



## Measurements of the CKM angle $\gamma$ at LHCb

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on behalf of the LHCb collaboration

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• Cabibbo-Kobayashi-Maskawa (CKM) matrix describes the quark mixing

$$\begin{pmatrix} d'\\s'\\b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub}\\V_{cd} & V_{cs} & V_{cb}\\V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d\\s\\b \end{pmatrix}$$

• Unitarity of *V<sub>CKM</sub>* represented by a **triangle**<sup>1</sup> **in the complex plane** 

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

• Weak phase  $\gamma$  is the only angle **easily accessible at tree level** 

$$\gamma = \arg\left(-\frac{V_{ud} \ V_{ub}^*}{V_{cd} \ V_{cb}^*}\right)$$

Hadronic parameters can be determined from data
 => theoretical uncertainty on γ is negligible





Tree-level (direct measurement)<sup>2</sup>

Loop-level (indirect measurement)<sup>2</sup>

- Direct measurements of  $\gamma$  at tree-level are expected to be benchmarks of the Standard Model
- Indirect measurements consist of global fits to the unitary triangle, where some inputs include loop processes and assuming closed triangle. New Physics expected to contribute through loop processes
- A discrepancy between direct and indirect measurements would be a clear sign of New Physics

### Introduction



•  $D \rightarrow K_{S}^{0}h^{+}h^{-}$ : wide single solution presenting today latest results

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100

50

γ [°]

150

### Measuring $\gamma$

- Direct measurements of the CKM angle  $\gamma$  in  $B \rightarrow DK$  decays
- The *D* meson is a superposition of  $D^0$  and  $\overline{D}^0$  states, which are reconstructed in common final states
- Both  $D^0$  and  $\overline{D}^0$  should be able to decay to the same final state
- Interference between  $b \rightarrow cW$  and  $b \rightarrow uW$  transitions gives sensitivity to  $\gamma$







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### Measuring $\gamma$ : three-body self-conjugate final states

[6] Phys. Rev. D68 (2003) 054018[7] Phys. Rev. D70 (2004) 072003

- Three-body self-conjugate final states<sup>6,7</sup>
  - $D \rightarrow K_s^0 \pi^+ \pi^-$ ,  $D \rightarrow K_s^0 K^+ K^-$ : complex system of resonances
  - The kinematics of the *D* decay can be represented in 2D in a Dalitz plot
  - *CP* observables  $x_{\pm} = r_B \cdot \cos(\delta_B \pm \gamma)$  $y_{\pm} = r_B \cdot \sin(\delta_B \pm \gamma)$   $x_{\pm} + iy_{\pm} = r_B \cdot e^{i(\delta_B \pm \gamma)}$
  - Interference appears as different distributions of the D meson Dalitz plot for  $B^-$  and  $B^+ \rightarrow$  counting experiment in each bin
  - Yields in each Dalitz bin

$$N_{\pm i}^{-} \propto F_{\pm i} + (x_{-}^{2} + y_{-}^{2})F_{\mp i} + 2\sqrt{F_{i}F_{-i}} (x_{-}c_{\pm i} + y_{-}s_{\pm i})$$

$$\uparrow$$
Fractional yield of  
flavour-tagged  $D^{0}$ 
Strong-phase differences  
(input from CLEO+BESIII)



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 $\underline{B^0} \rightarrow DK^{*0}, D \rightarrow K^0_S h^+ h^-$ 

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- Measurement of  $\gamma$  in  $B^0 \rightarrow D[K_S^0 h^+ h^-]K^{*0}$  decays, in phase-space bins of the D decay, superseding previous results published by LHCb
- The  $K_S^0$  particles are reconstructed in  $K_S^0 \rightarrow \pi^+\pi^-$  and defined in two categories:
  - Long tracks (LL): tracks reconstructed inside the Vertex Locator
  - Downstream tracks (DD): tracks only reconstructed in the tracking system





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## $B^{0} \to DK^{*0}, D \to K_{S}^{0}h^{+}h^{-}$

- Asymmetry varies in the different phase-space bins, with nonzero asymmetries in regions of the phase space
- Limited statistics => CP violation still to be observed in these modes
- Asymmetries (for  $B^0 \overline{B}^0$ ) observed in some bins





LHCb-PAPER-2023-009 (in preparation)

• The physics parameters of interest can be interpreted from the measured CP observables  $x_{\pm}$ ,  $y_{\pm}$ 

$$\gamma = (49^{+23}_{-18})^{\circ}$$
$$\delta_{B^0} = (236^{+19}_{-21})^{\circ}$$
$$r_{B^0} = (0.271^{+0.068}_{-0.068})$$

• Model-independent results, using strong-phase 
$$c_i$$
,  $s_i$  inputs from CLEO and BESIII

• Result for  $\gamma$  consistent with superseded results and LHCb  $\gamma$  combination (and closer to the average value obtained with  $B^{\pm}$  decays)



