

# The angle $\gamma$ of the Cabibbo-Kobayashi-Maskawa ansatz: a journey towards precision at LHCb

Martin Tat, on behalf of the LHCb collaboration

University of Oxford

CERN LHC seminar

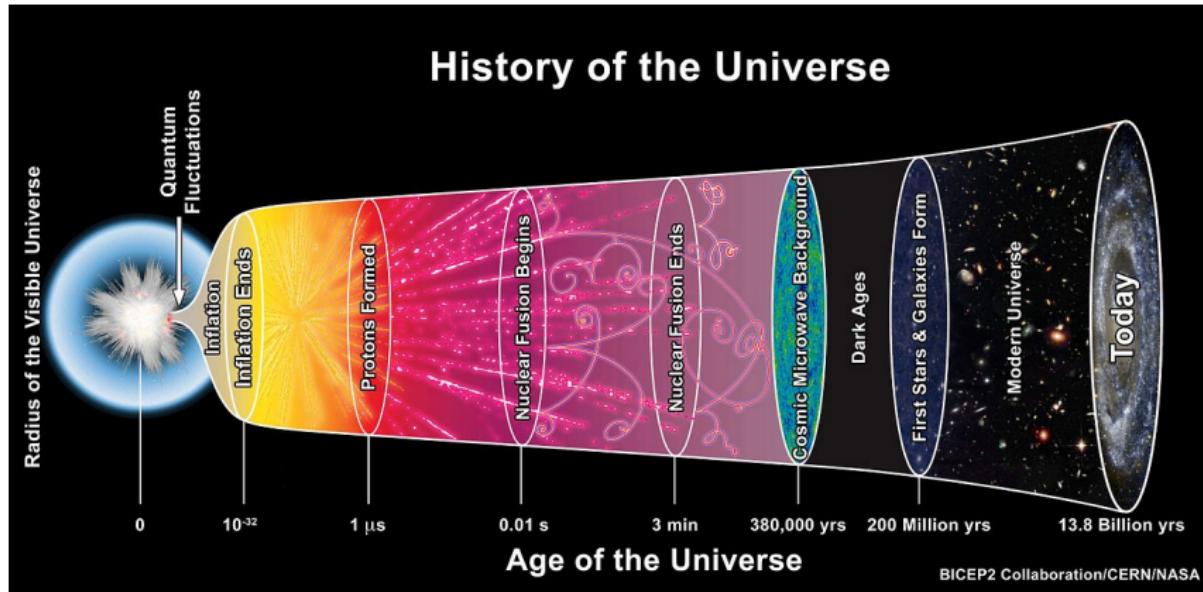
25th July 2023



## Introduction to $CP$ violation

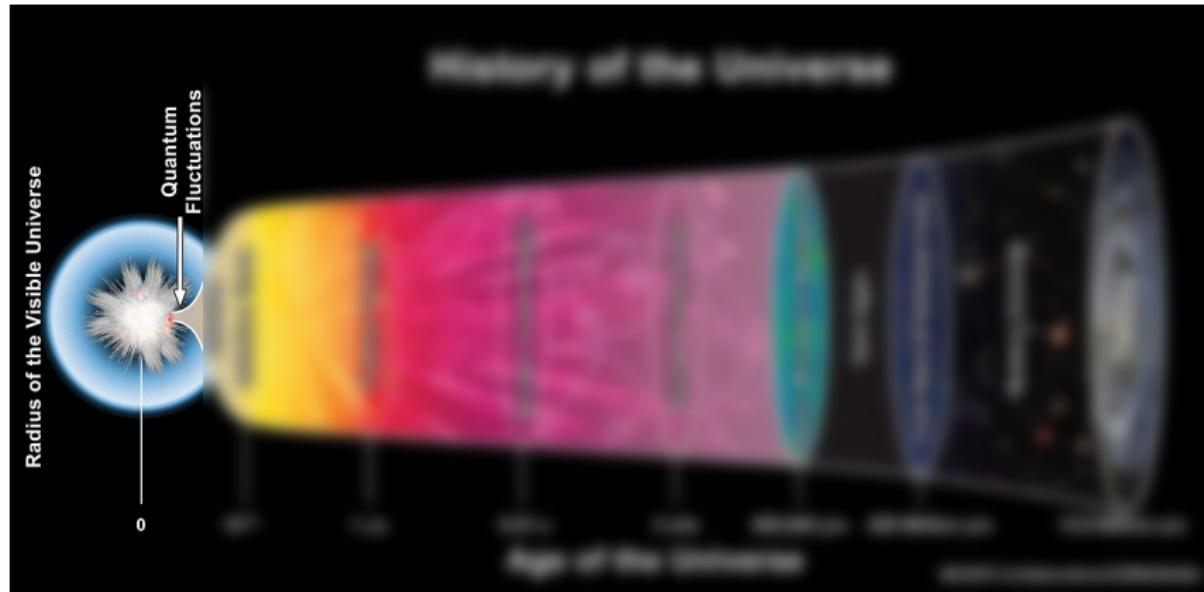
What is  $\gamma$  and why measure it?

# Big Bang and matter-antimatter asymmetry



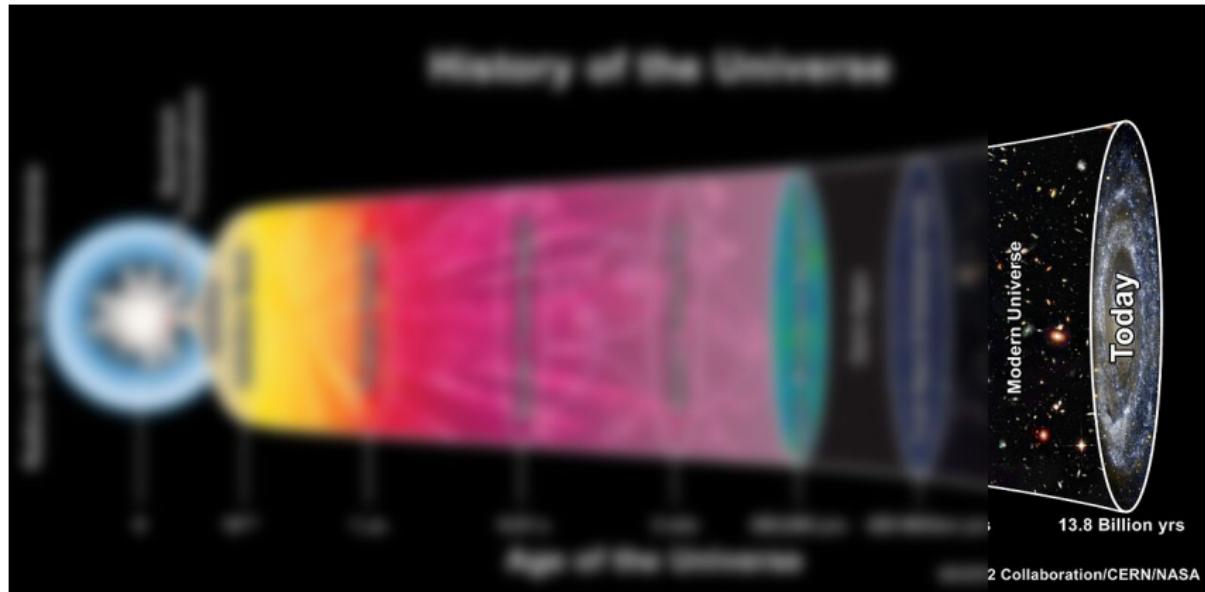
Where is the antimatter in the universe?

# Big Bang and matter-antimatter asymmetry



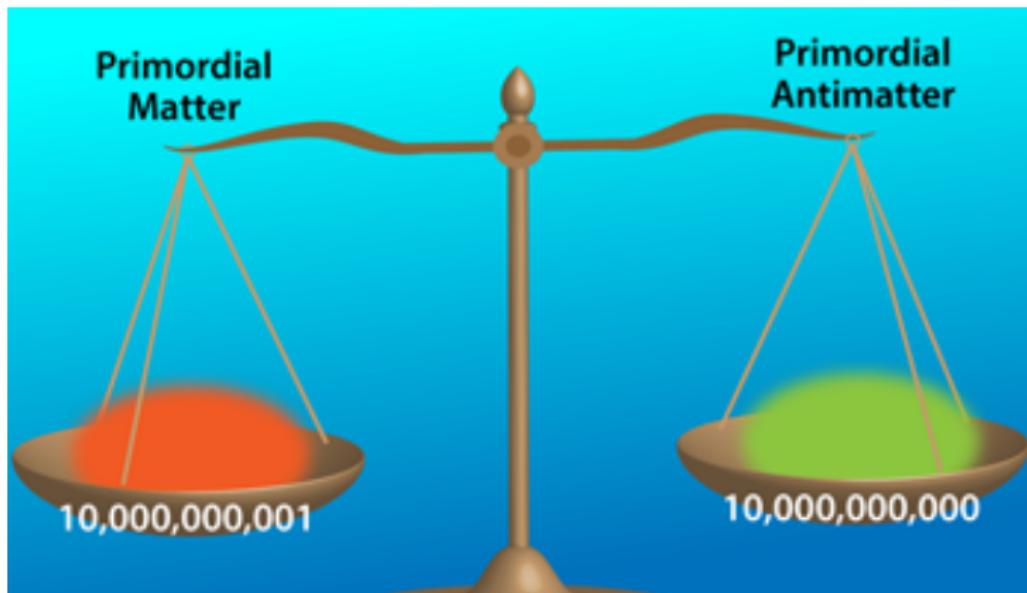
Initially equal amounts of matter and antimatter...

# Big Bang and matter-antimatter asymmetry



... but today we only see matter!

# Big Bang and matter-antimatter asymmetry



APS/Alan Stonebraker

The difference is very small...

# Big Bang and matter-antimatter asymmetry



Quantum Diaries: "Why B physics? Why not A Physics?"

... but the effects we observe today are obviously huge!  
How can we explain this?

# Big Bang and matter-antimatter asymmetry

## The Nobel Peace Prize 1975



Photo from the Nobel Foundation archive.  
Andrei Dmitrievich Sakharov

Prize share: 1/1

The Nobel Peace Prize 1975 was awarded to Andrei Dmitrievich Sakharov "for his struggle for human rights in the Soviet Union, for disarmament and cooperation between all nations"

In 1967, Andrei Sakharov proposed three conditions for baryogenesis:

- Baryon number violation
- C and CP violation
- Interactions out of thermal equilibrium

Therefore, to understand matter-antimatter asymmetry, we must understand CP violation

# $CP$ violation

## The Nobel Prize in Physics 1980



Photo from the Nobel Foundation archive.  
James Watson Cronin

Prize share: 1/2

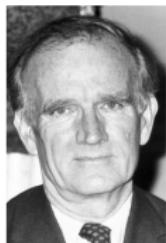


Photo from the Nobel Foundation archive.  
Val Logsdon Fitch

Prize share: 1/2

The Nobel Prize in Physics 1980 was awarded jointly to James Watson Cronin and Val Logsdon Fitch "for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"

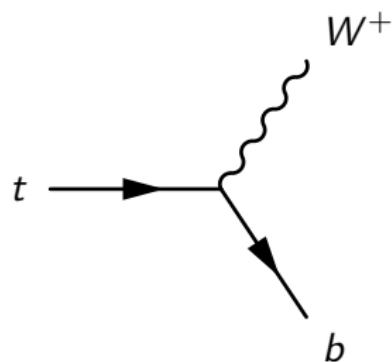
- $CP$  violation discovery in 1964
- Phys. Rev. Lett. **13**, 138
- Observed  $K_L^0 \rightarrow \pi^+ \pi^-$
- Since,  $CP$  violation has also been observed in the  $B$ ,  $B_s$  and  $D$  systems

Unfortunately, CPV in SM is too small to explain baryogenesis...  
... perhaps there are new physics effects?

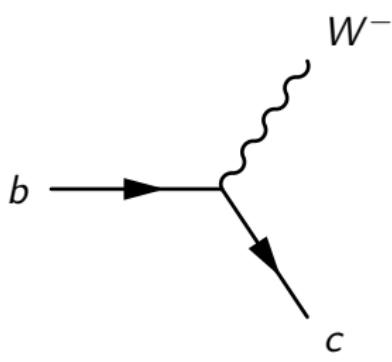
# The CKM matrix and the Unitary Triangle

In SM, the charged current  $W^\pm$  interactions couple (left-handed) up- and down-type quarks, given by

$$\frac{-g}{\sqrt{2}} \begin{bmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{bmatrix} \gamma^\mu W_\mu V_{CKM} \begin{bmatrix} d_L \\ s_L \\ b_L \end{bmatrix} + \text{h.c.}$$



(a)  $t \rightarrow b W^+$



(b)  $b \rightarrow c W^-$

# The CKM matrix and the Unitary Triangle

The Cabibbo-Kobayashi-Maskawa matrix  $V_{\text{CKM}}$  has a single complex phase that is responsible for all CPV in SM

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}(\lambda^4)$$

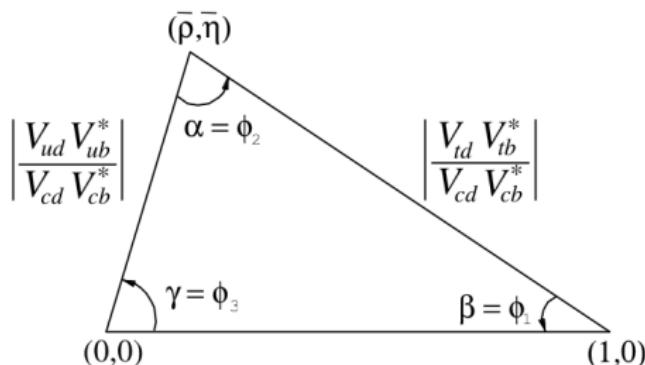
In SM, with only 3 generations of quarks,  $V_{\text{CKM}}$  must be unitary  
This gives us 9 constraints, one of which is:

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

# The CKM matrix and the Unitary Triangle

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R. L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

# The CKM matrix and the Unitary Triangle

## The Nobel Prize in Physics 2008



Photo: University of Chicago  
Yoichiro Nambu  
Prize share: 1/2



© The Nobel Foundation Photo:  
U. Montan  
Makoto Kobayashi  
Prize share: 1/4



© The Nobel Foundation Photo:  
U. Montan  
Toshihide Maskawa  
Prize share: 1/4

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu "for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics", the other half jointly to Makoto Kobayashi and Toshihide Maskawa "for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

- Kobayashi and Maskawa extended Cabibbo's  $2 \times 2$  rotation matrix
- The additional complex phase in  $V_{\text{CKM}}$  matrix explains CPV in SM
- This also predicted the third generation of quarks, which were discovered later

We must verify if  $V_{\text{CKM}}$  is unitary, and gain a deeper understanding of quark interactions

# The CKM matrix and the Unitary Triangle

## The Nobel Prize in Physics 2008



Photo: University of Chicago  
Yoichiro Nambu  
Prize share: 1/2



© The Nobel Foundation Photo:  
U. Montan  
Makoto Kobayashi  
Prize share: 1/4



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Toshihide Maskawa  
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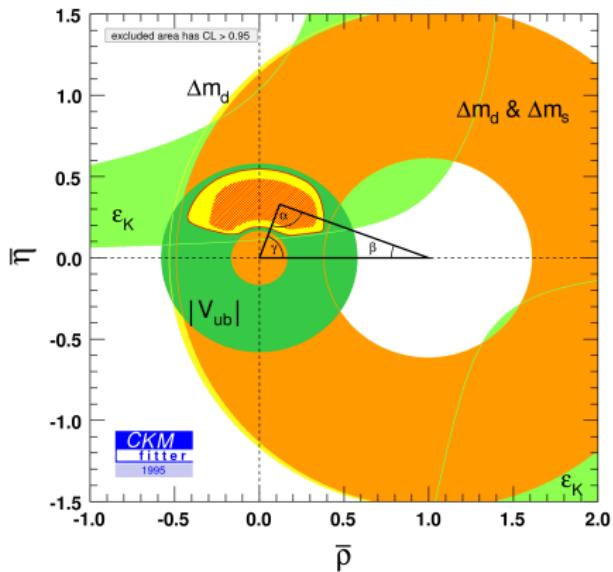
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- This also predicted the third generation of quarks, which were discovered later

Precise knowledge of quark interactions will help us search for new physics with CPV, which may not have the same CKM structure

# The CKM matrix and the Unitary Triangle

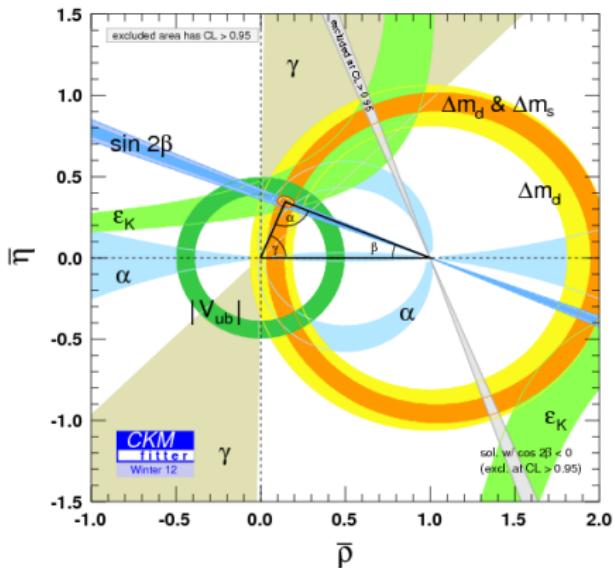
Before Belle and BaBar, the Unitary Triangle was poorly constrained



CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005), updated results and plots available at:  
<http://ckmfitter.in2p3.fr>

# The CKM matrix and the Unitary Triangle

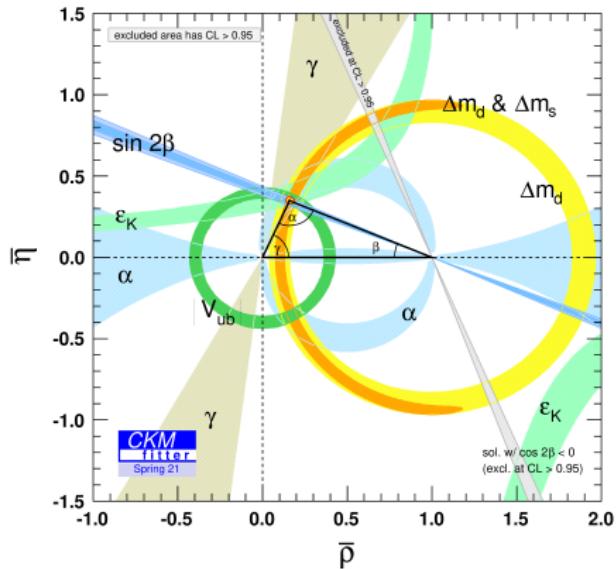
Huge progress by b-factories, but  $\gamma$  is the least precisely measured angle...



CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005), updated results and plots available at:  
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# The CKM matrix and the Unitary Triangle

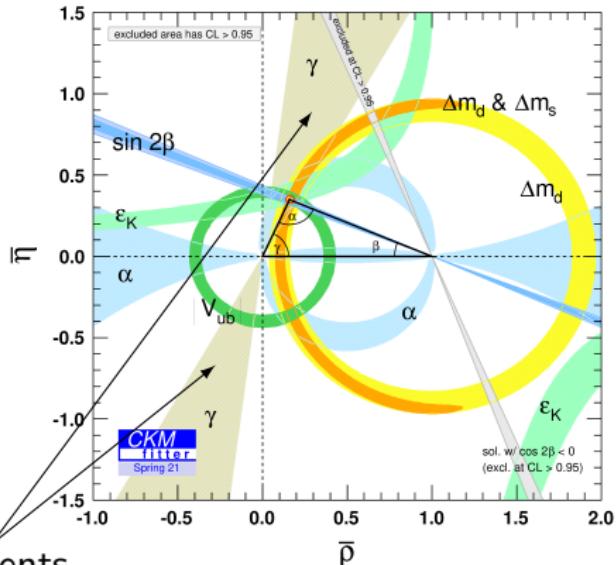
... but with LHCb, this is no longer the case!



CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005), updated results and plots available at:  
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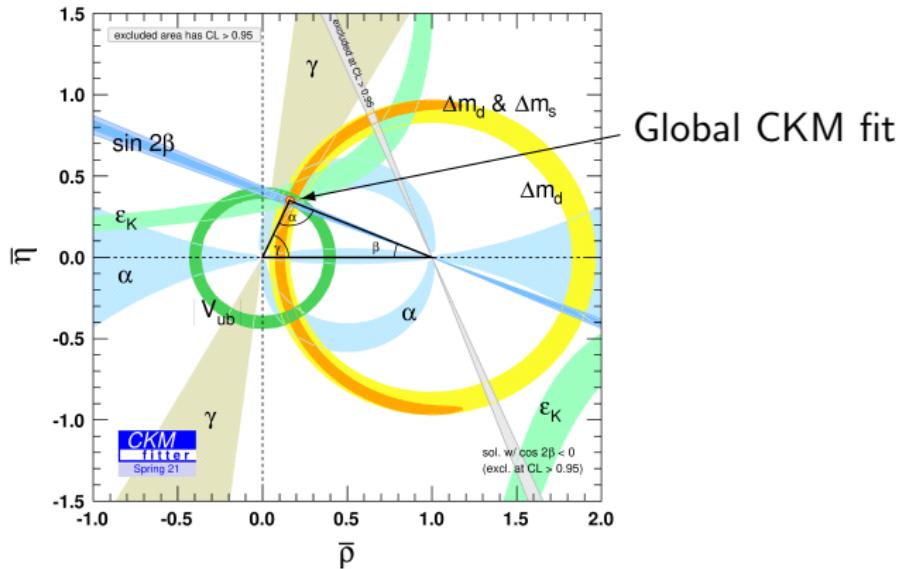


Direct  $\gamma$  measurements

CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005), updated results and plots available at:  
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# The CKM matrix and the Unitary Triangle

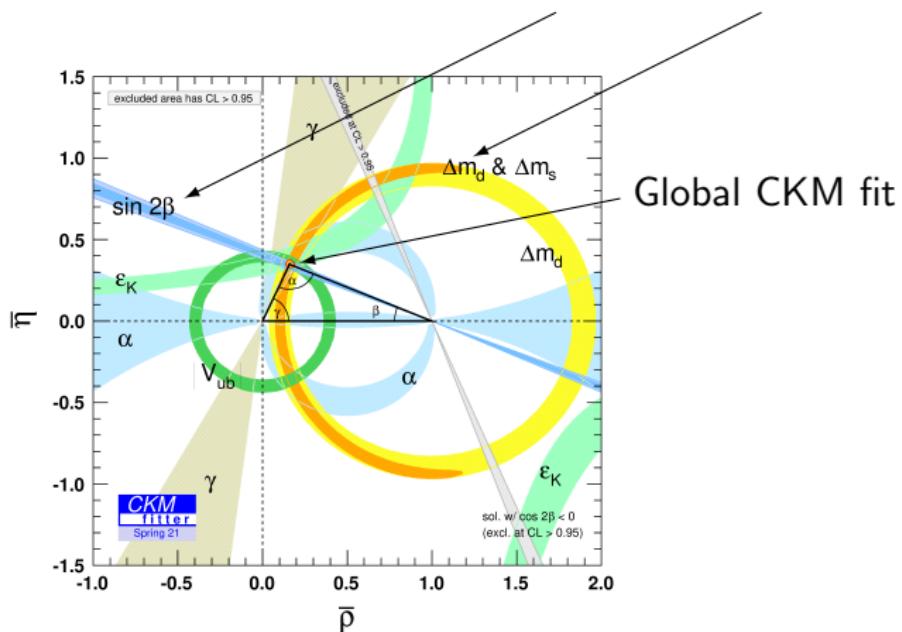
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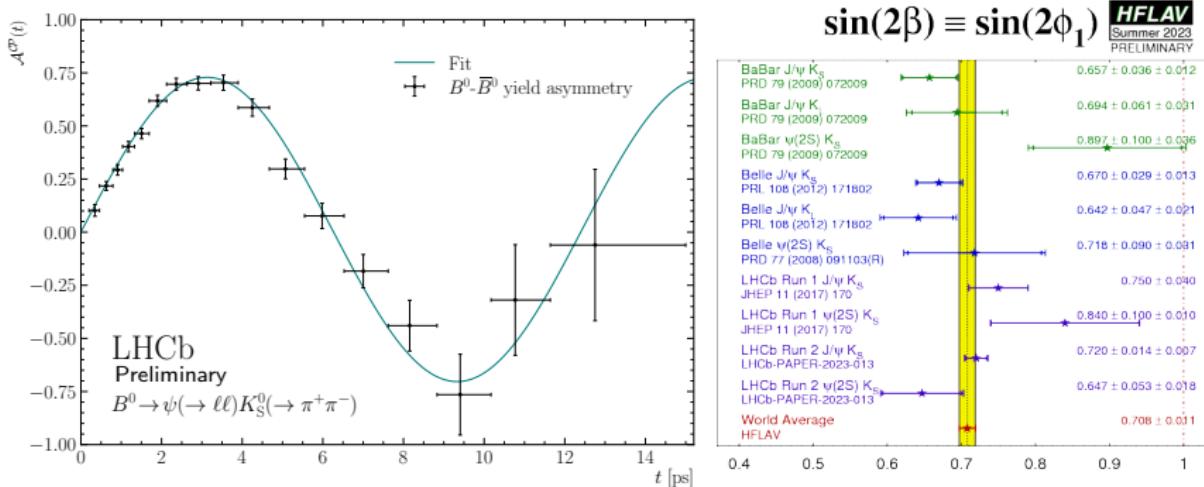
Loop level measurements of  $\gamma$  are dominated by  $\sin(2\beta)$  and  $B^0/B_s^0$  mixing



CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005), updated results and plots available at:  
<http://ckmfitter.in2p3.fr>

# The CKM matrix and the Unitary Triangle

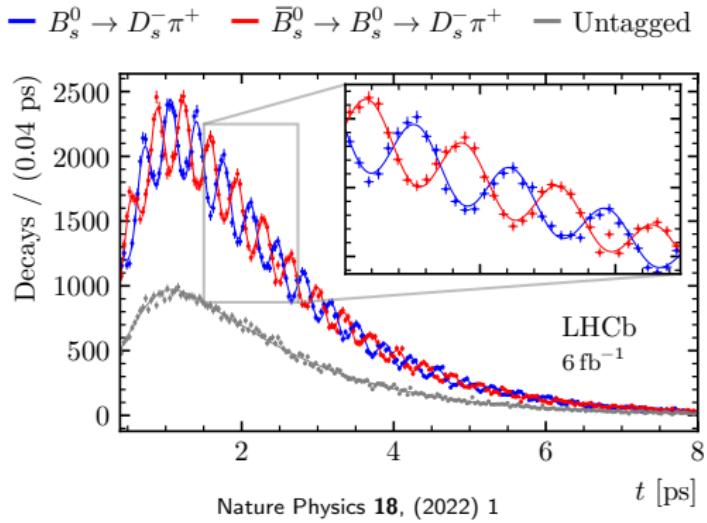
LHC seminar by P. Li and V. Jevtic on 13th June 2023:  
Single most precise measurement of  $\sin(2\beta)$



World average:  $\sin(2\beta) = 0.708 \pm 0.011$   
 $\beta = (22.5 \pm 0.4)^\circ$

# The CKM matrix and the Unitary Triangle

From  $B^0/B_s^0$  mixing,  $|V_{td} V_{tb}^*|$  is measured  
This is dominated by lattice QCD uncertainties



Nature Physics 18, (2022) 1

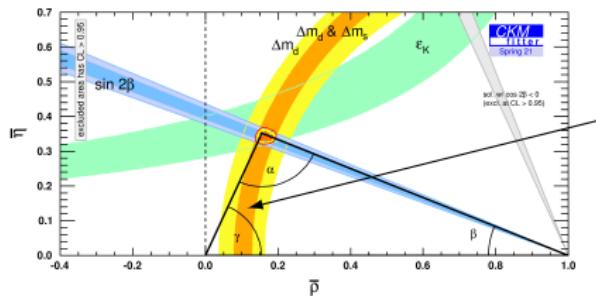
HFLAV averages:

$$\Delta m_d = (0.5065 \pm 0.0019) \text{ ps}^{-1} \quad \& \quad \Delta m_s = (17.765 \pm 0.006) \text{ ps}^{-1}$$

# The CKM matrix and the Unitary Triangle

## Why is the CKM angle $\gamma$ of interest?

- ① Negligible theoretical uncertainties: Ideal SM benchmark
  - Hadronic parameters are free parameters
- ② Only CKM angle accessible in tree level decays
  - Don't expect new physics at tree level, new particles appear in loops
- ③ We want to overconstrain the Unitary Triangle



$$\text{Loop level: } \gamma = (65.5^{+1.1}_{-2.7})^\circ$$

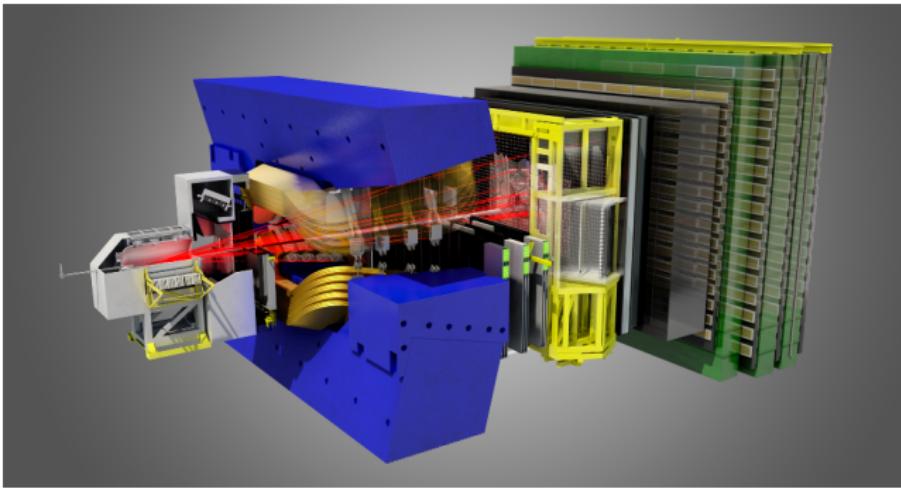
CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005), updated results and plots available at:  
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With precise  $\gamma$  measurements, we can compare with the indirect loop level measurements, which assume unitarity ("SM prediction")

# The LHCb detector

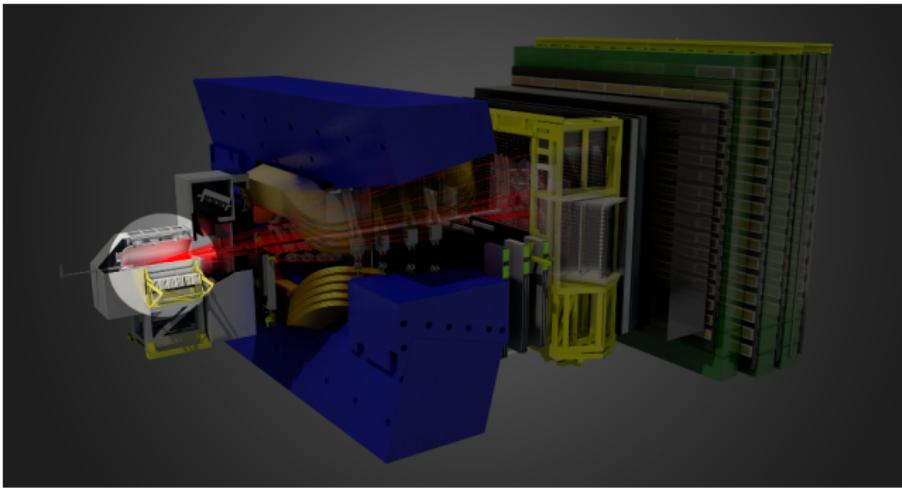
(Original Run 1 and 2 detector)

# The LHCb detector



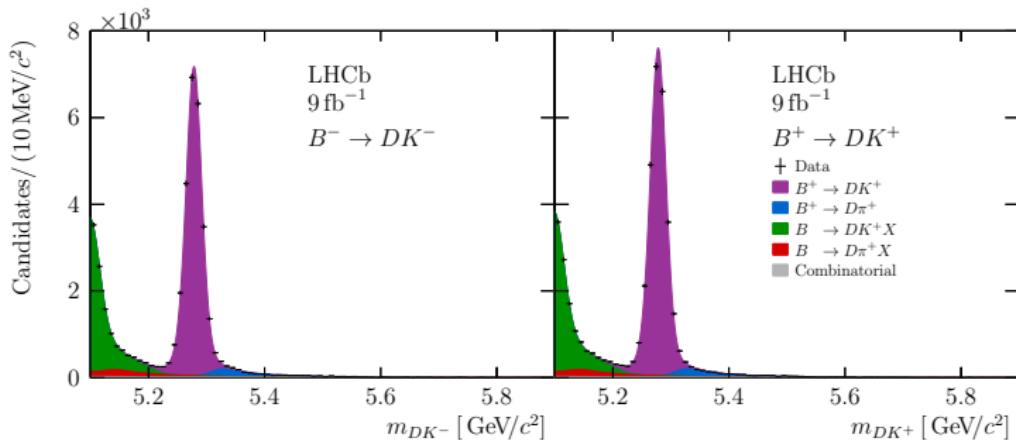
LHCb: A beauty experiment with a lot of charm

