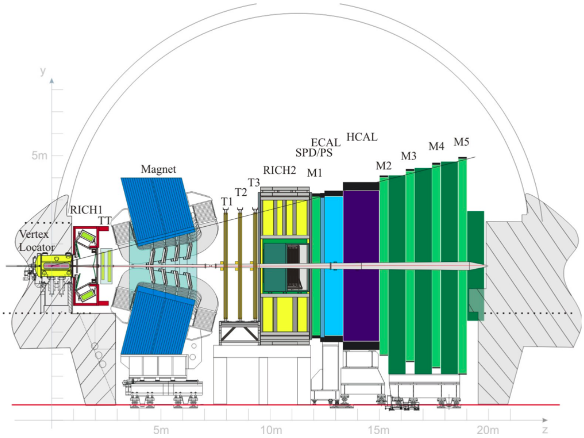
CP Violation in Beauty to Open Charm at LHCb

Jonathan Davies, on behalf of LHCb

BEAUTY2CHARM
European Research Council
Established by the European Commission

MANCHESTER 1824
The University of Manchester

The LHCb Experiment



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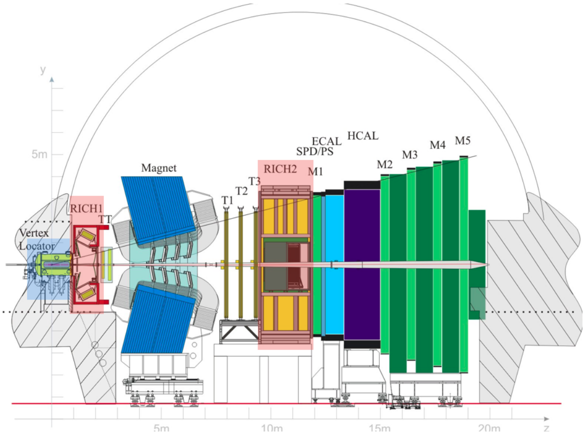
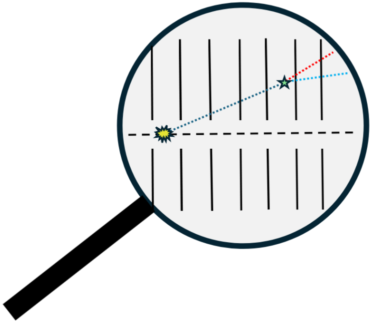
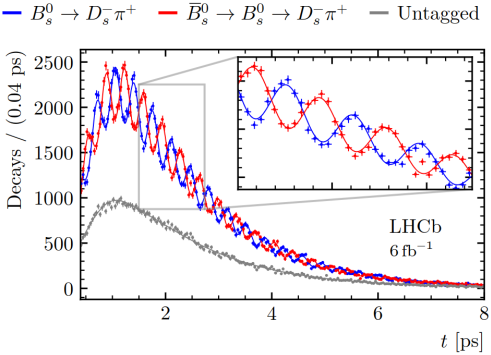


The *VELO* and *RICH* in particular make LHCb a great place to study beauty decays to *open charm* final states i.e. containing c but no $c\bar{c}$ particles e.g. J/ψ.

Why LHCb?

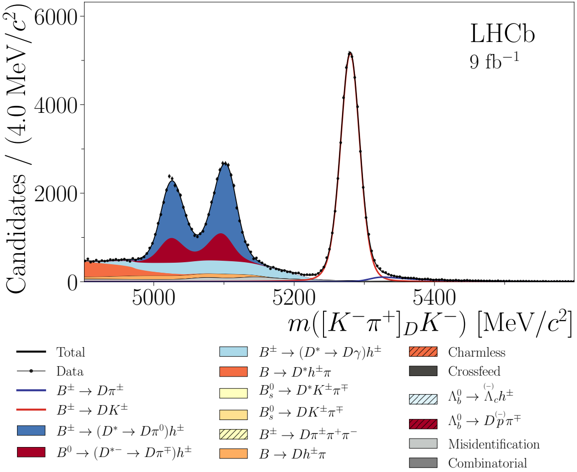
The VELO is the superstar for finding the B vertex position





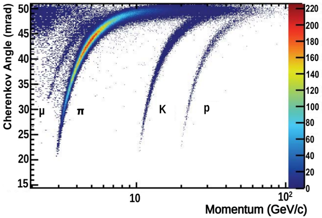
Good knowledge of B vertex position is essential for precise measurements of e.g. meson mixing [Nat. Phys. 18, 1–5 (2022)].

