompt and SL samples ($\sim$ 2.3 M events)

Mass difference between neutral charm-meson eigenstates

Allowing for CPV in mixing

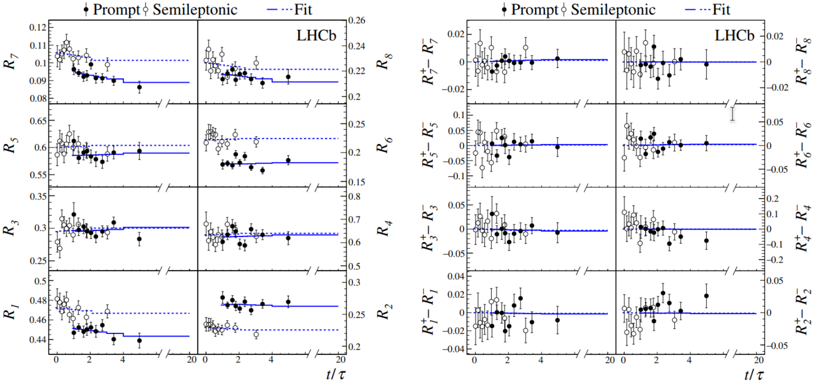
$x_{CP} = [2.7 \pm 1.6(stat) \pm 0.4(syst)] \times 10^{-3}$

$\Delta x = [-0.53 \pm 0.70(stat) \pm 0.22(syst)] \times 10^{-3}$

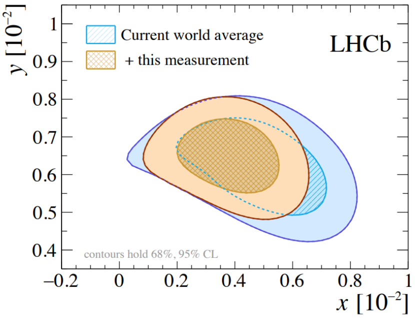
$y_{CP} = [7.4 \pm 3.6(stat) \pm 1.1(syst)] \times 10^{-3}$

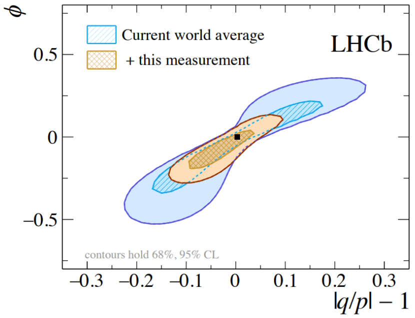
$\Delta x = [0.6 \pm 1.6(stat) \pm 0.3(syst)] \times 10^{-3}$

Most precise determination of x from a single experiment!



Mass difference between neutral charm-meson eigenstates

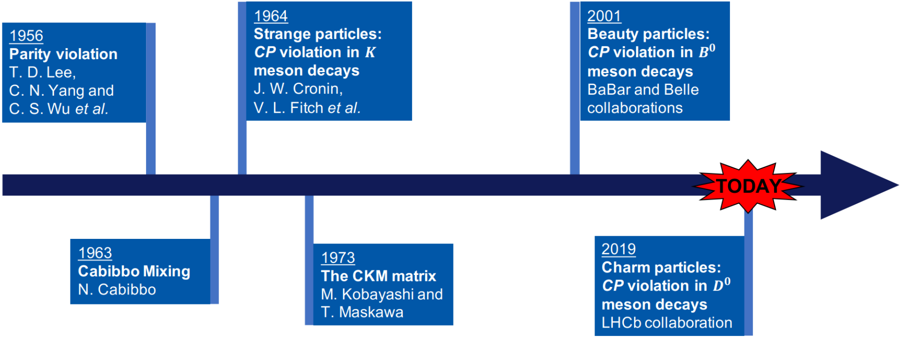




Combination with previous measurements yields the first evidence for a positive x. Extremely important since sensitivity to ϕ relies on observables $\propto x \sin \phi$