# The LHCb detector



VELO: Vertex locator to reconstruct  $B$  and  $D$  vertices

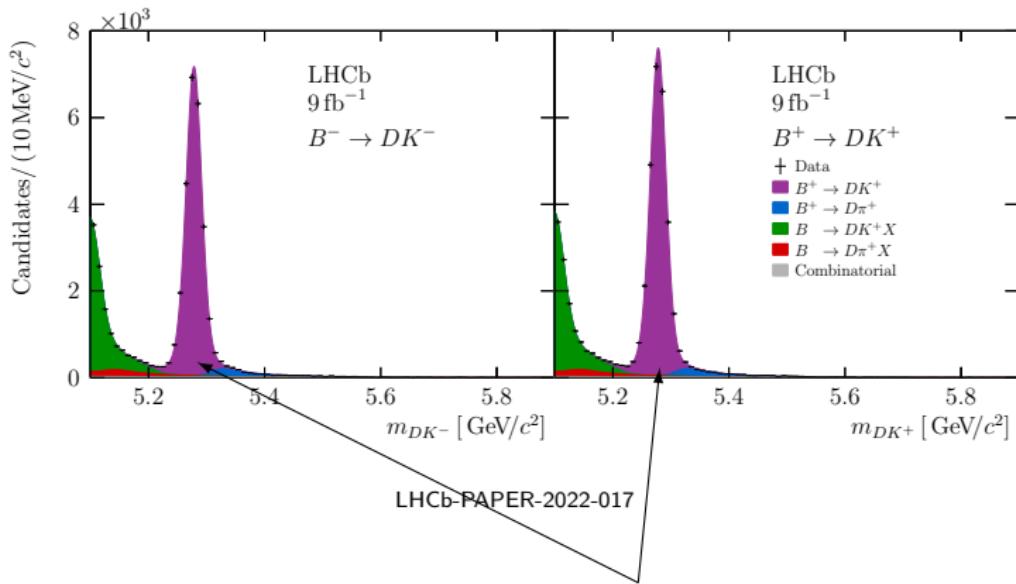
# The LHCb detector



LHCb-PAPER-2022-017

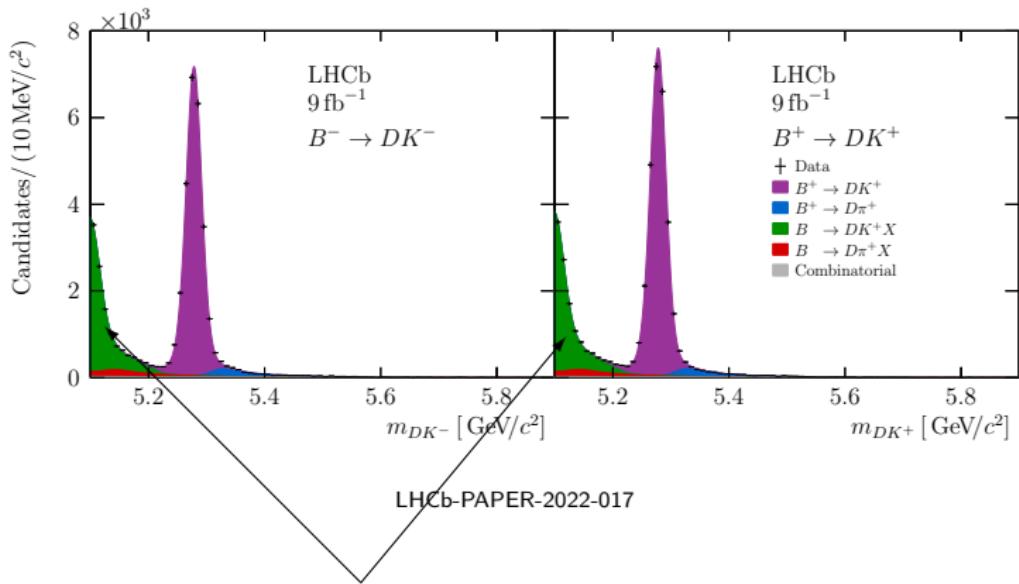
Example of  $B^\pm \rightarrow DK^\pm$  selection  
 $(D \rightarrow K^-\pi^+\pi^-\pi^+)$

# The LHCb detector



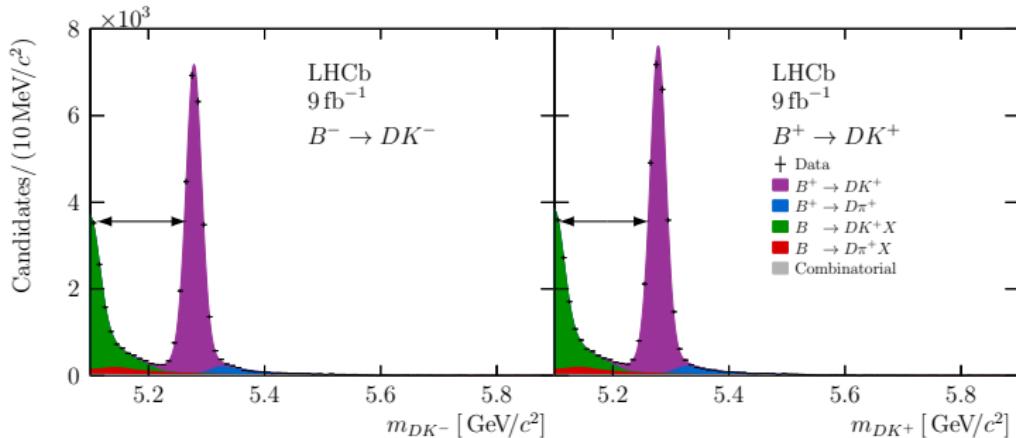
Correctly reconstructed  $B^\pm$  candidates  
High signal efficiency

# The LHCb detector



Partially reconstructed background  
 $B$  decays with missing pion or photon

# The LHCb detector

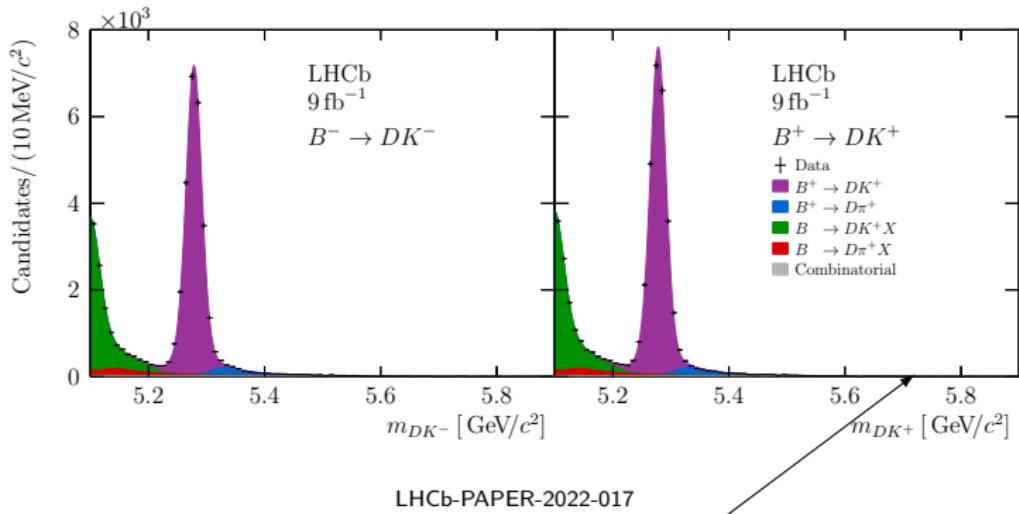


LHCb-PAPER-2022-017

Excellent mass resolution

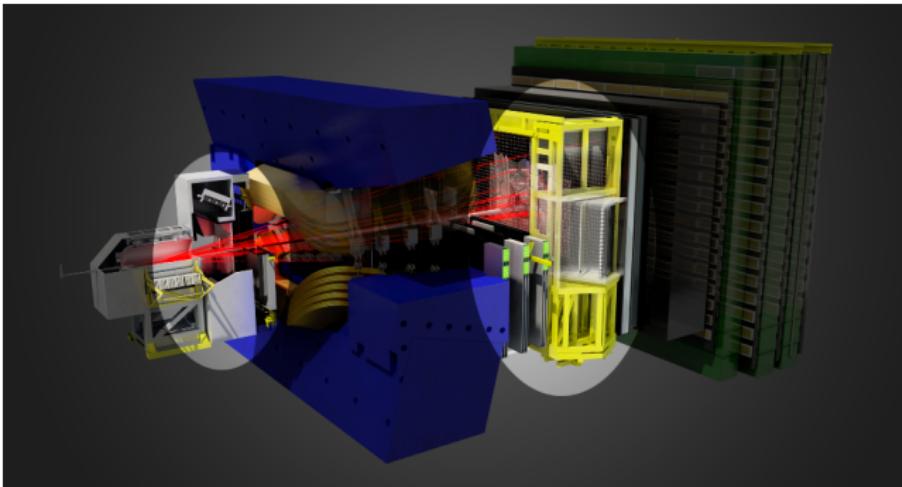
Signal is well separated from partially reconstructed background

# The LHCb detector



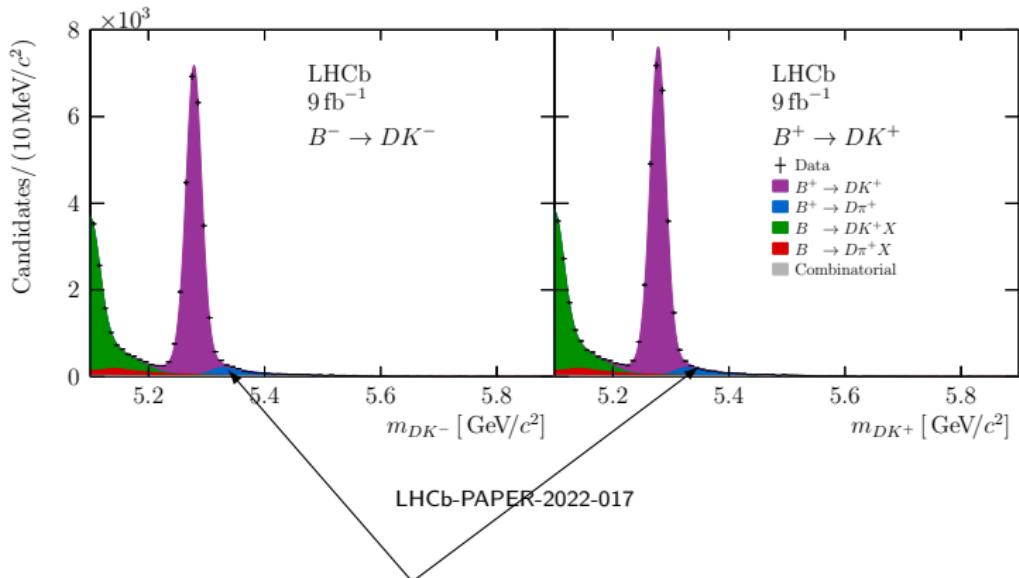
Extremely low combinatorial background  
Clean environment at a hadron collider

# The LHCb detector



RICH: Identify particles from  $B$  and  $D$

# The LHCb detector



Mis-ID from  $B^\pm \rightarrow D\pi^\pm \rightarrow DK^\pm$  is almost negligible  
Without PID, this background would be 13 times larger!

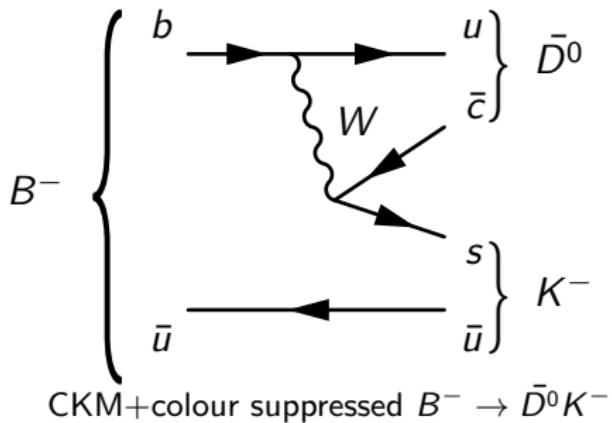
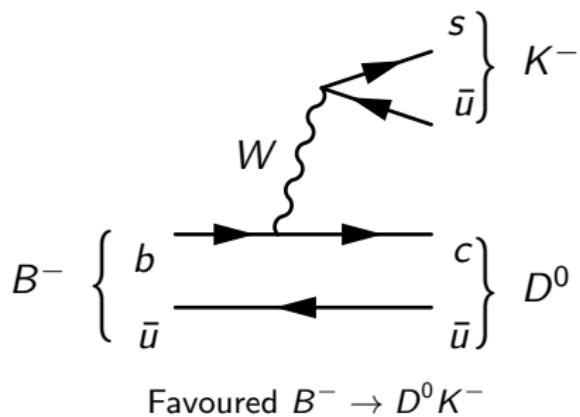
How to measure  $\gamma$ ?

# How to measure $\gamma$ ?

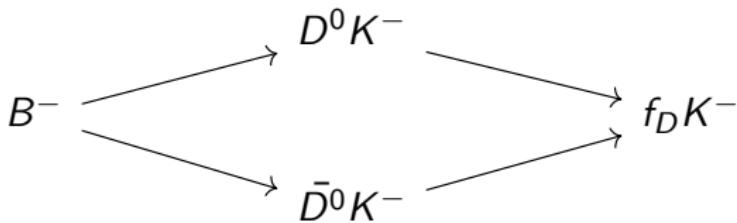
It's all about interferences!

# Sensitivity through interference

Measure  $\gamma$  through interference effects in  $B^\pm \rightarrow DK^\pm$

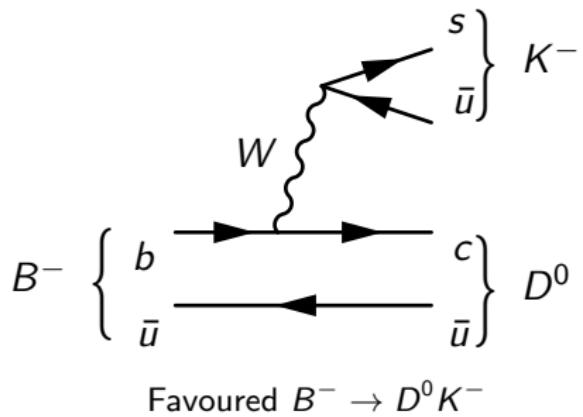


Interference when  $D^0$  and  $\bar{D}^0$  decay to a common final state  $f_D$

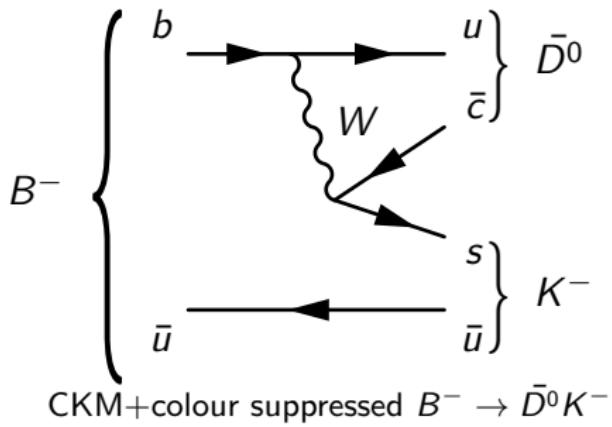


# Sensitivity through interference

Measure  $\gamma$  through interference effects in  $B^\pm \rightarrow DK^\pm$



Favoured  $B^- \rightarrow D^0 K^-$



CKM+colour suppressed  $B^- \rightarrow \bar{D}^0 K^-$

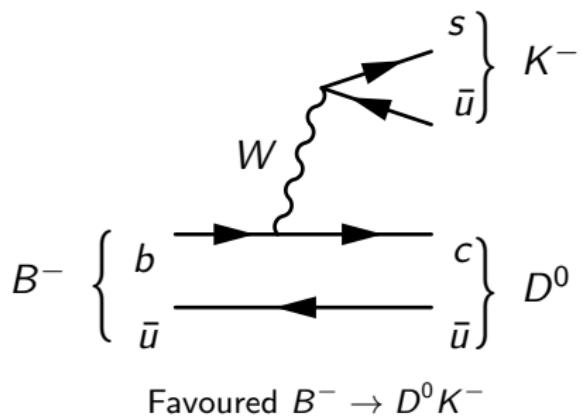
$b \rightarrow u\bar{c}s$  and  $b \rightarrow c\bar{u}s$  interference  $\rightarrow$  Sensitivity to  $\gamma$

$$\mathcal{A}(B^-) = \mathcal{A}_B (\mathcal{A}_{D^0} + r_B e^{i(\delta_B - \gamma)} \mathcal{A}_{\bar{D}^0})$$