Why LHCb?

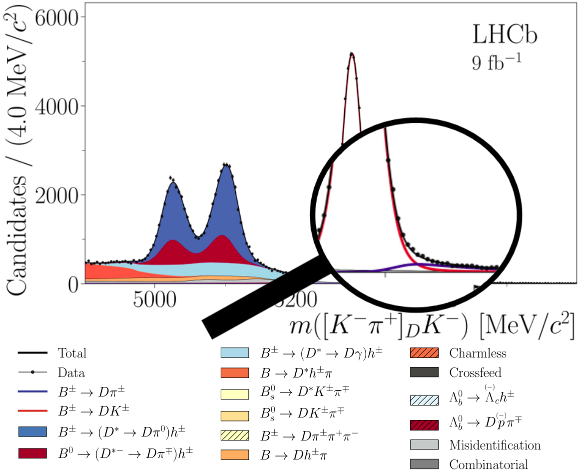


[J. High Energ. Phys. 2022, 99 (2022).]

Ring Image CHerenkov (RICH) detectors allow for excellent particle ID discrimination between π, K, p, μ, e.



Int. J. Mod. Phys. A 30, 1530022 (2015)



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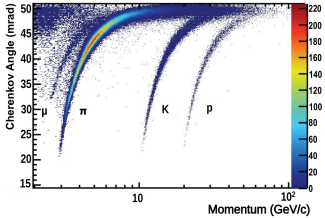


Int. J. Mod. Phys. A 30, 1530022 (2015)

MisID backgrounds can be dramatically reduced!

CPV with Beauty to Open Charm

CP symmetry is not a fundamental SM symmetry $\implies$ any generic New Physics (NP) theory expects contributions at $\mathcal{O}(1)$.

Interference of dominant tree amplitudes with sub-dominant contributions produces direct CP asymmetries, which are predicted to be small in the SM for $b \to c\bar{c}D$ transitions, at the level of 1% (5%) for $D = s(d)$.

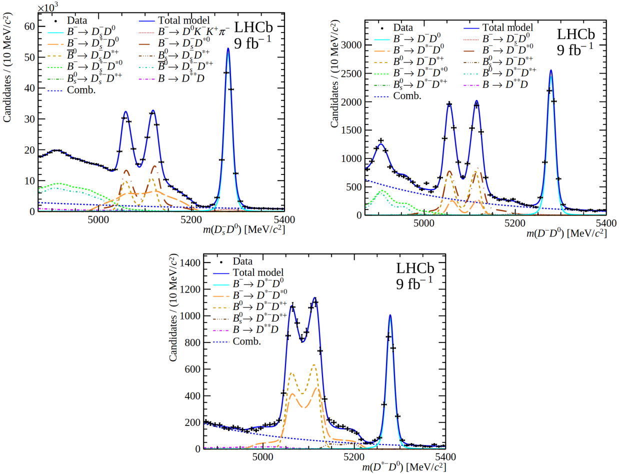
[JHEP09(2023)202] measured CP asymmetries for 7 $B^- \to D_{(s)}^{(*)-} D^{(*)0}$ modes

$$\mathcal{A}^{\rm CP} = \frac{\Gamma(B^- \to D_{(s)}^{(*)-} D^{(*)0}) - \Gamma(B^+ \to D_{(s)}^{(*)+} \overline{D}^{(*)0})}{\Gamma(B^- \to D_{(s)}^{(*)-} D^{(*)0}) + \Gamma(B^+ \to D_{(s)}^{(*)+} \overline{D}^{(*)0})}$$
$$= \mathcal{A}_{\rm raw} - \mathcal{A}_{\rm P} - \mathcal{A}_{\rm D}$$

Insight can be gained from measuring families of decays.