Observation of CP violation in charm

Key dates for CPV



Courtesy of Angelo Carbone

Observation of CP violation in charm

- Observable is mainly sensitive to direct CPV

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$

$$\text{assuming universal } a_{cp}^{ind} \Rightarrow \simeq \Delta a_{CP}^{dir}\left(1 + \frac{\langle \bar{t} \rangle}{\tau_{D^0}} y_{cp}\right) + \frac{\Delta \langle t \rangle}{\tau_{D^0}} a_{CP}^{ind}$$

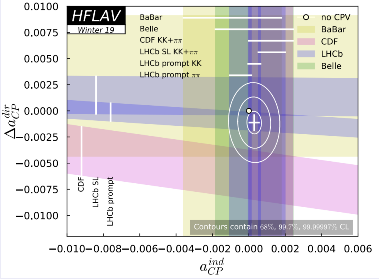
$$\langle \bar{t} \rangle = (\langle t \rangle_{KK} + \langle t \rangle_{\pi\pi})/2, \quad \Delta\langle t \rangle = \langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}$$

Previous status

- HFLAV combination
  $\Delta a_{cp}^{dir} = (-11.2 \pm 7.1) \times 10^{-4}$
  $a_{cp}^{ind} = (2.9 \pm 2.6) \times 10^{-4}$

  CPV at 1.38σ

Experiment	ΔA_{CP}	
CDF	$(-62 \pm 21 \pm 10) \times 10^{-4}$	PRL 109 (2012) 111801
BaBar	$(+24 \pm 62 \pm 26) \times 10^{-4}$	PRL 100 (2008) 061803
Belle	$(-87 \pm 41 \pm 6) \times 10^{-4}$	PLB 670 (2008) 190
LHCb (3.0 fb^{-1}, muon-tagged)	$(+14 \pm 16 \pm 8) \times 10^{-4}$	JHEP 07 (2014) 041
LHCb (3.0 fb^{-1}, pion-tagged)	$(-10 \pm 8 \pm 3) \times 10^{-4}$	PRL 116 (2016) 191601



Observation of CP violation in charm

- New measurement performed with full Run2($6\,\mathrm{fb}^{-1}$) data + combination with Run1($3\,\mathrm{fb}^{-1}$). Both prompt and semilep. samples are used.
- Experimentally very clean, main systematics cancel at first order

$$A_{raw} = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)} = A_{CP} + A_D(\pi_s^+/\mu) + A_P(D^{*+}/D^0_{\text{from } B})$$

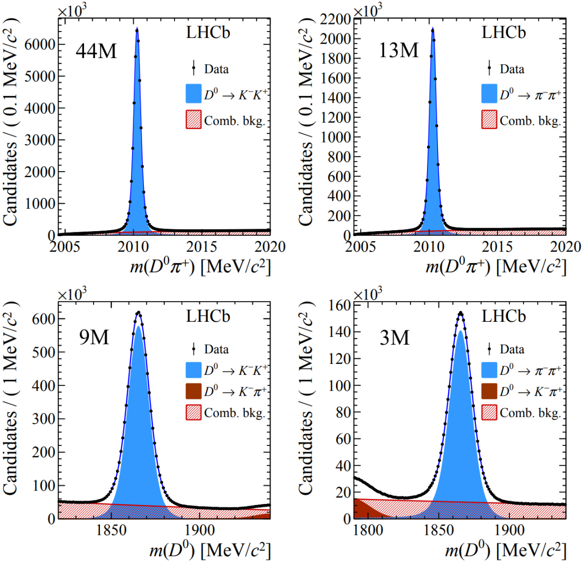
$$\Delta A_{CP} = A_{raw}(KK) - A_{raw}(\pi\pi) \cong A_{CP}(KK) - A_{CP}(\pi\pi)$$

- Production and detection asymmetries cancel (after kinematical reweighting)
- D^0 decay is charge symmetric

Observation of CP violation in charm

Pion tag

Muon tag



Observation of CP violation in charm

Run2 results

$$\Delta A_{CP}^{\pi-tagged} = [-18.2 \pm 3.2(stat) \pm 0.9(syst)] \times 10^{-4}$$

$$\Delta A_{CP}^{\mu-tagged} = [-9 \pm 8(stat) \pm 5(syst)] \times 10^{-4}$$

Compatible with previous LHCb results and the WA

Combination with LHCb Run1 gives:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

CP violation observed at 5.3σ!