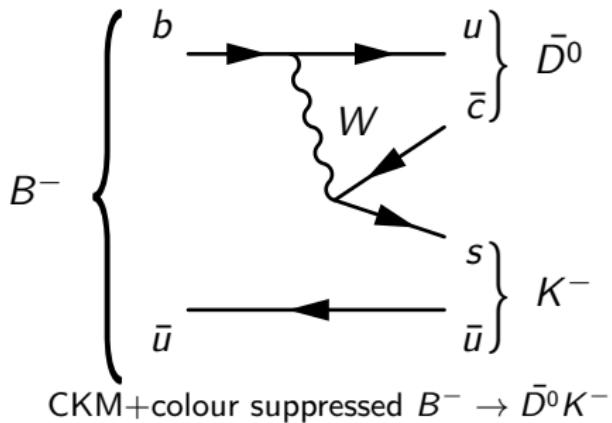
$$\mathcal{A}(B^+) = \mathcal{A}_B (\mathcal{A}_{\bar{D}^0} + r_B e^{i(\delta_B + \gamma)} \mathcal{A}_{D^0})$$

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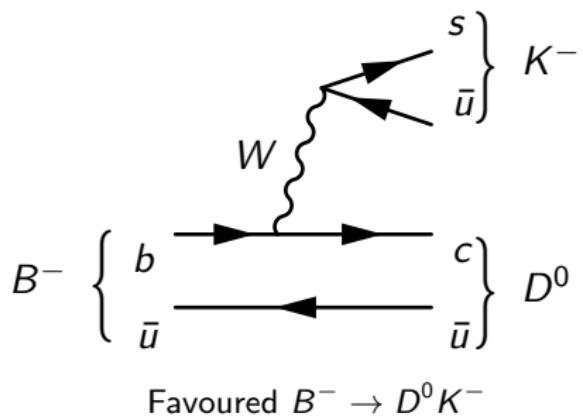
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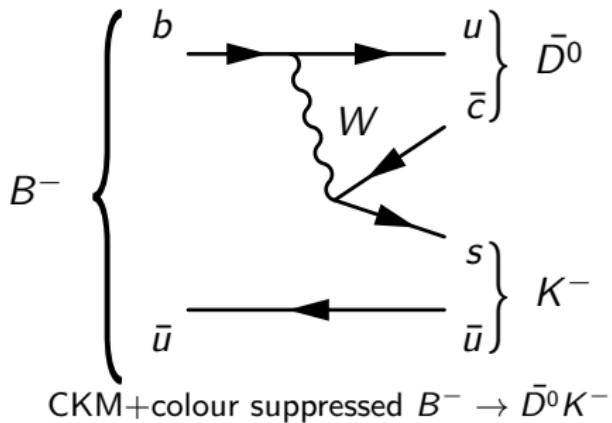
The magnitude of interference effects governed by  $r_B \approx 0.1$

# Sensitivity through interference

Measure  $\gamma$  through interference effects in  $B^\pm \rightarrow DK^\pm$



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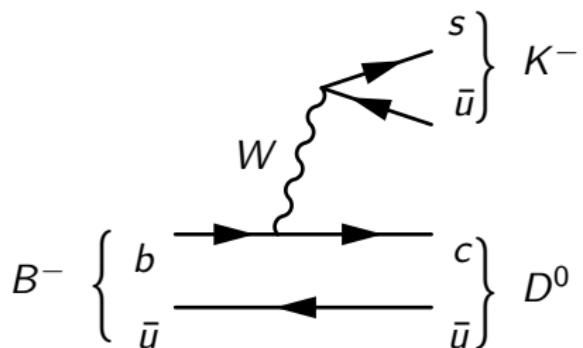
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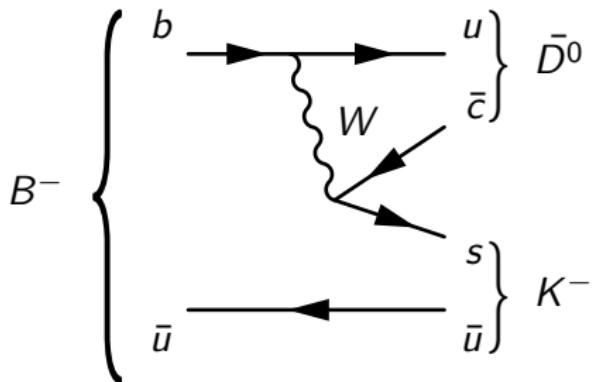
The strong-phase difference  $\delta_B$  accounts for all unknown QCD phase shifts

# Sensitivity through interference

Measure  $\gamma$  through interference effects in  $B^\pm \rightarrow DK^\pm$



Favoured  $B^- \rightarrow D^0 K^-$



CKM+colour suppressed  $B^- \rightarrow \bar{D}^0 K^-$

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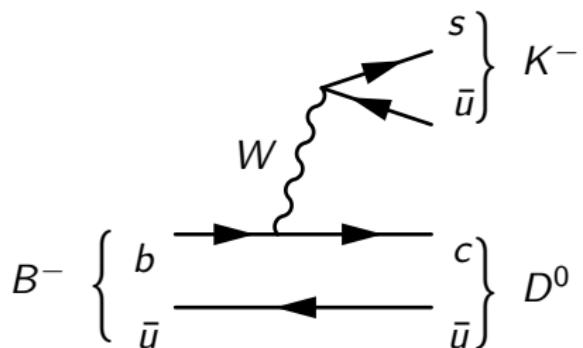
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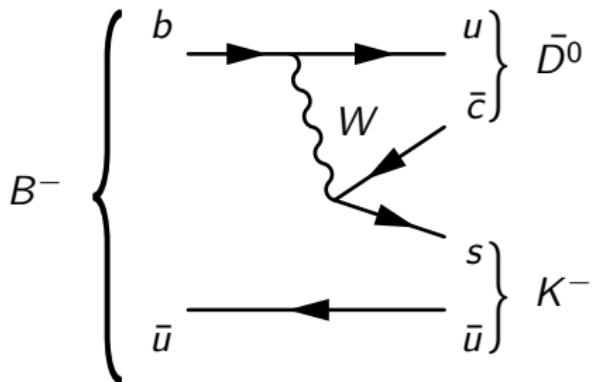
The weak phase  $\gamma$  swaps sign under CP

# Sensitivity through interference

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$$\mathcal{A}(B^+) = \mathcal{A}_B (\mathcal{A}_{\bar{D}^0} + r_B e^{i(\delta_B + \gamma)} \mathcal{A}_{D^0})$$

$\gamma, r_B, \delta_B$  are free parameters  $\implies$  No need for inputs from theory

# What $D$ final states?

Several methods are used to measure  $\gamma$  precisely

1

2

3

# What $D$ final states?

Several methods are used to measure  $\gamma$  precisely

① CP eigenstates (“GLW method”)

- $D \rightarrow K^+ K^-$ ,  $\pi^+ \pi^-$ , ...
- Phys. Lett. B **253** (1991) 483, Phys. Lett. B **265** (1991) 172

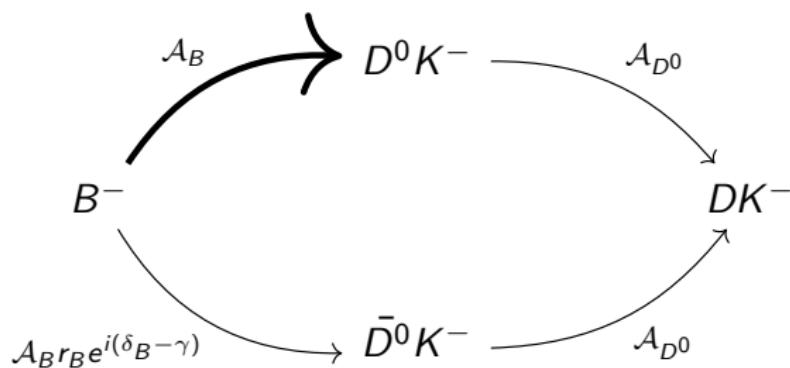
②

③

# $D$ decays to a $CP$ eigenstate

Naively, we expect the size of CPV effects to be around  $r_B \approx 10\%$

For  $CP$  eigenstates,  $\mathcal{A}_{D^0} = \mathcal{A}_{\bar{D}^0}$

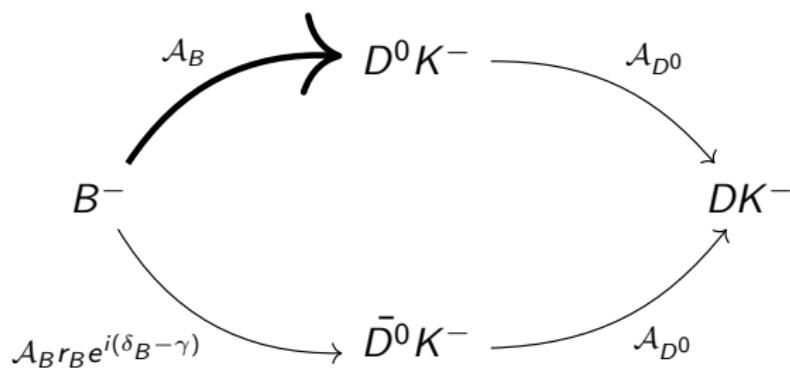


$$|\mathcal{A}(B^-)|^2 \propto 1 + r_B^2 + 2r_B \cos(\delta_B - \gamma)$$

# $D$ decays to a $CP$ eigenstate

Naively, we expect the size of CPV effects to be around  $r_B \approx 10\%$

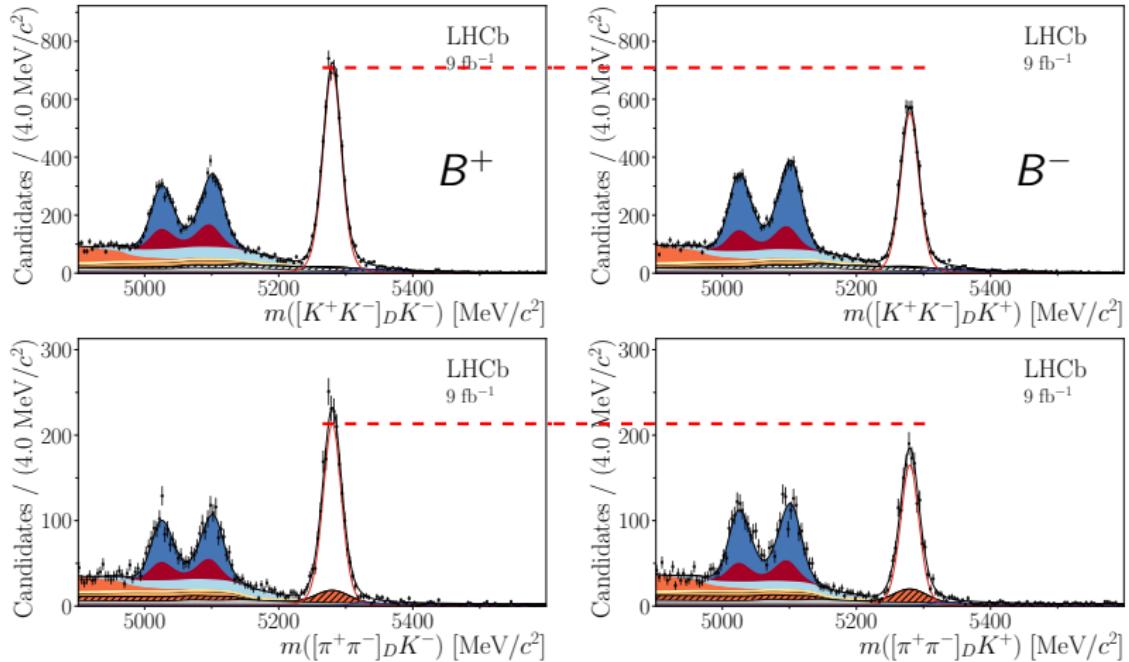
For  $CP$  eigenstates,  $\mathcal{A}_{D^0} = \mathcal{A}_{\bar{D}^0}$



$$|\mathcal{A}(B^-)|^2 \propto 1 + r_B^2 + 2r_B \cos(\delta_B - \gamma)$$

4-fold degeneracy:  $(\gamma, \delta_B) \rightarrow (\delta_B, \gamma)$  or  $(\pi - \gamma, \pi - \delta_B)$

# $D$ decays to a $CP$ eigenstate



JHEP 04 (2021) 081

In  $B^\pm \rightarrow [h^+ h^-]_D K^\pm$ , we see significant CPV effects

# What $D$ final states?

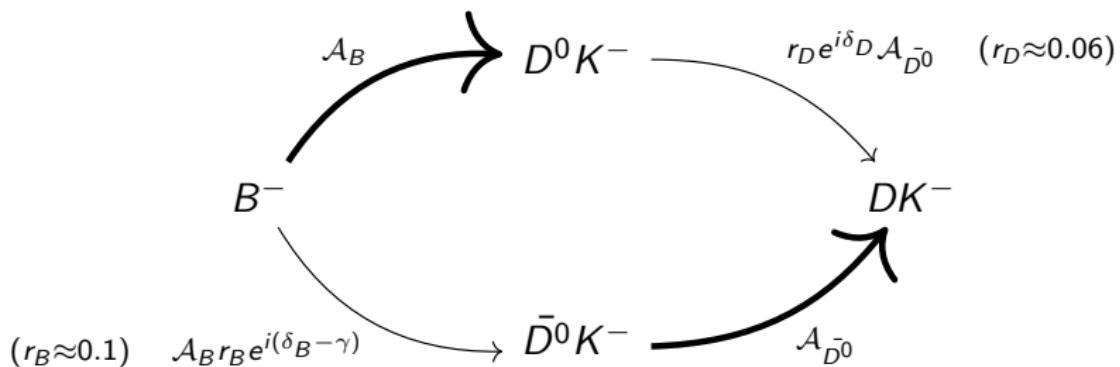
Several methods are used to measure  $\gamma$  precisely

- ① CP eigenstates (“GLW method”)
  - $D \rightarrow K^+ K^-, \pi^+ \pi^-, \dots$
  - Phys. Lett. B **253** (1991) 483, Phys. Lett. B **265** (1991) 172
- ② Doubly-Cabibbo Suppressed decays (“ADS method”)
  - $D \rightarrow K^- \pi^+, K^- \pi^+ \pi^- \pi^+, \dots$
  - Phys. Rev. Lett. **78** (1997) 3257
- ③

# Doubly Suppressed Cabibbo $D$ decays

Asymmetries can be enhanced with a DCS decay:  $\mathcal{A}_{D^0} = r_D e^{i\delta_D} \mathcal{A}_{\bar{D}^0}$

Interference between CF and DCS decays

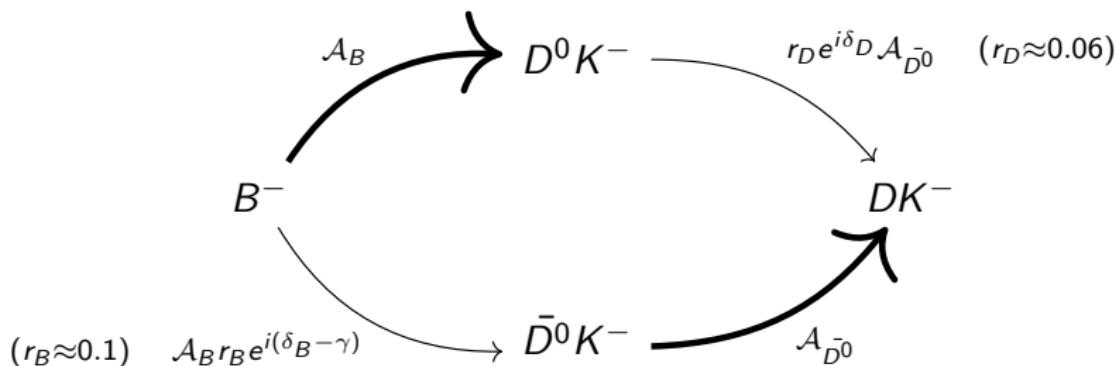


$$|\mathcal{A}(B^-)|^2 \propto r_D^2 + r_B^2 + 2r_B r_D \cos(\delta_B - \gamma + \delta_D)$$

# Doubly Suppressed Cabibbo $D$ decays

Asymmetries can be enhanced with a DCS decay:  $\mathcal{A}_{D^0} = r_D e^{i\delta_D} \mathcal{A}_{\bar{D}^0}$