$\mathcal{A}_{\text{raw}}$

Raw asymmetries and yields are determined with an extended maximum-likelihood fit to the invariant-mass distribution of $B^- \to D_{(s)}^{(*)-} D^0$ candidates in the data.



[JHEP09(2023)202]

Binned simultaneous fit for all modes, charges, and for Run 1 and Run 2.

The model includes:

- Signal
- Missing γ/π^0 from D^*
- Part-reconstructed with D^{**}
- $B^- \to D^0 K^- K^+ \pi^-$
- Cross-feed of $B^- \to D_s^- D^0$ to $B^- \to D^- D^0$
- Combinatorial background

Production and Detection Asymmetries, $\mathcal{A}_P$ and $\mathcal{A}_D$

Samples reweighted to match kinematic distributions of simulated selected signal.

Source	Asymmetry	Calibration	Ref.
Production	$\sim 1\%$	$B^+ \to J/\psi K^+$	[1703.08464]
$K\pi$ Tracking	$\sim \mathcal{O}(1\%)$	$D^+ \to K^-\pi^+\pi^+$, $D^+ \to K^0\pi^+$	[1505.2797]
π Tracking	$\sim \mathcal{O}(0.1\%)$	$D^{*+} \to (D^0 \to K^-\pi^+\pi^-\pi^+)\pi^+$	[1605.09768]
Particle ID	$\sim 0.3\%$	$D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$	[LHCb-PUB-2016-021]
Trigger	$\mathcal{O}(0.1\%)$	$B \to \overline{D}^0\mu^+\nu_\mu X$ $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$	[1701.05501] [LHCb-PUB-2011-026]

[JHEP09(2023)202]

Results

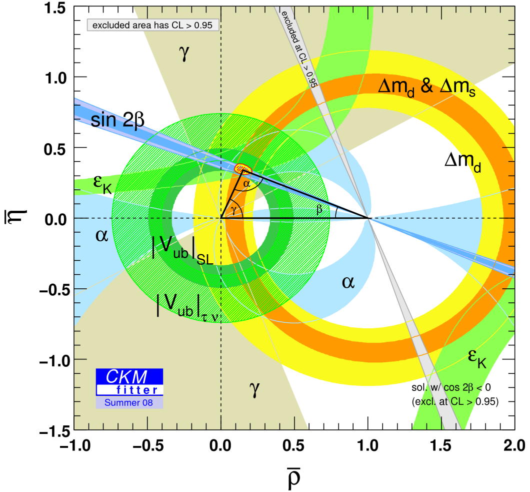
Combining asymmetry contributions, one obtains, with uncertainties from statistics, systematics, and $A^{CP}(B^+ \to J/\psi K^+)$, respectively [JHEP09(2023)202]:

$$
\begin{aligned}
A^{CP}(B^- \to D_s^- D^0) &= (+0.5 \pm 0.2 \pm 0.5 \pm 0.3)\%, \\
A^{CP}(B^- \to D_s^{*-} D^0) &= (-0.5 \pm 1.1 \pm 1.0 \pm 0.3)\%, \\
A^{CP}(B^- \to D_s^- D^{*0}) &= (+1.1 \pm 0.8 \pm 0.6 \pm 0.3)\%, \\
A^{CP}(B^- \to D^- D^0) &= (+2.5 \pm 1.0 \pm 0.4 \pm 0.3)\%, \\
A^{CP}(B^- \to D^- D^{*0}) &= (-0.2 \pm 2.0 \pm 1.4 \pm 0.3)\%, \\
A^{CP}(B^- \to D^{*-} D^0) &= (+3.3 \pm 1.6 \pm 0.6 \pm 0.3)\%, \\
A^{CP}(B^- \to D^{*-} D^{*0}) &= (+2.3 \pm 2.1 \pm 1.7 \pm 0.3)\%.
\end{aligned}
$$

All measurements **consistent with zero**, but having a comprehensive set of $A_{CP}(B \to D^{(*)} D'^{(*)})$ can provide great sensitivity to new physics [JD, M. Jung, S. Schacht, 2023].