Observation of CP violation in charm - Interpretation

- For the full LHCb dataset: $\langle\bar{t}\rangle/\tau_{D^0} = 0.115 \pm 0.002$ and $\Delta\langle t\rangle/\tau_{D^0} = 1.71 \pm 0.10$
- Using the LHCb averages:

$$y_{CP} = (5.7 \pm 1.5) \times 10^{-3}$$ [JHEP04(2012)129, PRL122(2019)011802]

$$A_\Gamma \simeq -a_{cp}^{ind} = (-2.8 \pm 2.8) \times 10^{-4}$$ [JHEP04(2015)043, PRL118(2017)261803]

Substituting in

$$\Delta A_{CP} \simeq \Delta a_{CP}^{dir}\left(1 + \frac{\langle\bar{t}\rangle}{\tau_{D^0}} y_{cp}\right) + \frac{\Delta\langle t\rangle}{\tau_{D^0}} a_{CP}^{ind}$$

$$\Delta a_{cp}^{dir} = (-15.6 \pm 2.9) \times 10^{-4}$$

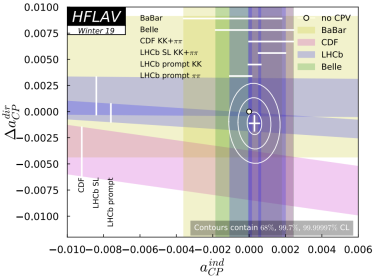
Observation of CP violation in charm - World averages

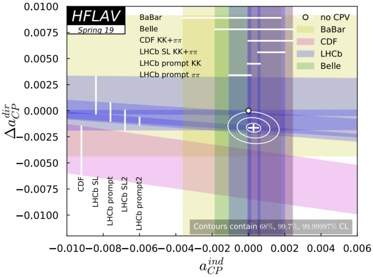
Including ΔA_{CP} measurement

$$\Delta a_{cp}^{dir} = (-16.4 \pm 2.8) \times 10^{-4}$$

$$a_{cp}^{ind} = (2.8 \pm 2.6) \times 10^{-4}$$

CPV at 5.44σ





Observation of CP violation in charm - SM comparison

- Result broadly compatible with SM predictions that range from 10^{-3} to 10^{-4}

Golden et. al., PLB 222 (1989) 501
Buccella et al., PRD 51 (1995) 3478
Bianco et al., Riv. Nuovo Cim . 26N7 (2003) 1
Grossman et al, PRD 75 (2007) 036008
Artuso et al., AR Nucl. Part. Sci. 58 (2008) 249
Khodjamirian et al., PLB 774 (2017) 235
Pirtskhalava et al. , PLB 712 (2012) 81
Cheng et al., PRD 85 (2012) 034036
Feldmann et al., JHEP 06 (2012) 007
Li et al., PRD 86 (2012) 036012
Franco et al., JHEP 05 (2012) 140
Brod et al., JHEP 10 (2012) 161
Atwood et al., PTEP 2013 (2013) 093B05
Hiller et al., PRD 87 (2013) 014024
Grossman et al., JHEP 04 (2013) 067
Müller et al., PRL 115 (2015) 251802
Buccella et al., arXiv:1902.05564 (2019)

- However contributions from NP cannot be excluded at the moment
- Need further measurement in the charm sector, also with other channels and possibly theoretical improvements to clarify the physics picture

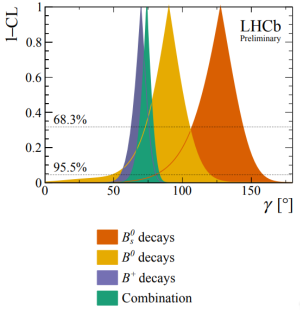
Conclusions

- New LHCb results in the beauty and charm sector that dominate the world averages
- Intriguing results on ϕ_s, CPV discovery in B_s^0 mixing may be around the corner
- First observation of CPV in charm
- All results presented are statically limited, still a lot of work to do, both with current data and in the upgrade
- Stay tuned for more exciting results!