Interference between CF and DCS decays



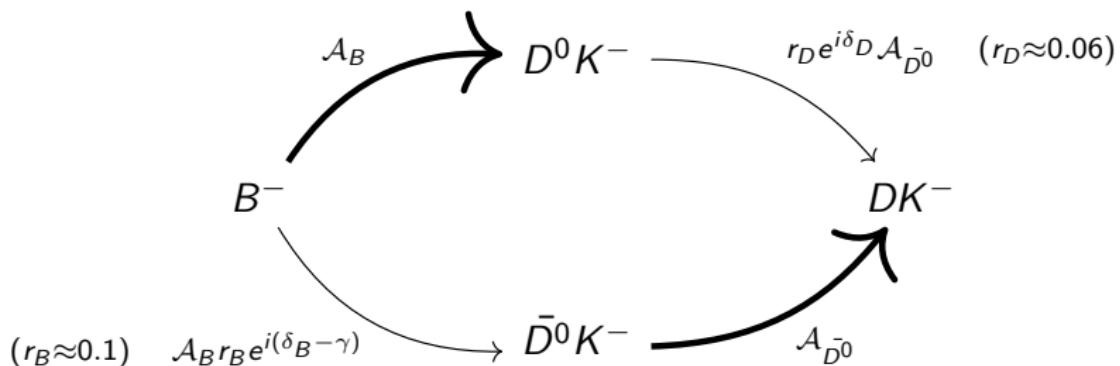
$$|\mathcal{A}(B^-)|^2 \propto r_D^2 + r_B^2 + 2r_B r_D \cos(\delta_B - \gamma + \delta_D)$$

$$r_D \approx \tan^2(\theta_c) \text{ due to CKM suppression}$$

# Doubly Suppressed Cabibbo $D$ decays

Asymmetries can be enhanced with a DCS decay:  $\mathcal{A}_{D^0} = r_D e^{i\delta_D} \mathcal{A}_{\bar{D}^0}$

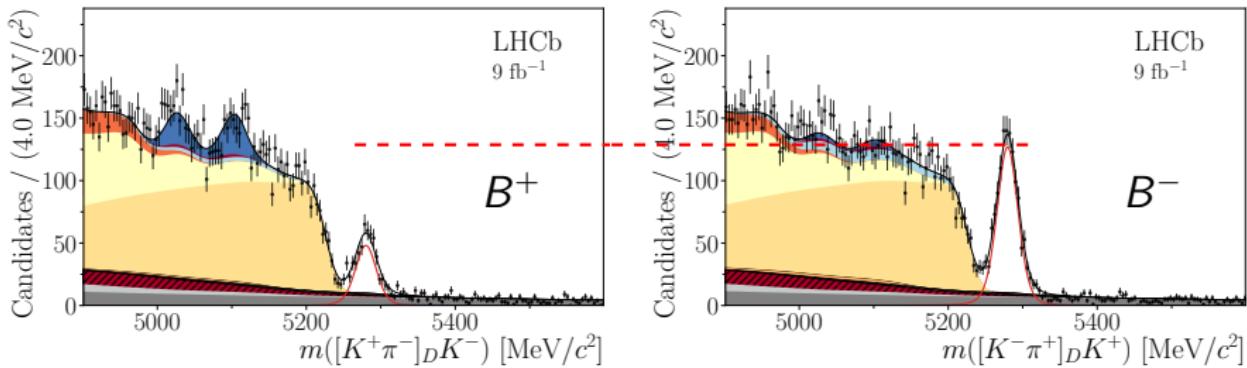
Interference between CF and DCS decays



$$|\mathcal{A}(B^-)|^2 \propto r_D^2 + r_B^2 + 2r_B r_D \cos(\delta_B - \gamma + \delta_D)$$

Almost 4-fold degeneracy since  $\delta_D \approx 180^\circ$

# Doubly Suppressed Cabibbo $D$ decays

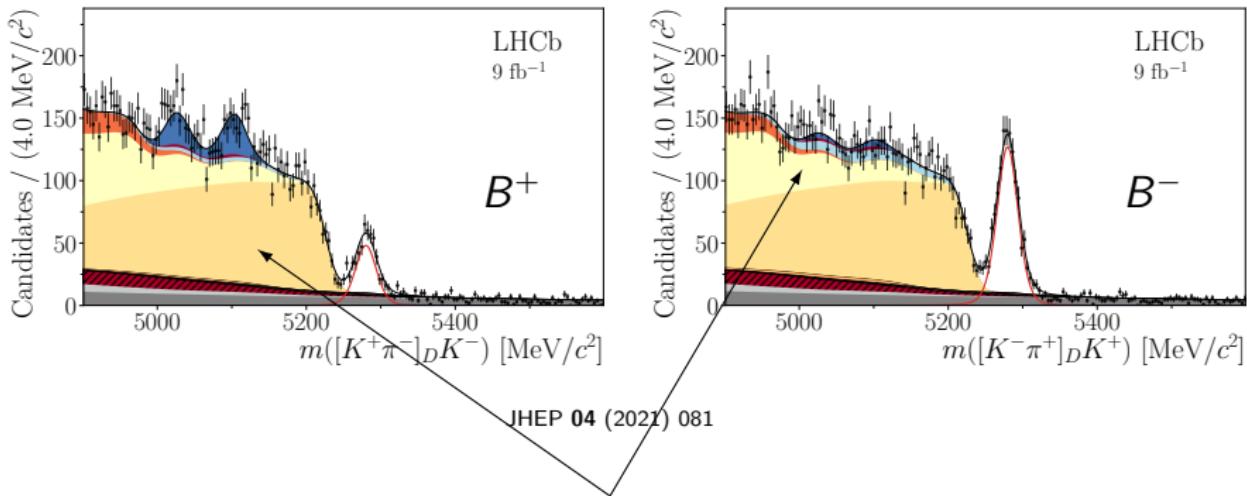


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$B^\pm \rightarrow [K^\mp\pi^\pm]_D K^\pm$  has lower statistics, but a spectacular asymmetry!

Note: Total branching fraction is  $5.5 \times 10^{-8}!$

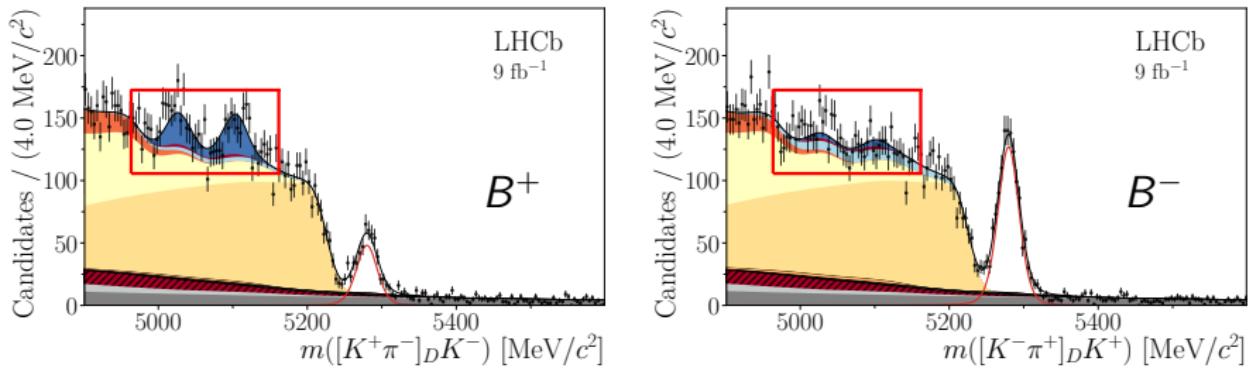
# Doubly Suppressed Cabibbo $D$ decays



Large background from  $B_s^0 \rightarrow \bar{D}^{(*)0} K^- \pi^+$  with missing  $\pi^+$

Since  $\bar{D}^{(*)0}$  has the opposite flavour to signal, it is Cabibbo favoured

# Doubly Suppressed Cabibbo $D$ decays

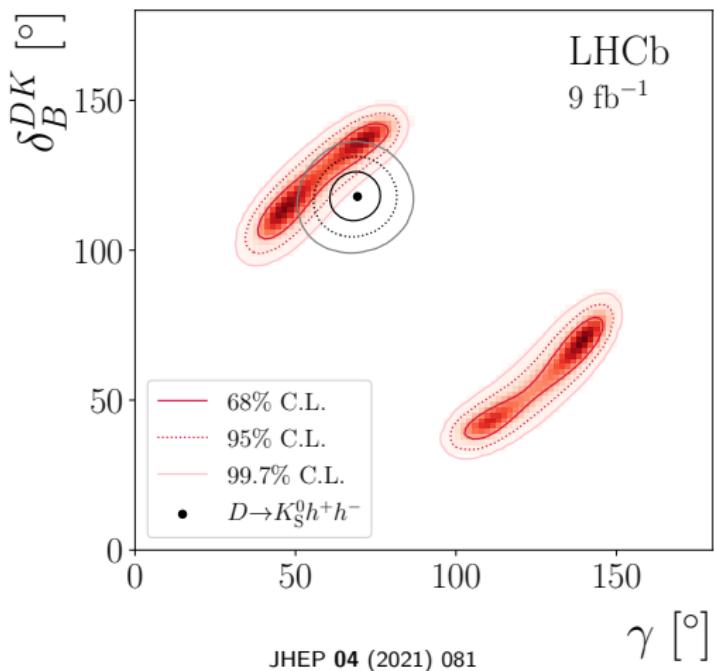


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Asymmetry is also seen in the double-peaked background

Partially reconstructed  $B^\pm \rightarrow D^* K^\pm$  decays, where  $D^* \rightarrow D^0 \pi^0$

# Combined CP eigenstate and DCS decays



4 solutions from CP eigenstates and DCS decays  
Need further inputs to resolve this degeneracy

# What $D$ final states?

Several methods are used to measure  $\gamma$  precisely

- ① CP eigenstates (“GLW method”)
  - $D \rightarrow K^+K^-, \pi^+\pi^-, \dots$
  - Phys. Lett. B **253** (1991) 483, Phys. Lett. B **265** (1991) 172
- ② Doubly-Cabibbo Suppressed decays (“ADS method”)
  - $D \rightarrow K^-\pi^+, K^-\pi^+\pi^-\pi^+, \dots$
  - Phys. Rev. Lett. **78** (1997) 3257
- ③ Self-conjugate multi-body final states (“BPGGSZ method”)
  - $D \rightarrow K_S^0\pi^+\pi^-, K_S^0K^+K^-, \dots$
  - Eur. Phys. J. C **47** (2006) 347, Phys. Rev. D **68** (2003) 054018

# Multi-body $D$ decays

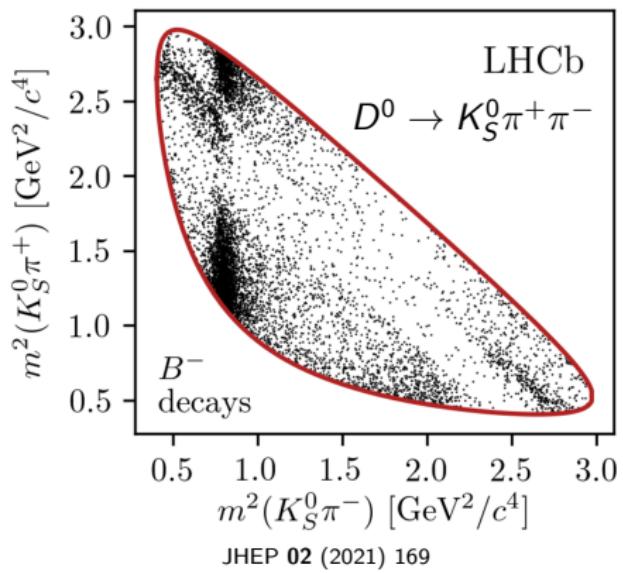
- Multi-body decays can have many intermediate resonances
- Decay amplitudes therefore vary across “phase space”

## Degrees of freedom for an $N$ -body decay

$$\begin{aligned} & 4N \text{ (momentum components)} \\ & - N \text{ ( $E_i^2 - p_i^2 = m_i^2$ )} \\ & - 4 \text{ (energy-momentum conservation)} \\ & - 3 \text{ (choice of frame)} \\ \hline & = 3N - 7 \text{ degrees of freedom} \end{aligned}$$

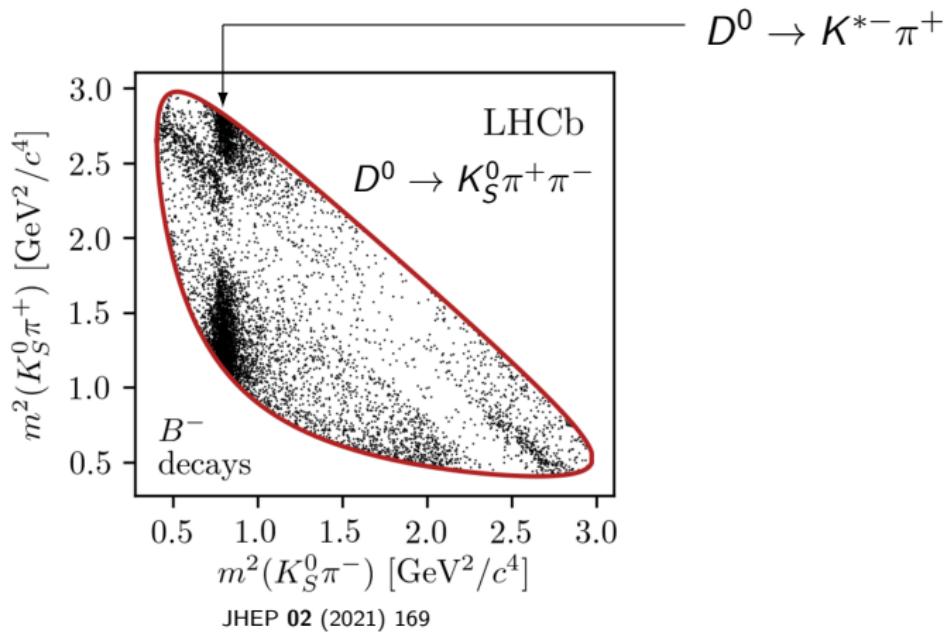
# Multi-body $D$ decays

For 3-body decays, phase space is two-dimensional: Dalitz plots



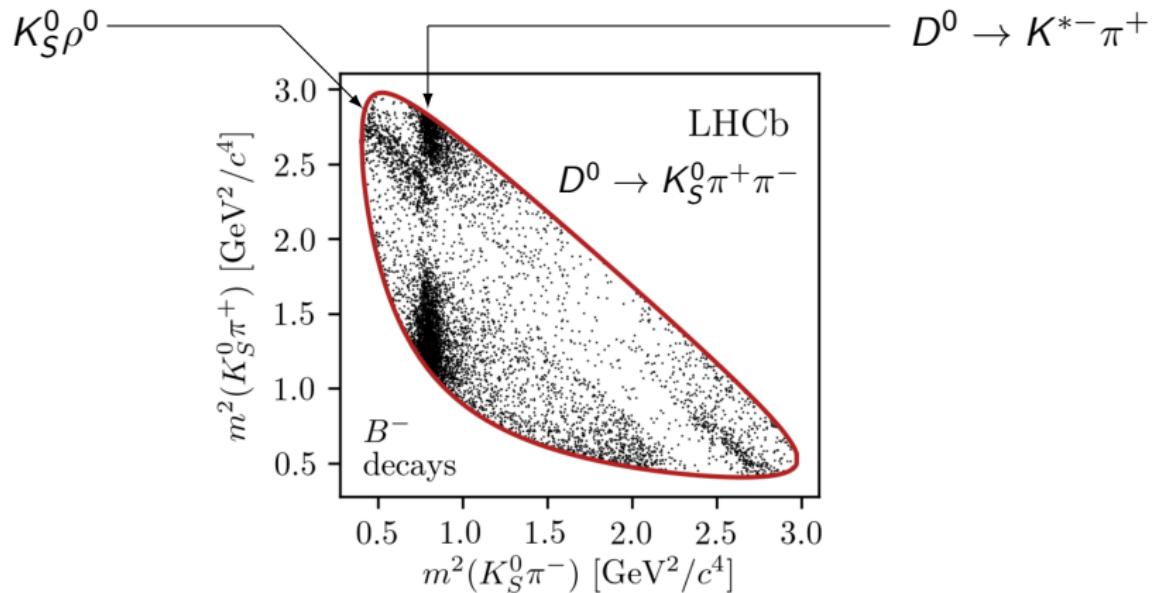
# Multi-body $D$ decays

For 3-body decays, phase space is two-dimensional: Dalitz plots



# Multi-body $D$ decays

For 3-body decays, phase space is two-dimensional: Dalitz plots

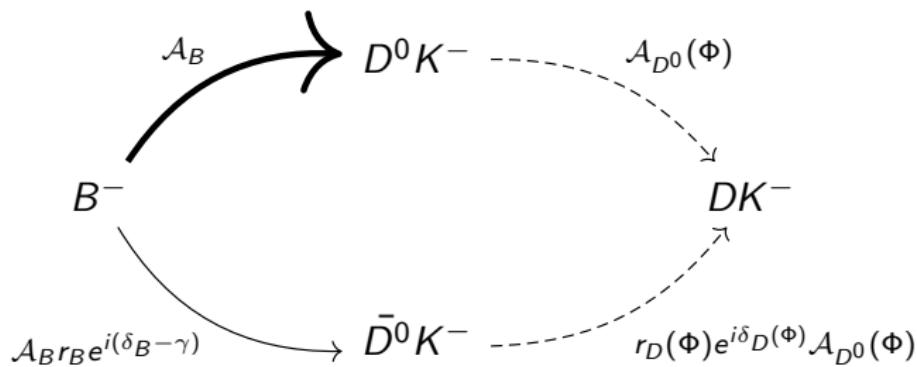


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# Multi-body $D$ decays

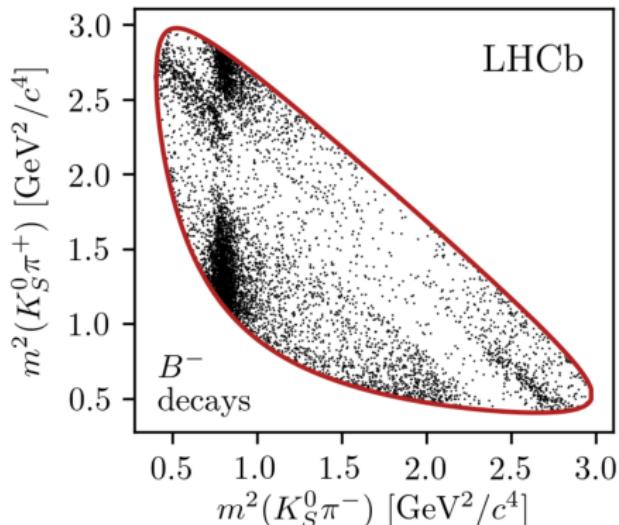
$B^\pm$  decay rate depends on the phase space position  $\Phi$