γ- the SM benchmark

CKM matrix unitarity is a key assumption of the SM $\Longrightarrow$ triangle with angles α, β, γ.



bLHC (before LHC)

$B^{\pm} \to Dh^{\pm}$, with $h = \{\pi, K\}$, have excellent sensitivity to

$$\gamma \equiv \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*),$$

with small theory uncertainties, $\mathcal{O}(10^{-7})$ [1308.5663]

Two types:

- **Direct measurements** provide a SM benchmark, assuming no tree-level NP.
- **Indirect determinations** can be inferred from observables more likely to receive NP contributions.

$$\gamma_{\text{dir.}} = (65.9^{+3.3}_{-3.5})^\circ, \gamma_{\text{indir.}} = (65.29^{+0.72}_{-1.86})^\circ$$

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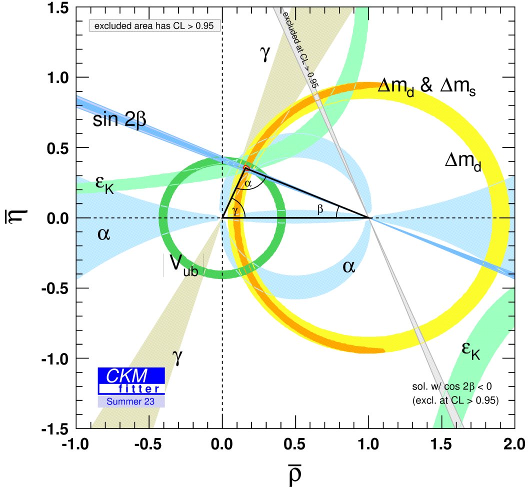
CKM matrix unitarity is a key assumption of the SM $\implies$ triangle with angles α, β, γ.



Including LHCb

http://ckmfitter.in2p3.fr/

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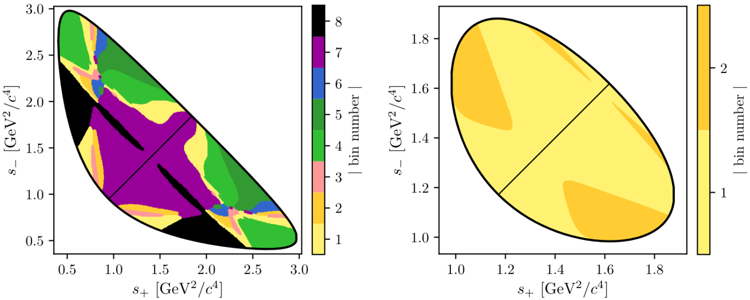
Measuring γ with D^*

Measurements with excited D mesons, $B^\pm \to D^* h^\pm$, are also sensitive to γ but are largely unmeasured $\implies$ cue [JHEP12(2023)013], [2311.10434].

Reconstructed with $D^* \to D\gamma/\pi^0$, $D \to K^0_S h^+ h^-$ and binned in $s^\pm \equiv m^2(K^0_S h^\pm)$; "optimal" scheme (left) for $h = \pi$, and "2-bins" scheme (right) for lower yield $h = K$.



Binning schemes taken from [PhysRevD.101.112002], and [PhysRevD.102.052008], respectively.

Bins where $s_- > s_+$ are given a positive index (+i), with the matching negative index (-i) given to the corresponding bin that is a reflection in the $s_- = s_+$ line.

Accessing γ

Comparing bin yields, $N_i^{\pm}$ for $B^{\pm}$ allows access to γ through

$$x_{\pm}^{D^*h} = r_B^{D^*h}\cos(\delta_B^{D^*h} \pm \gamma),\ y_{\pm}^{D^*h} = r_B^{D^*h}\sin(\delta_B^{D^*h} \pm \gamma),$$

where $r_B^{D^*h}$ and $\delta_B^{D^*h}$ are the relative amplitude and strong phase between favoured and suppressed modes.

$$N_{\pm i} = H^{\pm}\left[F_{\mp i} + \left(x_{\pm}^{D^*h\,2} + y_{\pm}^{D^*h\,2}\right)F_{\pm i} + 2f_{D^*}\sqrt{F_i F_{-i}}(c_i\, x_{\pm}^{D^*h} + s_i\, y_{\pm}^{D^*h})\right]$$

[JHEP12(2023)013]

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- F_i ; efficiency weighted intensities of the amplitudes per bin (fitted).