Backups

[LHCb-CONF-2018-002]

Status of the CKM γ determination



B decay	D decay	Method	Ref.	Dataset†	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \to DK^+$	$D \to K_S^0 h^+h^-$	GGSZ	[17]	Run 1	As before
$B^+ \to DK^+$	$D \to K_S^0 h^+h^-$	GGSZ	[18]	Run 2	New
$B^+ \to DK^+$	$D \to K_S^0 K^+\pi^-$	GLS	[19]	Run 1	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	GGSZ	[24]	Run 1	As before
$B_s^0 \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	[25]	Run 1	Updated results
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1	New

† Run 1 corresponds to an integrated luminosity of 3 fb^{-1} taken at centre-of-mass energies of 7 and 8 TeV. Run 2 corresponds to an integrated luminosity of 2 fb^{-1} taken at a centre-of-mass energy of 13 TeV.

Combination:

$$\gamma = (74.0^{+5.0}_{-5.8})^{\circ}$$

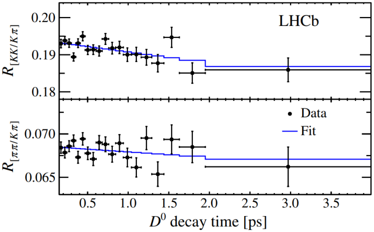
- Most precise determination from a single experiment
- In agreement with world averages

Measurement of y_{CP} in charm decays

- Use $D^0 \to h^+h^-$ and $D^0 \to K^-\pi^+$ from semileptonic B decays, full Run1
- Equal to the mixing parameter y if CP is conserved

$$y_{CP} = \frac{\Gamma_{CP+}}{\Gamma} - 1$$

- Experimentally determined from yield ratio vs τ_{D^0}

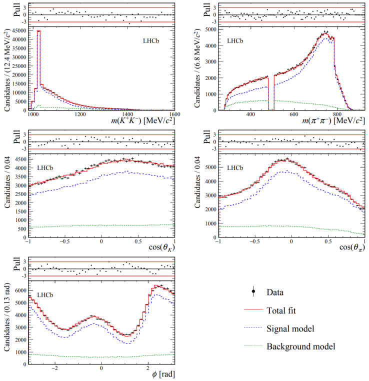


- $y_{CP} = [0.57 \pm 0.13(stat) \pm 0.099(syst)]\%$
- Compatible with world average $y_{CP} = (0.62 \pm 0.07)\%$
- No evidence for CPV in mixing

Search for CPV in $D^0 \to K^+K^-\pi^+\pi^-$

- Amplitude analysis of $D^0 \to K^+K^-\pi^+\pi^-$ decays coming from B mesons
- Full Run1 data is used ($\sim$ 163K signal decays)