More importantly, the asymmetries across the Dalitz plot depend on the  $D^0$  and  $\bar{D}^0$  strong-phase difference  $\delta_D$

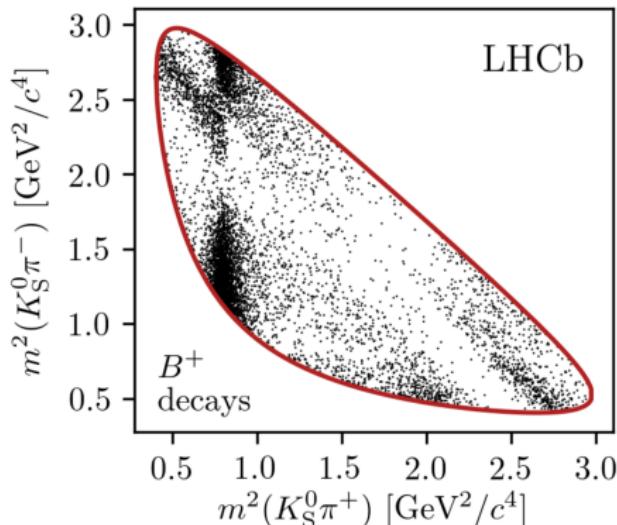


$$|\mathcal{A}(B^-)|^2 \propto 1 + r_B^2 r_D^2(\Phi) + 2r_B r_D(\Phi) \cos(\delta_B - \gamma + \delta_D(\Phi))$$

# Multi-body $D$ decays



$$B^- \rightarrow [K_S^0 \pi^+ \pi^-]_D K^-$$

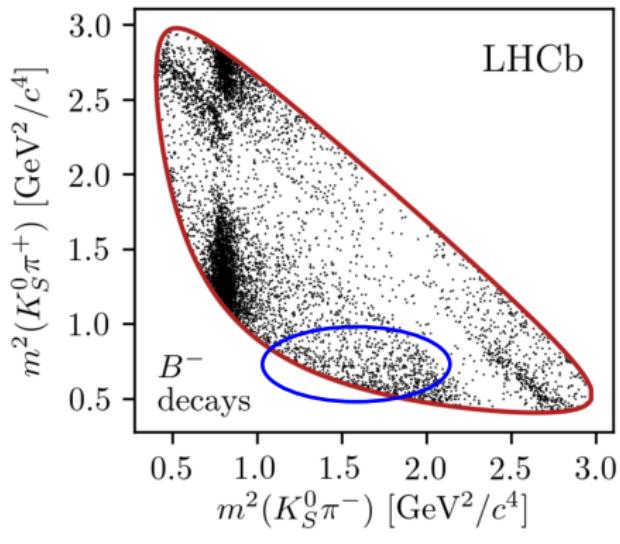


$$B^+ \rightarrow [K_S^0 \pi^+ \pi^-]_D K^+$$

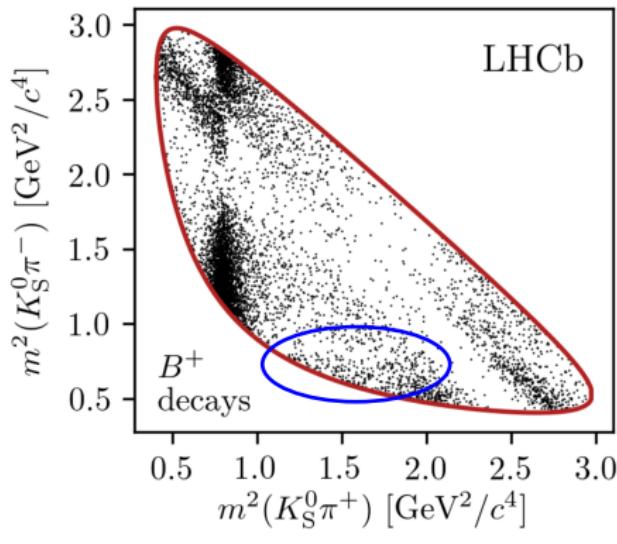
JHEP 02 (2021) 169

Can you find the asymmetries?

# Multi-body $D$ decays



$$B^- \rightarrow [K_S^0 \pi^+ \pi^-]_D K^-$$

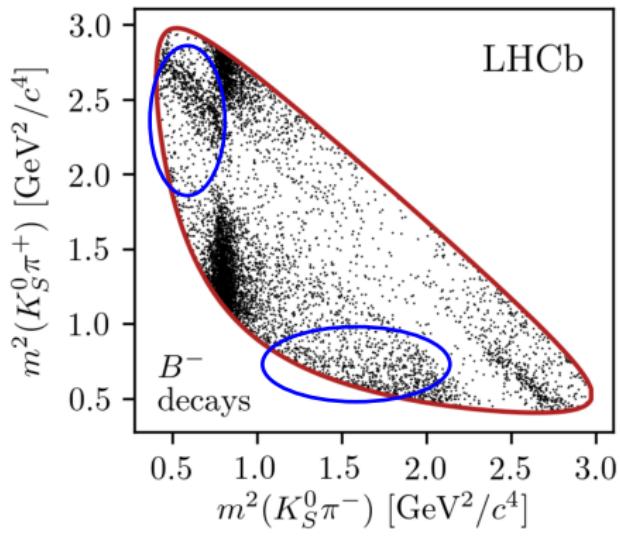


$$B^+ \rightarrow [K_S^0 \pi^+ \pi^-]_D K^+$$

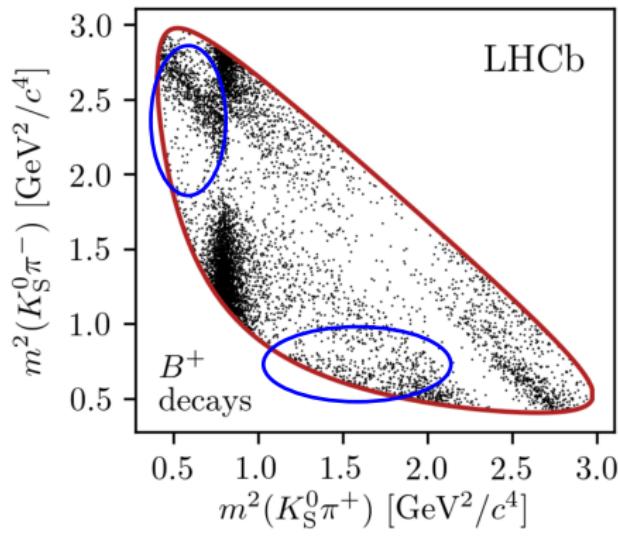
JHEP 02 (2021) 169

Can you find the asymmetries?

# Multi-body $D$ decays



$$B^- \rightarrow [K_S^0 \pi^+ \pi^-]_D K^-$$



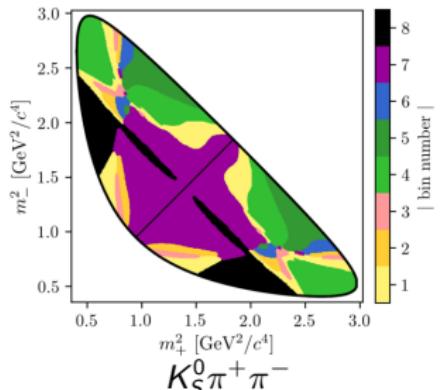
$$B^+ \rightarrow [K_S^0 \pi^+ \pi^-]_D K^+$$

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Can you find the asymmetries?

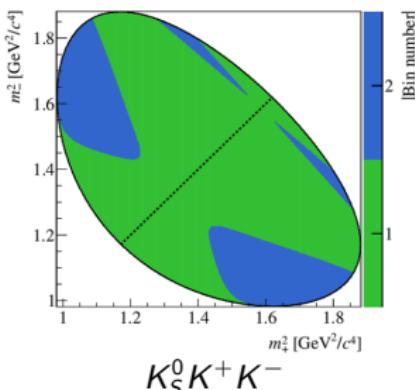
# Multi-body $D$ decays

- Interpretation of  $\gamma$  from the multi-body charm decays require external inputs of the charm strong-phase differences
- The three-body decays  $D \rightarrow K_S^0 h^+ h^-$  have been studied extensively, using an optimised phase-space binning:
  - CLEO Phys. Rev. **D82** (2010) 112006
  - BESIII Phys. Rev. **D101** (2020) 112002
- With charm inputs from CLEO and BESIII, the measurement of  $\gamma$  becomes model independent



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CERN LHC seminar



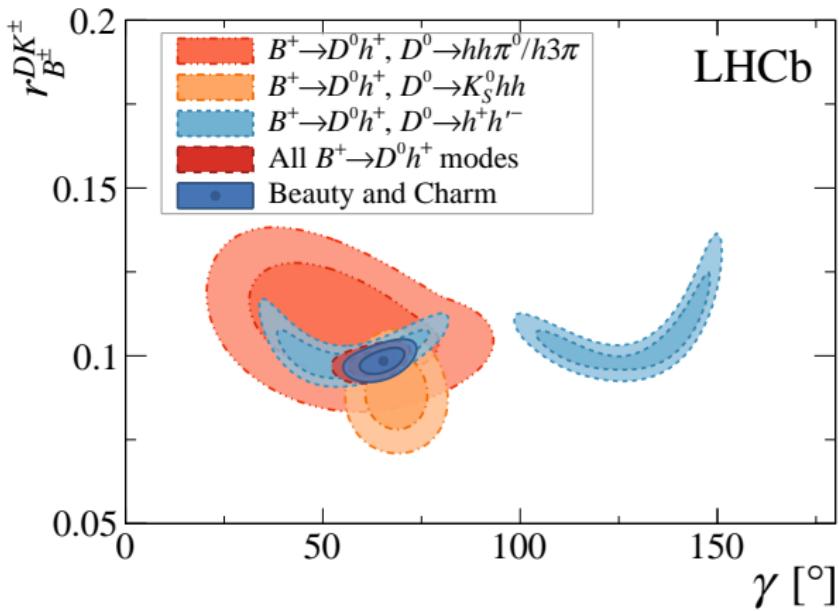
25th July 2023

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# The LHCb $\gamma$ combination

How to combine a decade of  $\gamma$  measurements

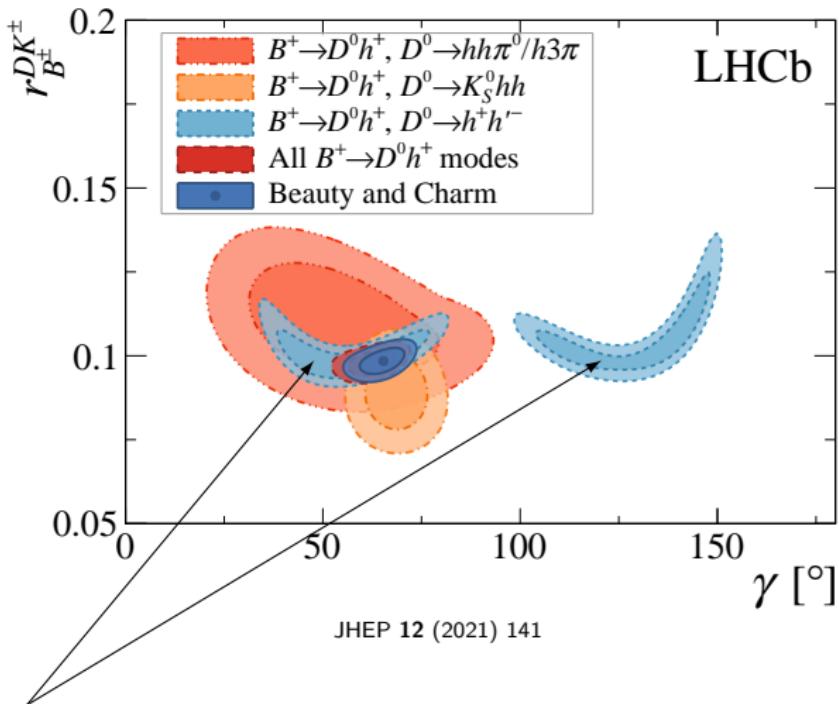
# The LHCb $\gamma$ combination



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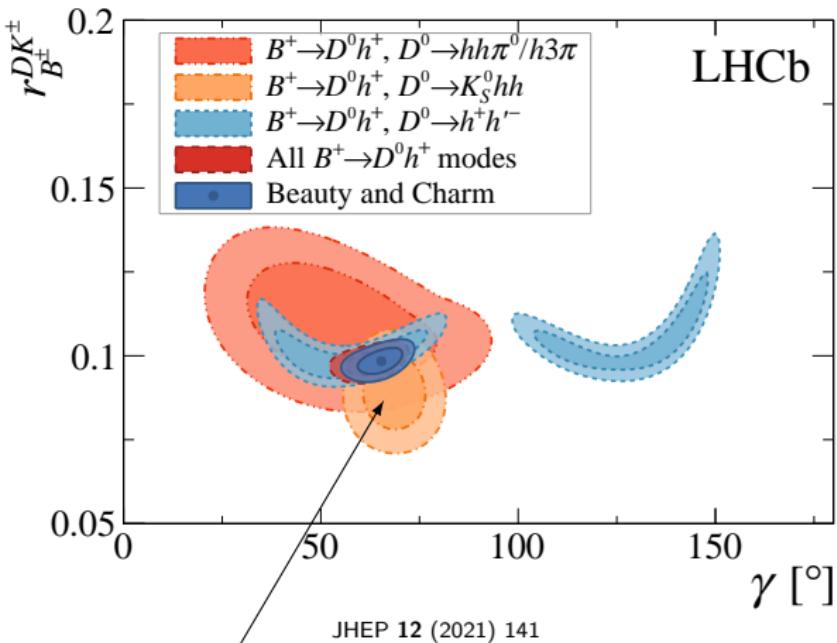
Currently,  $\gamma$  measurements are dominated by  $B^\pm \rightarrow Dh^\pm$

# The LHCb $\gamma$ combination



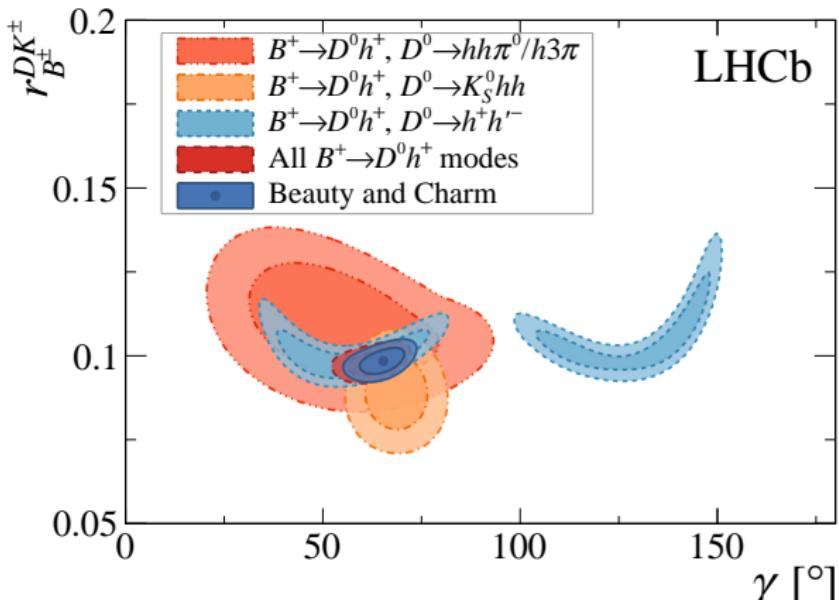
CP eigenstates and DCS decays: Narrow bands of degenerate solutions

# The LHCb $\gamma$ combination



Self-conjugate multi-body decays: Wider, but unique solution

# The LHCb $\gamma$ combination



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A combination of direct  $\gamma$  measurements is necessary!