[JHEP12(2023)013]

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- F_i ; efficiency weighted intensities of the amplitudes per bin (fitted).
- c_i, s_i ; cosines/sines of D strong phase- from BESIII [2003.00091, 2007.07959] and CLEO [PhysRevD.82.112006].

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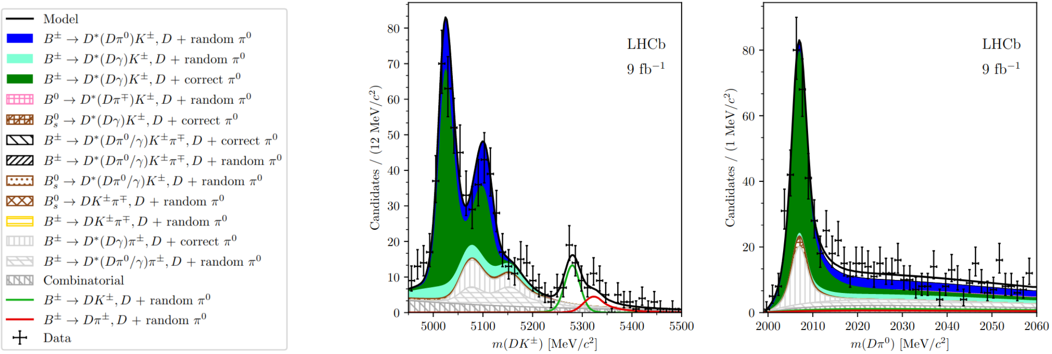
- c_i, s_i ; cosines/sines of D strong phase- from BESIII [2003.00091, 2007.07959] and CLEO [PhysRevD.82.112006].
- f_{D^*} ; +1(-1) for $D^* \to D\pi^0$ ($D^* \to D\gamma$) [0409281].

[JHEP12(2023)013]

Fitting

- Data split according to; the charge of the parent B meson, $B^{\pm}$ decay mode, D^* decay mode, D decay mode, and DP bins.
- Simultaneous fit performed on the 2D invariant-mass distributions, $m(Dh^{\pm})$ and $m(D\pi^0/\gamma)$, for all above categories.



Unbinned fits for $B^{\pm} \to D^*K^{\pm}, D \to K^0_S\pi^+\pi^-$.

[JHEP12(2023)013]

Results

The final results are:

$$
\begin{aligned}
\gamma &= (69^{+13}_{-14})^\circ, \\
r_B^{D^*K} &= 0.15 \pm 0.03, \\
r_B^{D^*\pi} &= 0.01 \pm 0.01, \\
\delta_B^{D^*K} &= (311 \pm 14)^\circ, \\
\delta_B^{D^*\pi} &= (37 \pm 37)^\circ.
\end{aligned}
$$

- The combined uncertainty in the γ measurement is dominated by the statistical uncertainties and is larger than that in the $B^{\pm} \to Dh^{\pm}$ measurement.
- These results are consistent with the world average and those from the $B^{\pm} \to D^{(*)}h^{\pm}$ measurements.
- The measurement gives the most precise determination to date of γ using these channels and will help improve the sensitivity in the global fit to γ.

[JHEP12(2023)013]

Summary

- The LHCb experiment is excellently suited to make a wide range of heavy flavour measurements
- Beauty to Open Charm plays an important role in LHCb's physics programme, including making both SM measurements, with γ, and probing for BSM effects with CP asymmetries
- The removal of our hardware trigger means that hadronic final states, in particular, will have much improved efficiencies and reduced uncertainties
- With luminosity expected from LHC's Run 3, we will predict $\sim 2-3$ times more signal events than in Run2 so statistically-dominated measurements, such as these, will be ever-more sensitive to the effects of BSM Physics
- Recently-observed tensions in $\mathcal{B}(B^0_{(s)} \to D^{(*)\pm} h^{\mp})$ [PhysRevD.105.115023] make this an exciting area for the near future.

Any Questions?