Amplitude	$A_{\lvert c_k \rvert}$ [%]	$\Delta \arg(c_k)$ [%]	$A_{\mathcal{F}_k}$ [%]
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=0}$	0 (fixed)	0 (fixed)	$-1.8 \pm 1.5 \pm 0.2$
$D^0 \to K_1(1400)^+K^-$	$-1.4 \pm 1.1 \pm 0.2$	$1.3 \pm 1.5 \pm 0.3$	$-4.5 \pm 2.1 \pm 0.3$
$D^0 \to [K^-\pi^+]_{L=0}[K^+\pi^-]_{L=0}$	$1.9 \pm 1.1 \pm 0.3$	$-1.2 \pm 1.3 \pm 0.3$	$2.0 \pm 1.8 \pm 0.7$
$D^0 \to K_1(1270)^+K^-$	$-0.4 \pm 1.0 \pm 0.2$	$-1.1 \pm 1.4 \pm 0.2$	$-2.6 \pm 1.7 \pm 0.2$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=0}$	$-1.3 \pm 1.3 \pm 0.3$	$-1.7 \pm 1.5 \pm 0.2$	$-4.3 \pm 2.2 \pm 0.5$
$D^0 \to K^*(1680)^0[K^-\pi^+]_{L=0}$	$2.2 \pm 1.3 \pm 0.3$	$1.4 \pm 1.5 \pm 0.2$	$2.6 \pm 2.2 \pm 0.4$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=1}$	$-0.4 \pm 1.7 \pm 0.2$	$3.7 \pm 2.0 \pm 0.2$	$-2.6 \pm 3.2 \pm 0.3$
$D^0 \to K_1(1270)^-K^+$	$2.6 \pm 1.7 \pm 0.4$	$-0.1 \pm 2.1 \pm 0.3$	$3.3 \pm 3.5 \pm 0.5$
$D^0 \to [K^+K^-]_{L=0}[\pi^+\pi^-]_{L=0}$	$3.5 \pm 2.5 \pm 1.5$	$-5.5 \pm 2.6 \pm 1.6$	$5.1 \pm 5.1 \pm 3.1$
$D^0 \to K_1(1400)^-K^+$	$0.2 \pm 2.9 \pm 0.7$	$2.5 \pm 3.5 \pm 1.0$	$-1.3 \pm 6.0 \pm 1.0$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=0}$	$4.0 \pm 2.7 \pm 0.8$	$-5.4 \pm 2.8 \pm 0.8$	$6.2 \pm 5.2 \pm 1.5$
$D^0 \to [\overline{K}^*(1680)^0K^*(892)^0]_{L=1}$	$-0.4 \pm 2.1 \pm 0.3$	$0.4 \pm 2.1 \pm 0.3$	$-2.5 \pm 3.9 \pm 0.4$
$D^0 \to \overline{K}^*(1680)^0[K^+\pi^-]_{L=0}$	$2.1 \pm 2.0 \pm 0.6$	$-1.8 \pm 2.2 \pm 0.3$	$2.4 \pm 3.7 \pm 1.1$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=2}$	$0.8 \pm 1.9 \pm 0.3$	$-1.2 \pm 2.0 \pm 0.5$	$-0.1 \pm 3.3 \pm 0.5$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=2}$	$-0.6 \pm 2.5 \pm 0.4$	$0.6 \pm 2.6 \pm 0.4$	$-3.0 \pm 5.0 \pm 0.7$
$D^0 \to \phi(1020)[\pi^+\pi^-]_{L=0}$	$3.8 \pm 3.1 \pm 0.7$	$-0.5 \pm 3.9 \pm 0.7$	$5.8 \pm 6.1 \pm 0.8$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=1}$	$1.6 \pm 2.8 \pm 0.5$	$0.7 \pm 3.0 \pm 0.4$	$1.3 \pm 5.3 \pm 0.6$
$D^0 \to [\phi(1020)\rho(1450)^0]_{L=1}$	$4.6 \pm 4.1 \pm 0.6$	$9.3 \pm 3.3 \pm 0.6$	$7.5 \pm 8.5 \pm 1.1$
$D^0 \to a_0(980)^0f_2(1270)^0$	$1.6 \pm 3.6 \pm 0.7$	$-7.3 \pm 3.3 \pm 0.8$	$1.5 \pm 7.2 \pm 1.3$
$D^0 \to a_1(1260)^+\pi^-$	$-4.4 \pm 5.6 \pm 3.7$	$9.3 \pm 6.1 \pm 1.3$	$-10.6 \pm 11.7 \pm 7.0$
$D^0 \to a_1(1260)^-\pi^+$	$-3.4 \pm 7.0 \pm 1.9$	$-5.8 \pm 5.6 \pm 4.3$	$-8.7 \pm 13.7 \pm 2.9$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=1}$	$2.1 \pm 5.2 \pm 0.8$	$-12.2 \pm 5.5 \pm 0.6$	$2.4 \pm 11.0 \pm 1.4$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=2}$	$5.2 \pm 7.1 \pm 1.9$	$-5.6 \pm 8.1 \pm 1.3$	$8.5 \pm 14.3 \pm 3.5$
$D^0 \to [K^+K^-]_{L=0}(\rho-\omega)^0$	$11.7 \pm 6.0 \pm 1.9$	$4.8 \pm 6.2 \pm 1.1$	$21.3 \pm 12.5 \pm 2.8$
$D^0 \to [\phi(1020)f_2(1270)^0]_{L=1}$	$2.7 \pm 6.7 \pm 1.7$	$0.9 \pm 6.0 \pm 1.7$	$3.6 \pm 13.3 \pm 3.0$
$D^0 \to [K^*(892)^0\overline{K}^*_2(1430)^0]_{L=1}$	$3.9 \pm 5.2 \pm 1.0$	$6.8 \pm 6.4 \pm 1.4$	$6.1 \pm 10.8 \pm 1.8$