 $B^{\pm} \rightarrow D^{*0}h^{\pm}$ ,  $D^{*0} \rightarrow D \pi^0/\gamma$ ,  $D \rightarrow K_S^0 h^+ h^-$ 

h

 $D^{*0}$ 

B

PV

 $K_S^0$ 

 $h^+$ 

 $\pi^0/\gamma$ 

- Measurement of  $\gamma$  in  $B^{\pm} \rightarrow D^{*0}h^{\pm}$  with  $D_{9\,fb}^{*0} \rightarrow D\pi^{0}/\gamma$ ,  $D \rightarrow K_{S}^{0}h^{+}h^{-}$  decays, in pease-space bins of the *D* decay
- 0.5
   Irreducible backgrounds remain after the candidate selection
  - Broad and overlapping => difficult to distinguish
- $2 \stackrel{\vee}{\underline{D}}_{3000}$  invertant-mass fit used to measure CP observables:  $m(D^0 \pi^0 / \gamma), m(D^0 h^{\pm})$ 5200  $m(D\pi^{\pm})[M_0 V/c^2]$
- Additional phase shift of  $\pi$  between  $D^{*} \to D\pi^{0}$  and  $D^{*0} \to D\gamma$  decays (opposite CP asymmetries)



• 2D invariant-mass fit used to measure CP observables:  $m(D^0\pi^0/\gamma)$ ,  $m(D^0h^{\pm})$ 



## $B^{\pm} \rightarrow D^{*0}h^{\pm}$ , $D^{*0} \rightarrow \overline{D \ \pi^0/\gamma}$ , $D \rightarrow K_S^0 h^+ h^-$

• The physics parameters of interest can be interpreted from the measured CP observables  $x_{\pm}$ ,  $y_{\pm}$ 

$$\gamma = (69 \pm 14)^{\circ}$$
  
 $\delta_B^{D^{*0}K} = (311 \pm 15)^{\circ}$   
 $r_B^{D^{*0}K} = (0.15 \pm 0.03)$ 

- Model-independent results, using strong-phase  $c_i$ ,  $s_i$  inputs from CLEO and BESIII
- Result for  $\gamma$  consistent with LHCb  $\gamma$  combination and world average
- First measurement in these decays at LHCb



- First CP violation study in  $B^{\pm} \rightarrow D[K^+K^-\pi^+\pi^-] h^{\pm}$  decays, in bins of the *D*-meson decay
- 5-dimensional phase space
- Binning scheme is more complicated
- Strong-phase parameters  $c_i$ ,  $s_i$  required: currently taken from an **amplitude model**





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# $B^{\pm} \rightarrow Dh^{\pm}$ , $D \rightarrow K^{+}K^{-}\pi^{+}\pi^{-}$

- Unbinned, extended maximum-likelihood fit performed to invariant-mass distributions
- Second fit performed in each of the 64 categories (split by charge and phase-space bins)
- Observation of CP violation effects through local (normalised) asymmetries in each bin, which are model independent





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• The physics parameters of interest can be interpreted from the measured CP-violating observables

$$\gamma = (116^{+12}_{-14})^{\circ}$$
$$\delta_B^{DK} = (81^{+14}_{-13})^{\circ}$$
$$r_B^{DK} = (0.110^{+0.020}_{-0.020})$$

- These results are **model dependent**
- Model-independent  $c_i$ ,  $s_i$  inputs required for a modelindependent measurement from the binned asymmetries, expected to be measured by BESIII
- In the future, both binned and unbinned results will be performed to obtain a model-independent determination of  $\gamma$



#### [8] Eur. Phys. J**. C73** (2013) 2373 [9] arXiv:1808.08865

### Future prospects

- Future  $\gamma$  combinations will include recent and future results to **further improve precision** on  $\gamma$
- Recent results expected to have a strong impact in the future combination as they combine with other measurements of *γ* from the same *B* decay channels
- Strategy to cover all B and D decay **combinations** to improve sensitivity to  $\gamma$ . There are **ongoing analyses** with the full Run 1+2 LHCb dataset, e.g. using  $B^{\pm} \rightarrow DK^{*\pm}$ decays
- Sub-dominant channels => further constraints and crosschecks (different backgrounds and systematic uncertainties)
- A precision of less than 1° is expected<sup>8,9</sup> with the data to be collected in Run 3 and beyond, while the expected sensitivity for Run 1-2 of 4° was surpassed (and still going)



Precision in 2013	LHCb 2018	Upgrade I (50 $fb^{-1}$ )	Upgrade II (300 $fb^{-1}$ )
~10-12°	4°	1°	0.35°

- Presented recent measurements of the CKM angle γ at LHCb:
  - LHCb  $\gamma$ +charm combination
  - $B^0 \to DK^{*0}, D \to K_S^0 h^+ h^-$
  - $B^{\pm} \rightarrow D^{*0}h^{\pm}, D^{*0} \rightarrow D \pi^0/\gamma, D \rightarrow K_S^0 h^+ h^-$
  - $B^{\pm} \rightarrow Dh^{\pm}, D \rightarrow K^{+}K^{-}\pi^{+}\pi^{-}$

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- Recent LHCb  $\gamma$  combination: expected sensitivity of about 4° for Run 1-2 achieved, which is still being improved
- New results expected to have a significant contribution to the future combination
- With more data to be collected, a more precise (<  $1^{\circ}$ ) tree-level determination of the CKM angle  $\gamma$  will be possible, which is a standard candle measurement of CP violation in the Standard Model



- First measurement of CP parameters in  $B^{\pm} \rightarrow D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$  decays, in phase-space bins
- Experimentally beneficial: only charged particles in final state and high branching fraction. One of the most precise measurements of  $\gamma$  from a single analysis (and single decay mode)  $\gamma = (54.8^{+6.0+0.6+6.7}_{-5.8-0.6-4.3})^{\circ}$
- Largest CP violation measured in one of the bins