Decay	$\mathcal{A}_{\rm raw}$	$\mathcal{A}_{\rm P}$	$\mathcal{A}_{\rm D}$
$D_s^- D^0$	$-1.3 \pm 0.2 \pm 0.1$	$-1.1 \pm 0.3 \pm 0.3$	-0.7 ± 0.2
$D_s^{*-} D^0$	$-2.4 \pm 1.1 \pm 0.9$	$-1.1 \pm 0.4 \pm 0.3$	-0.8 ± 0.2
$D_s^- D^{*0}$	$-0.8 \pm 0.8 \pm 0.4$	$-1.1 \pm 0.4 \pm 0.3$	-0.8 ± 0.2
$D^- D^0$	$1.5 \pm 1.0 \pm 0.2$	$-1.1 \pm 0.4 \pm 0.3$	0.1 ± 0.2
$D^- D^{*0}$	$-1.3 \pm 2.0 \pm 1.3$	$-1.1 \pm 0.4 \pm 0.3$	0.1 ± 0.2
$D^{*-} D^0$	$2.4 \pm 1.6 \pm 0.2$	$-1.2 \pm 0.4 \pm 0.3$	0.2 ± 0.3
$D^{*-} D^{*0}$	$1.3 \pm 2.1 \pm 1.6$	$-1.1 \pm 0.5 \pm 0.3$	0.1 ± 0.2

Values of $\mathcal{A}_{\rm raw}$, $\mathcal{A}_P$ and $\mathcal{A}_D$ in percent, averaged over all D^0 decay modes and data-taking periods. The uncertainties on $\mathcal{A}_{\rm raw}$ are statistical and systematic, respectively. The first uncertainty on $\mathcal{A}_P$ contains all sources of uncertainty except that on $A_{CP}(B^+ \to J/\psi K^+)$, which is the second uncertainty.

[JHEP09(2023)202]

	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
	$B^- \to D_s^- D^0$		$B^- \to D^- D^0$		$B^- \to D^{*-} D^0$	
Double charm model	0.01	0.02	0.11	0.08	0.21	0.18
Single charm model	0.05	0.05	—	—	—	—
Cross-feed model	—	—	0.00	0.00	—	—
Combinatorial model	0.01	0.00	0.14	0.13	0.52	0.15
External inputs	0.05	0.06	0.01	0.00	0.04	0.01
Total	0.07	0.08	0.18	0.15	0.56	0.23
	$B^- \to D_s^- D^{*0}$		$B^- \to D^- D^{*0}$		$B^- \to D^{*-} D^{*0}$	
Double charm model	0.14	0.23	1.10	1.04	1.51	1.19
Cross-feed model	—	—	0.00	0.00	—	—
Combinatorial model	0.08	0.04	1.14	0.92	4.49	1.02
External inputs	0.55	0.38	0.14	0.12	0.11	0.11
Total	0.57	0.45	1.59	1.40	4.74	1.57
	$B^- \to D_s^{*-} D^0$					
Double charm model	0.78	0.51				
Combinatorial model	0.55	0.22				
External inputs	0.89	0.73				
Total	1.31	0.91				

Systematic uncertainties on the raw asymmetries in percent, averaged over all D^0 decay modes.

[JHEP09(2023)202]

Final state	$D_s^- D^0$		$D^- D^0$		$D^{*-} D^0$	
	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
$\mathcal{A}_{\mathrm{P}}$	0.42	0.43	0.41	0.43	0.48	0.48
$\mathcal{A}^{CP}(B^+ \to J/\psi K^+)$	0.30	0.30	0.30	0.30	0.30	0.30
$\mathcal{A}_{K\pi}$	0.28	0.11	0.04	0.04	0.10	0.00
$\mathcal{A}_{\pi}$	0.09	0.09	0.06	0.06	0.18	0.17
$\mathcal{A}_{\mathrm{PID}}$	0.29	0.03	0.25	0.11	0.55	0.10
$\mathcal{A}_{\mathrm{TIS}}$	0.08	0.10	0.08	0.10	0.09	0.11
$\mathcal{A}_{\mathrm{TOS}}$	0.01	0.03	0.01	0.02	0.01	0.01
Weighting	0.01	0.00	0.04	0.00	0.01	0.00
Part. rec. weighting	0.03	0.02	0.02	0.01	0.03	0.01
Total	0.67	0.55	0.58	0.55	0.82	0.61

Systematic uncertainties on the corrections for ACP in percent, averaged over all D^0 decay modes.