- No CPV found

Correct for production and detection asymmetries

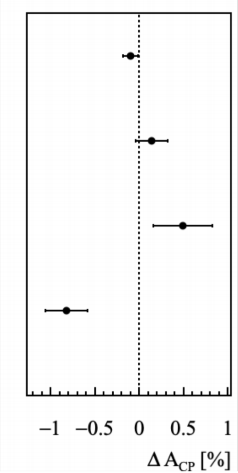
Production and detction asymmetries are corrected for using CF modes, wihich are known to have negligible CPV. If all asymmetries are small:

$$\begin{aligned}
\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) &\approx A(D_s^+ \to K_S^0\pi^+) - A(D_s^+ \to \phi\pi^+), \\
\mathcal{A}_{CP}(D^+ \to K_S^0K^+) &\approx A(D^+ \to K_S^0K^+) - A(D^+ \to K_S^0\pi^+) \\
&\quad - A(D_s^+ \to K_S^0K^+) + A(D_s^+ \to \phi\pi^+), \\
\mathcal{A}_{CP}(D^+ \to \phi\pi^+) &\approx A(D^+ \to \phi\pi^+) - A(D^+ \to K_S^0\pi^+),
\end{aligned}$$

[1]

Control samples have to be reweighted to match signal sample kinematics

ΔA_{CP} history in LHCb [2012-2016]



π-tagged (3 fb^{-1})	Phys. Rev. Lett. 116 (2016)
μ-tagged (3 fb^{-1})	JHEP 07 041 (2014)
μ-tagged (1 fb^{-1})	Phys. Lett. B723 33 (2013)
π-tagged (0.62 fb^{-1})	Phys. Rev. Lett. 108 (2012)

ϕ_s, systematic uncertainties

Source	$\|A_0\|^2$	$\|A_\perp\|^2$	ϕ_s [rad]	$\|\lambda\|$	$\delta_\perp - \delta_0$ [rad]	$\delta_\parallel - \delta_0$ [rad]	$\Gamma_s - \Gamma_d$ [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [ps^{-1}]
Mass width parametrisation	0.0006	0.0005	-	-	0.05	0.009	-	0.0002	0.001
Mass factorisation	0.0002	0.0004	0.004	0.0037	0.01	0.004	0.0007	0.0022	0.016
Multiple candidates	0.0006	0.0001	0.0011	0.0011	0.01	0.002	0.0003	0.0001	0.001
Fit bias	0.0001	0.0006	0.001	-	0.02	0.033	-	0.0003	0.001
$C_{\rm SP}$ factors	-	0.0001	0.001	0.0010	0.01	0.005	-	0.0001	0.002
Quadratic OS tagging	-	-	-	-	-	-	-	-	-
Time res.: statistical	-	-	-	-	-	-	-	-	-
Time res.: prompt	-	-	-	-	-	0.001	-	-	0.001
Time res.: mean offset	-	-	0.0032	0.0010	0.08	0.001	0.0002	0.0003	0.005
Time res.: Wrong PV	-	-	-	-	-	0.001	-	-	0.001
Ang. acc.: statistical	0.0003	0.0004	0.0011	0.0018	-	0.004	-	-	0.001
Ang. acc.: correction	0.0020	0.0011	0.0022	0.0043	0.01	0.008	0.0001	0.0002	0.001
Ang. acc.: low-quality tracks	0.0002	0.0001	0.0005	0.0014	-	0.002	0.0002	0.0001	-
Ang. acc.: t & σ_t dependence	0.0008	0.0012	0.0012	0.0007	0.03	0.006	0.0002	0.0010	0.003
Dec.-time eff.: statistical	0.0002	0.0003	-	-	-	-	0.0012	0.0008	-
Dec.-time eff.: $\Delta\Gamma_s = 0$ sim.	0.0001	0.0002	-	-	-	-	0.0003	0.0005	-
Dec.-time eff.: knot pos.	-	-	-	-	-	-	-	-	-
Dec.-time eff.: p.d.f. weighting	-	-	-	-	-	-	0.0001	0.0001	-
Dec.-time eff.: kin. weighting	-	-	-	-	-	-	0.0002	-	-
Length scale	-	-	-	-	-	-	-	-	0.004
Quadratic sum of syst.	0.0024	0.0019	0.0061	0.0064	0.10	0.037	0.0015	0.0026	0.018