# The LHCb $\gamma$ combination

Other  $B$  decays are also interesting for  $\gamma$  measurements:

- ①  $B^\pm \rightarrow D K^\pm$
- ②  $B^\pm \rightarrow D^{*0} K^\pm$
- ③  $B^0 \rightarrow D K^{*0}$
- ④  $B_s^0 \rightarrow D_s^- K^+$
- And many more...

# The LHCb $\gamma$ combination

Other  $B$  decays are also interesting for  $\gamma$  measurements:

- ①  $B^\pm \rightarrow DK^\pm \leftarrow$  Golden mode
- ②  $B^\pm \rightarrow D^{*0} K^\pm$
- ③  $B^0 \rightarrow DK^{*0}$
- ④  $B_s^0 \rightarrow D_s^- K^+$ 
  - And many more...

# The LHCb $\gamma$ combination

Other  $B$  decays are also interesting for  $\gamma$  measurements:

- ①  $B^\pm \rightarrow DK^\pm \leftarrow$  Golden mode
- ②  $B^\pm \rightarrow D^{*0} K^\pm \leftarrow$  New results!
- ③  $B^0 \rightarrow DK^{*0} \leftarrow$  New results!
- ④  $B_s^0 \rightarrow D_s^- K^+$ 
  - And many more...

# The LHCb $\gamma$ combination

Other  $B$  decays are also interesting for  $\gamma$  measurements:

- ①  $B^\pm \rightarrow DK^\pm \leftarrow$  Golden mode
- ②  $B^\pm \rightarrow D^{*0} K^\pm \leftarrow$  New results!
- ③  $B^0 \rightarrow DK^{*0} \leftarrow$  New results!
- ④  $B_s^0 \rightarrow D_s^- K^+ \leftarrow$  Coming soon
  - And many more...

# The LHCb $\gamma$ combination

Other  $B$  decays are also interesting for  $\gamma$  measurements:

Most Run 1 and 2 measurements are included,  
but today I will also report on several new results

- ➊  $B^\pm \rightarrow DK^\pm$
- ➋  $B^\pm \rightarrow D^{*0} K^\pm$
- ➌  $B^0 \rightarrow DK^{*0}$
- ➍  $B_s^0 \rightarrow D_s^- K^+$ 
  - And many more...

	Measurement	$\chi^2$	No. of obs.
Beauty sector	$B^\pm \rightarrow Dh^\pm, D \rightarrow h^\pm h'^\mp$	2.37	8
	$B^\pm \rightarrow Dh^\pm, D \rightarrow K_S^0 h^+ h^-$	4.80	6
	$B^\pm \rightarrow Dh^\pm, D \rightarrow K_S^0 K^\pm \pi^\mp$	7.29	7
	$B^\pm \rightarrow D^{*0} h^\pm, D \rightarrow h^\pm h'^\mp$	7.49	16
	$B^\pm \rightarrow DK^{*0}, D \rightarrow h^\pm h'^\mp (\pi^+ \pi^-)$	3.44	12
	$B^0 \rightarrow DK^{*0}, D \rightarrow h^\pm h'^\mp (\pi^+ \pi^-)$	9.90	12
	$B^0 \rightarrow DK^{*0}, D \rightarrow K_S^0 h^+ h^-$	3.36	4
	$B^\pm \rightarrow Dh^\pm \pi^+ \pi^-, D \rightarrow h^\pm h'^\mp$	1.36	11
	$B_s^0 \rightarrow D_s^+ K^\pm$	5.94	5
	$B_s^0 \rightarrow D_s^\mp K^\pm \pi^+ \pi^-$	2.75	5
	$B^0 \rightarrow D^\mp \pi^\pm$	0.00	2
	$B^\pm \rightarrow Dh^\pm, D \rightarrow h^\pm h'^\mp \pi^0$	5.91	11
	$B^\pm \rightarrow Dh^\pm, D \rightarrow K^\pm \pi^\mp \pi^+ \pi^-$	4.20	6
	$B^\pm \rightarrow Dh^\pm, D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$	0.81	3

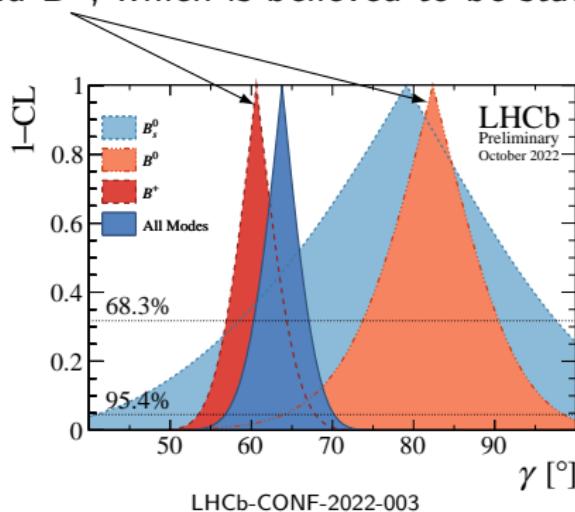
LHCb-CONF-2022-003

# The LHCb $\gamma$ combination

Other  $B$  decays are also interesting for  $\gamma$  measurements:

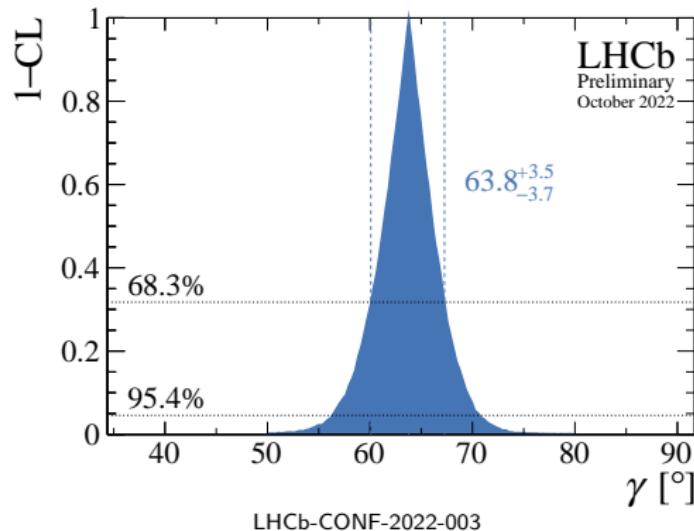
Small ( $2.2\sigma$ ) tension between  $B^\pm$  and  $B^0$ , which is believed to be statistical

- ①  $B^\pm \rightarrow DK^\pm$
- ②  $B^\pm \rightarrow D^{*0} K^\pm$
- ③  $B^0 \rightarrow DK^{*0}$
- ④  $B_s^0 \rightarrow D_s^- K^+$ 
  - And many more...



# The LHCb $\gamma$ combination

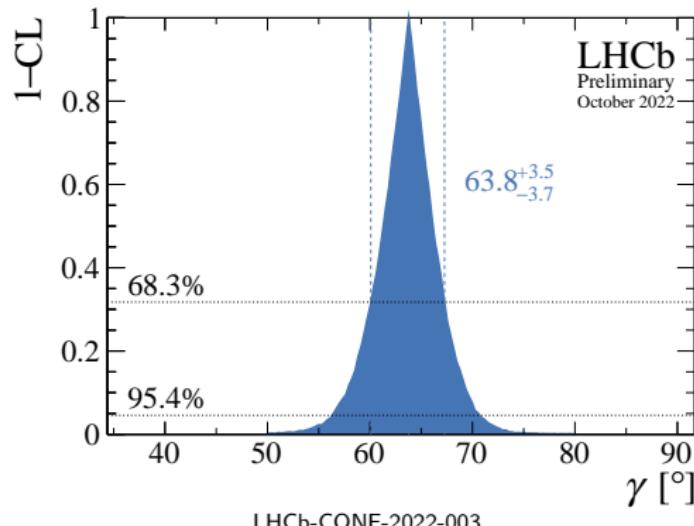
Our most precise knowledge of  $\gamma$  comes from the combination measurements



This is the most precise determination of  $\gamma$  by a single experiment!  
We also benefit from BESIII strong-phase and charm-mixing measurements

# The LHCb $\gamma$ combination

Our most precise knowledge of  $\gamma$  comes from the combination measurements

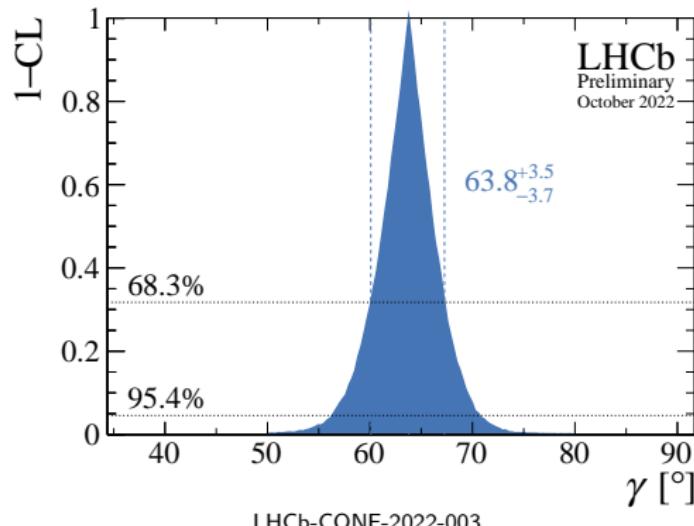


Combined result:  $\gamma = (63.8^{+3.5}_{-3.7})^\circ$

Run 2 target:  $\Delta\gamma = 4^\circ \rightarrow$  We did better than expected!

# The LHCb $\gamma$ combination

Our most precise knowledge of  $\gamma$  comes from the combination measurements

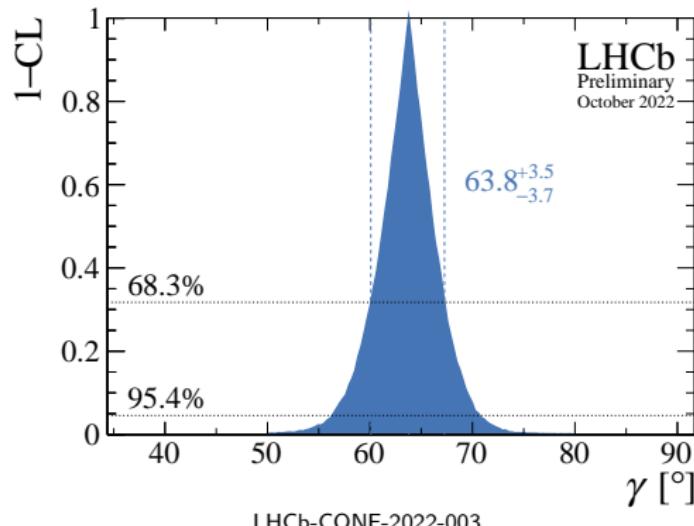


Combined result:  $\gamma = (63.8^{+3.5}_{-3.7})^\circ$

Compare with Belle:  $\gamma = (77.3^{+16.2}_{-16.0})^\circ$  Phys. Rev. D **85** (2012) 112014

# The LHCb $\gamma$ combination

Our most precise knowledge of  $\gamma$  comes from the combination measurements



Combined result:  $\gamma = (63.8^{+3.5}_{-3.7})^\circ$

Compare with BaBar:  $\gamma = (69^{+17}_{-16})^\circ$  Phys. Rev. D **87** (2013) 052015

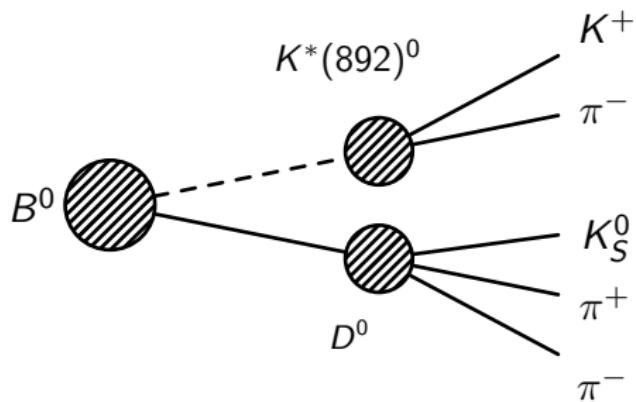
# Neutral $B$ decays

More interference with less statistics

## Neutral $B$ decays

Neutral  $B$  decays are analysed with an identical strategy:

LHCb-PAPER-2023-009 (in preparation) New results!

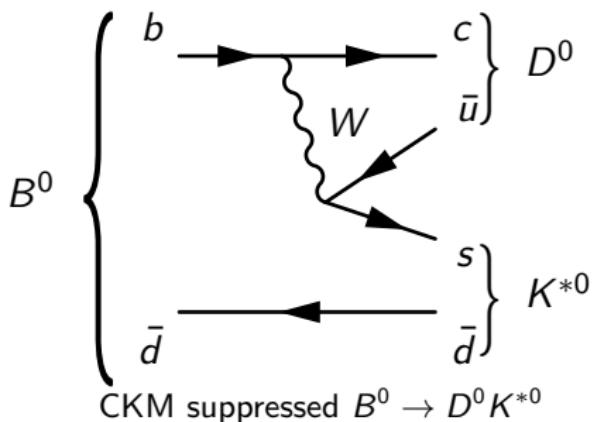
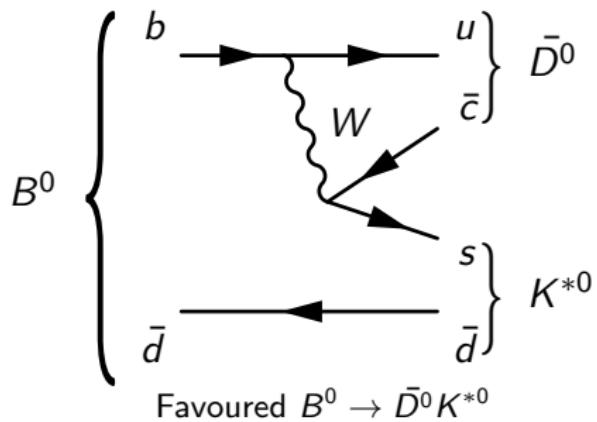


$$B^0 \rightarrow (K_S^0 h^+ h^-)_D (K^+ \pi^-)_{K^*}$$

This results supersedes that of JHEP **08** (2016) 137

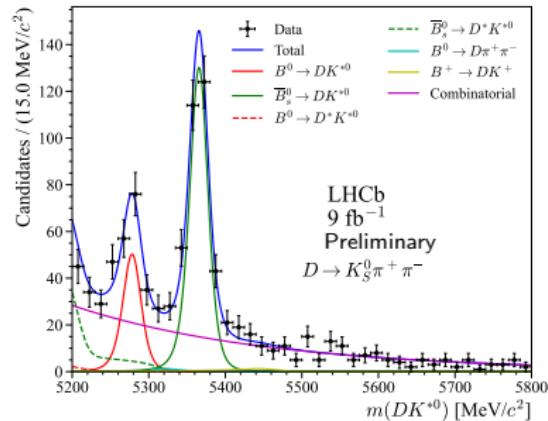
## Neutral $B$ decays

In  $B^0 \rightarrow D K^{*0}$ , there is no relative colour suppression



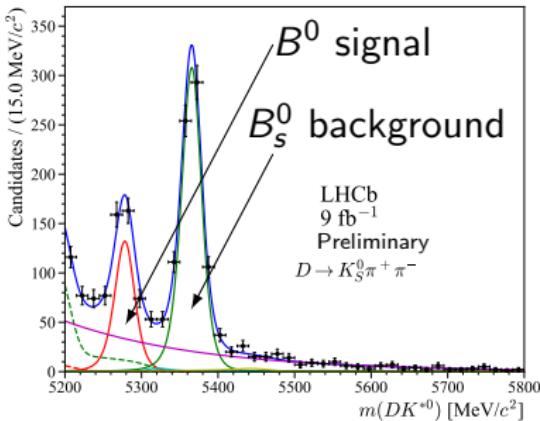
The interference is therefore expected to be  $\sim 3$  times larger