[JHEP09(2023)202]

	$D_s^- D^0$	$D_s^{*-} D^0$	$D_s^- D^{*0}$	$D^- D^0$	$D^- D^{*0}$	$D^{*-} D^0$	$D^{*-} D^{*0}$
$D_s^- D^0$	1						
$D_s^{*-} D^0$	0.335	1					
$D_s^- D^{*0}$	0.431	−0.282	1				
$D^- D^0$	0.386	0.186	0.234	1			
$D^- D^{*0}$	0.183	0.227	0.180	0.195	1		
$D^{*-} D^0$	0.286	0.161	0.177	0.166	0.130	1	
$D^{*-} D^{*0}$	0.190	0.227	0.211	0.168	0.311	0.189	1

Total correlations between the measured ACP.

[JHEP09(2023)202]

Source	$\sigma(x_+^{D^*K})$	$\sigma(x_-^{D^*K})$	$\sigma(y_+^{D^*K})$	$\sigma(y_-^{D^*K})$	$\sigma(x_\xi^{D^*\pi})$	$\sigma(y_\xi^{D^*\pi})$
Neglecting correlations	0.05	0.03	0.19	0.04	0.70	1.48
Efficiency correction of (c_i, s_i)	0.53	0.18	0.18	0.20	0.64	1.73
Invariant mass shape parameter	0.09	0.16	0.20	0.05	0.39	0.06
Fixed yield ratios	0.09	0.03	0.03	0.01	0.33	0.15
Bin dependence of the invariant-mass shape	0.40	0.38	0.41	0.33	1.78	1.57
DP bin migration	0.32	0.70	0.03	0.17	1.2	2.0
Λ_b^0 background	0.97	1.34	0.55	0.77	1.13	1.43
Semileptonic B backgrounds	0.27	1.29	0.02	0.67	0.03	0.04
Merging data subsamples	0.06	0.02	0.12	0.03	0.06	0.34
CP-violation in $B^{\pm,0} \to DK^{\pm}\pi^{0,\mp}$	0.03	0.13	1.97	0.99	0.13	0.68
Total systematic	1.26	2.04	2.12	1.48	2.66	3.78
Strong-phase inputs (external)	0.41	0.23	0.30	0.64	0.93	0.83
Statistical	3.16	3.55	4.41	3.98	5.00	5.04

Summary of uncertainties on the measurement of $x_{\pm}^{D^*K}$, $y_{\pm}^{D^*K}$, $x_{\xi}^{D^*\pi}$ and $y_{\xi}^{D^*\pi}$. All numbers have been scaled up by a factor of 100.

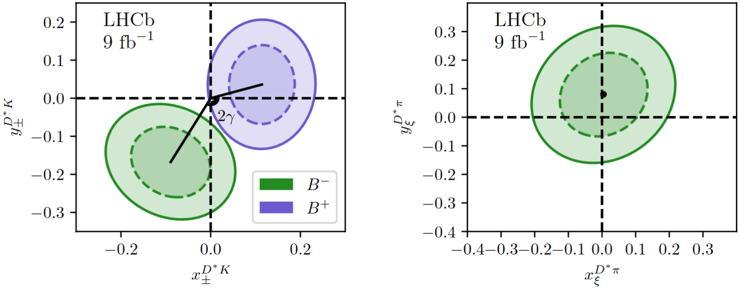
[JHEP12(2023)013]