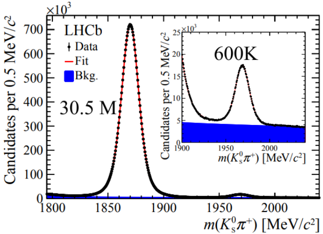
Observation of CP violation in charm

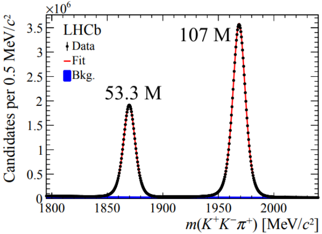
Systematic uncertainties

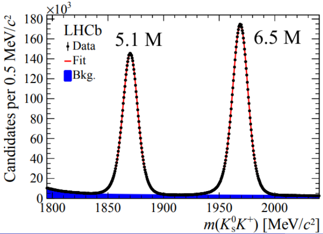
Source	π-tagged $[10^{-4}]$	μ-tagged $[10^{-4}]$
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B^0 fraction	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

A_{CP} in $D^+ \to K_S\pi^+$, $D_s^+ \to K_S K^+$, $D^+ \to \phi\pi^+$

- Analysis performed with the 2015-2017 datasets ($3.8\,\mathrm{fb}^{-1}$) using prompt charm from D^{*+} decays
- Correction for production and detection asymmetries using CF modes



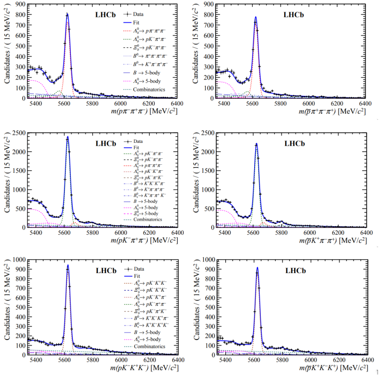


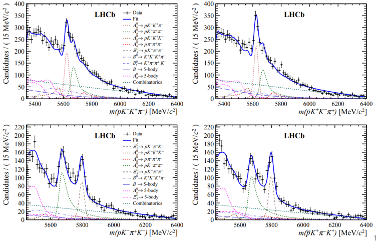


$$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) = (\ \ 1.3\ \ \pm 1.9\ \ \pm 0.5\ \ ) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to K_S^0 K^+) = (-0.09 \pm 0.65 \pm 0.48) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (\ \ 0.05 \pm 0.42 \pm 0.29) \times 10^{-3}$$

No CPV observed

CP asymmetries in four-body Λ_b^0 and Ξ_b^0 decays





Two-body low invariant mass

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (+3.7 \pm 4.1 \pm 0.5)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (+3.5 \pm 1.5 \pm 0.5)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) = (+2.7 \pm 2.3 \pm 0.6)\,\%$$

Quasi two-body

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pa_1(1260)^-) = (-1.5 \pm 4.2 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to N(1520)^0\rho(770)^0) = (+2.0 \pm 4.9 \pm 0.4)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to \Delta(1232)^{++}\pi^-\pi^-) = (+0.1 \pm 3.2 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK_1(1410)^-) = (+4.7 \pm 3.5 \pm 0.8)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to \Lambda(1520)\rho(770)^0) = (+0.6 \pm 6.0 \pm 0.5)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to N(1520)^0K^*(892)^0) = (+5.5 \pm 2.5 \pm 0.5)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to \Delta(1232)^{++}K^-\pi^-) = (+4.4 \pm 2.6 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to \Lambda(1520)\phi(1020)) = (+4.3 \pm 5.6 \pm 0.4)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to (pK^-)_{\text{high-mass}}\phi(1020)) = (-0.7 \pm 3.3 \pm 0.7)\,\%$$