$$
\begin{aligned}
x_+^{D^*K} &= (\ \ 11.42 \pm 3.16 \pm 1.26 \pm 0.41) \times 10^{-2}, \\
x_-^{D^*K} &= (-\ 8.91 \pm 3.55 \pm 2.04 \pm 0.23) \times 10^{-2}, \\
y_+^{D^*K} &= (\ \ \ 3.60 \pm 4.41 \pm 2.12 \pm 0.30) \times 10^{-2}, \\
y_-^{D^*K} &= (-16.75 \pm 3.98 \pm 1.48 \pm 0.64) \times 10^{-2}, \\
x_\xi^{D^*\pi} &= (\ \ \ 0.51 \pm 5.00 \pm 2.66 \pm 0.93) \times 10^{-2}, \\
y_\xi^{D^*\pi} &= (\ \ \ 7.92 \pm 5.04 \pm 3.78 \pm 0.83) \times 10^{-2},
\end{aligned}
$$

$$
x_\xi^{D^*\pi} = \mathrm{Re}(\xi^{D^*\pi}), \quad y_\xi^{D^*\pi} = \mathrm{Im}(\xi^{D^*\pi})
$$

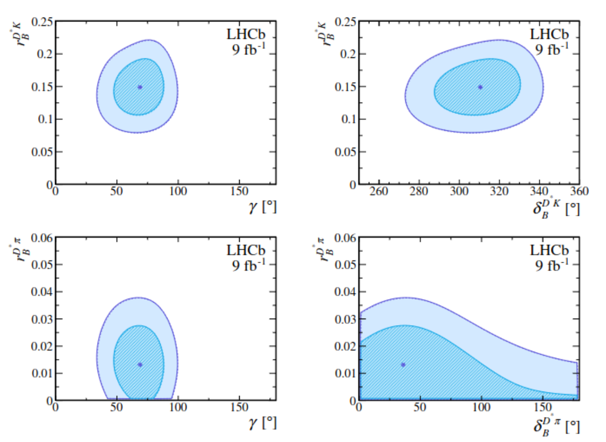
with

$$
\xi^{D^*\pi} = \left(r^{D^*\pi}/r^{D^*K}\right) \exp\left[i(\delta^{D^*\pi} - \delta^{D^*K})\right]
$$



Confidence level at 68.2% and 95.5% probability for (left, green) $x_+^{D^*K}$, $y_+^{D^*K}$, (left, violet) $x_-^{D^*K}$, $y_-^{D^*K}$ and (right, green) $x_\xi^{D^*\pi}$, $y_\xi^{D^*\pi}$ are measured in $B^\pm \to D^* h^\pm$ decays from a profile likelihood scan.

[JHEP12(2023)013]



Confidence level regions for the combination of physical parameters $(\gamma, \delta_B^{D^* K}, r_B^{D^* K}, \delta_B^{D^* \pi}, r_B^{D^* \pi})$ of interest. The 68% (hashed blue area) and 95% (light blue area) are determined from `GammaCombo` [ZENODO.3371421, JHEP12(2021)141]

[JHEP12(2023)013]

	$x_\xi^{D^*\pi}$	$x_-^{D^*K}$	$x_+^{D^*K}$	$y_\xi^{D^*\pi}$	$y_-^{D^*K}$	$y_+^{D^*K}$
$x_\xi^{D^*\pi}$	1	0.25	−0.16	0.18	0.00	0.00
$x_-^{D^*K}$		1	−0.05	0.06	−0.08	0.03
$x_+^{D^*K}$			1	−0.14	−0.08	−0.08
$y_\xi^{D^*\pi}$				1	0.33	−0.19
$y_-^{D^*K}$					1	−0.09
$y_+^{D^*K}$						1

Statistical correlation matrix for CP -violating observables.

[JHEP12(2023)013]

	$x_-^{D^*K}$	$x_+^{D^*K}$	$y_-^{D^*K}$	$y_+^{D^*K}$	$x_\xi^{D^*\pi}$	$y_\xi^{D^*\pi}$
$x_-^{D^*K}$	1	-0.01	0.01	0.02	-0.02	-0.05
$x_+^{D^*K}$		1	-0.01	0.00	-0.01	0.06
$y_-^{D^*K}$			1	-0.01	0.01	-0.10
$y_+^{D^*K}$				1	-0.09	-0.02
$x_\xi^{D^*\pi}$					1	0.02
$y_\xi^{D^*\pi}$						1

Systematic correlation matrix for considered LHCb related effects.

[JHEP12(2023)013]