# Neutral $B$ decays



LL

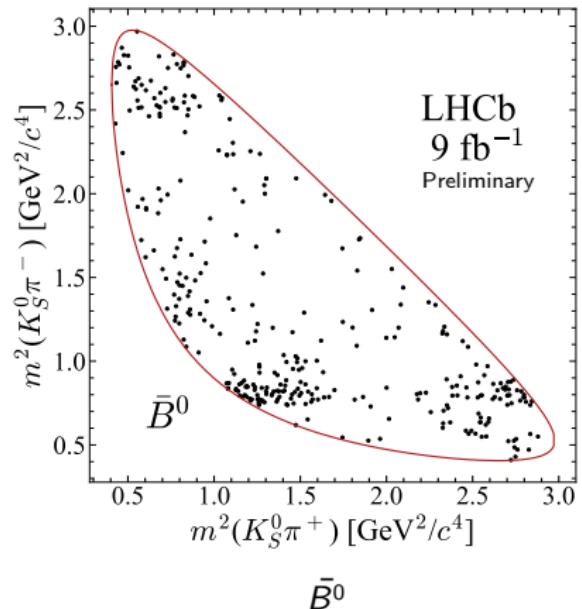
LHCb-PAPER-2023-009



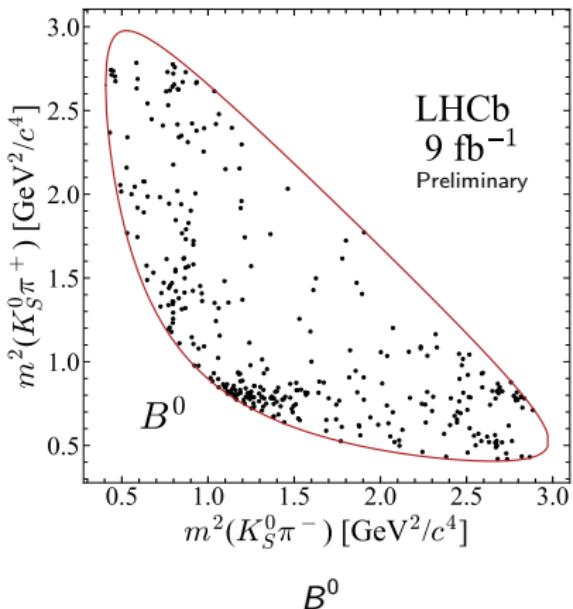
DD

- Two separate selections of  $K_S^0$ :
  - LL (long tracks):  $K_S^0$  decays in the VELO
  - DD (downstream tracks):  $K_S^0$  decays downstream of the VELO
- $B^0 \rightarrow DK^{*0}$  candidates with  $D \rightarrow K_S^0 \pi^+ \pi^-$  ( $D \rightarrow K_S^0 K^+ K^-$ ):
  - LL:  $102 \pm 17$  ( $12 \pm 6$ )
  - DD:  $288 \pm 25$  ( $32 \pm 8$ )

# Neutral $B$ decays

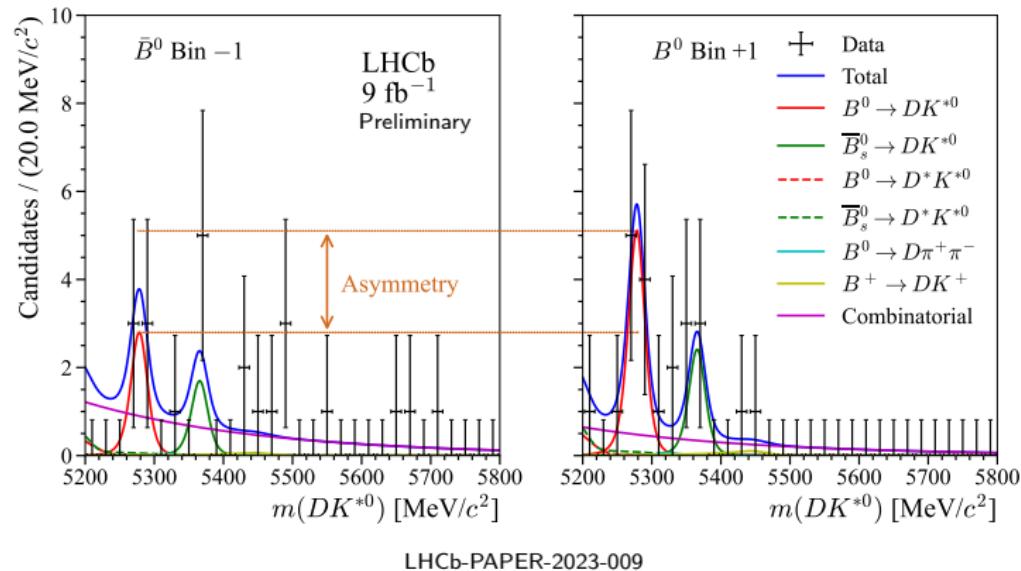


$$\bar{B}^0 \rightarrow [K_S^0\pi^+\pi^-]_D K^{*0} \text{ Dalitz plots}$$



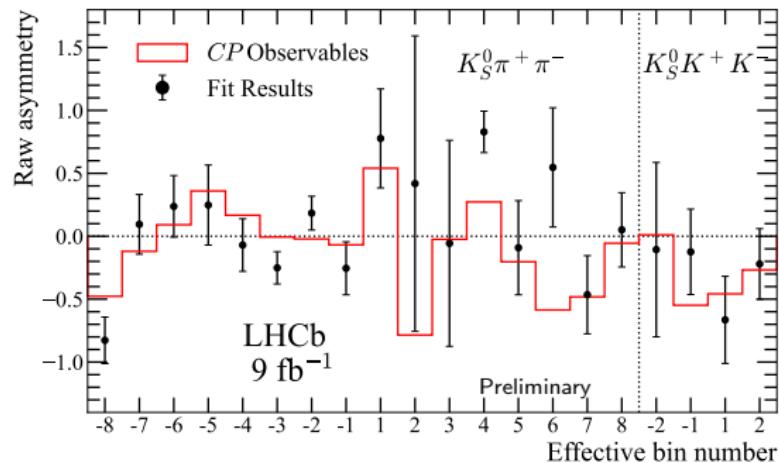
Can you find the asymmetries?

# Neutral $B$ decays



- Non-zero bin asymmetries are seen:
  - Large asymmetries between  $B^0$  ( $\bar{B}^0$ ) bin pairs
  - Very small CPV is expected in  $B_s^0$  decays, and these are not looked for

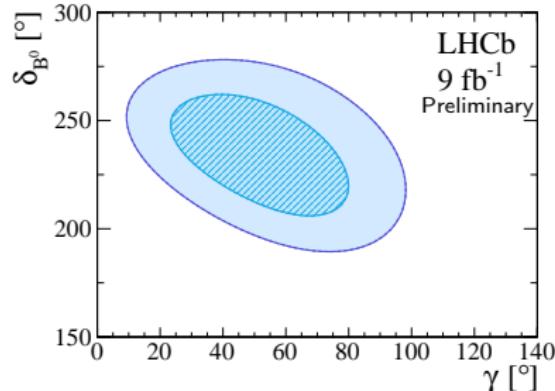
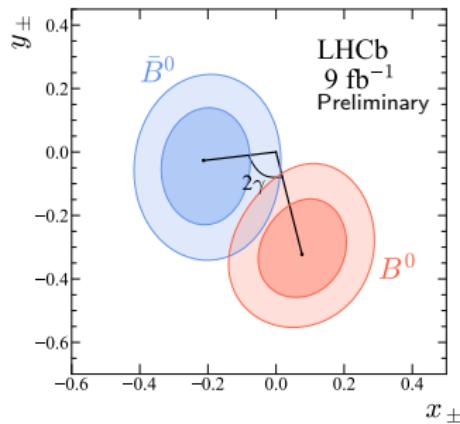
# Neutral $B$ decays



LHCb-PAPER-2023-009

- Non-zero bin asymmetries are seen:
  - Large asymmetries between  $B^0$  ( $\bar{B}^0$ ) bin pairs
  - Very small CPV is expected in  $B_s^0$  decays, and these are not looked for
- Asymmetries differ in size and magnitude across bins of phase space

# Neutral $B$ decays



LHCb-PAPER-2023-009

- Measured  $CP$ -violating observables:

$$x_{\pm} \equiv r_{B^0} \cos(\delta_{B^0} \pm \gamma) \text{ and } y_{\pm} \equiv r_{B^0} \sin(\delta_{B^0} \pm \gamma)$$

- Measured value of  $\gamma$  is consistent with world average:

- $\gamma = (49 \pm 20)^\circ$
- $\delta_{B^0} = (236 \pm 19)^\circ$
- $r_{B^0} = 0.27 \pm 0.07 \leftarrow 3 \text{ times larger than the } B^{\pm} \text{ modes!}$

B decays to excited  $D^*$  final states

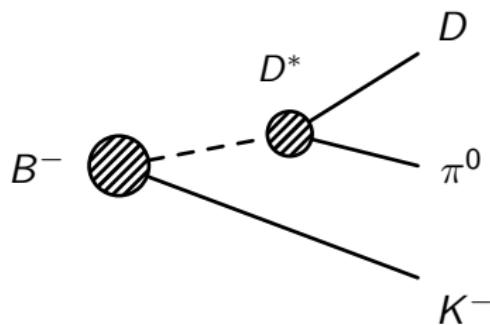
# B decays to excited $D^*$ final states

A measurement with neutral particles

## $B$ decays to excited $D^*$ final states

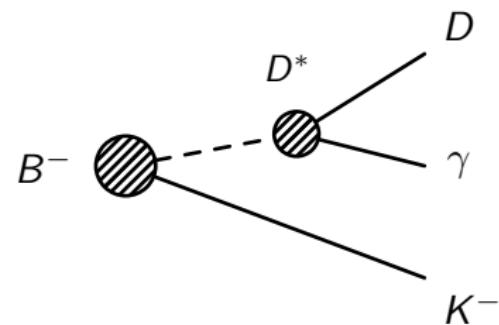
$B^- \rightarrow D^* K^-$  decays are also a powerful probe of CPV:

LHCb-PAPER-2023-012 (in preparation) New results!



$$B^- \rightarrow [D\pi^0]_{D^*} K^-$$

$$\mathcal{A}(D^0) + r_B e^{i(\delta_B - \gamma)} \mathcal{A}(\bar{D}^0)$$

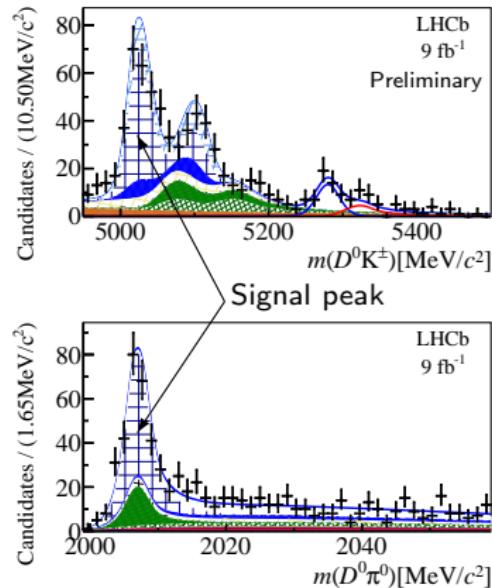


$$B^- \rightarrow [D\gamma]_{D^*} K^-$$

$$\mathcal{A}(D^0) - r_B e^{i(\delta_B - \gamma)} \mathcal{A}(\bar{D}^0)$$

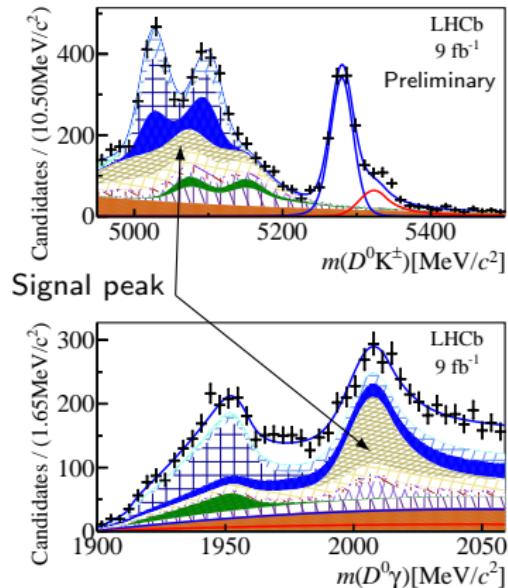
The relative sign swap, due to the phase difference of  $\pi$  between  $\pi^0$  and  $\gamma$ , results in opposite  $CP$  asymmetries between  $D^* \rightarrow D\pi^0$  and  $D^* \rightarrow D\gamma$

# $B$ decays to excited $D^*$ final states



$$D^* \rightarrow D\pi^0$$

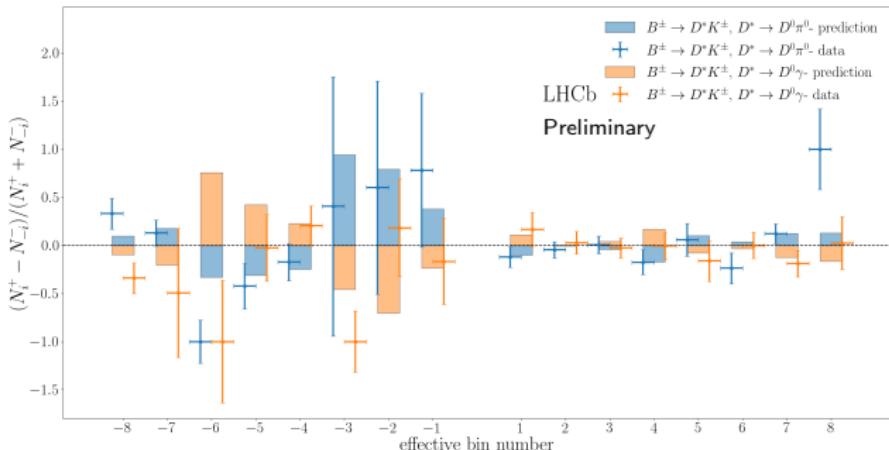
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$$(a) D^* \rightarrow D\gamma$$

A 2D fit is necessary to separate signal from background

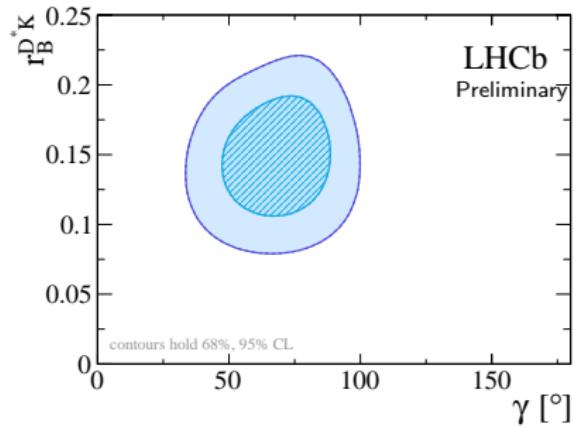
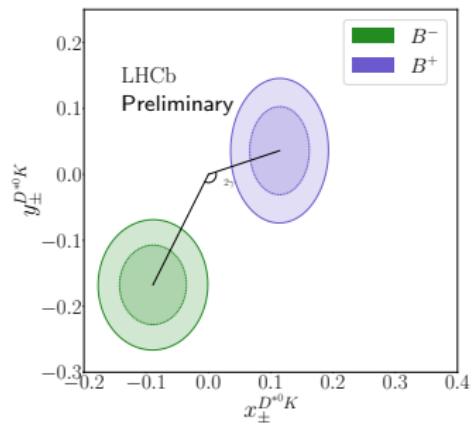
# $B$ decays to excited $D^*$ final states



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- Good agreement between individual bin asymmetries and the combined  $CP$  fit
- Bin asymmetries between  $D^* \rightarrow D\pi^0$  and  $D^* \rightarrow D\gamma$  are generally opposite in sign

# $B$ decays to excited $D^*$ final states



LHCb-PAPER-2023-012

These results provide strong constraints on  $\gamma$ :

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

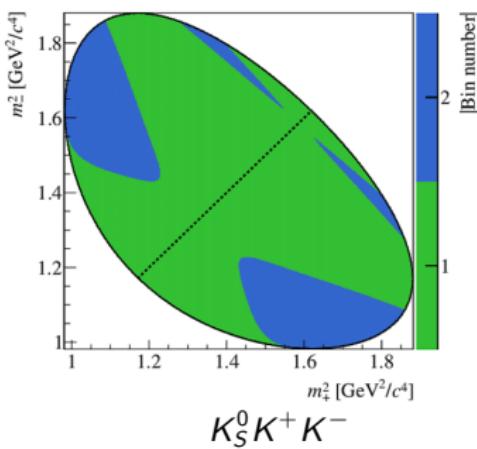
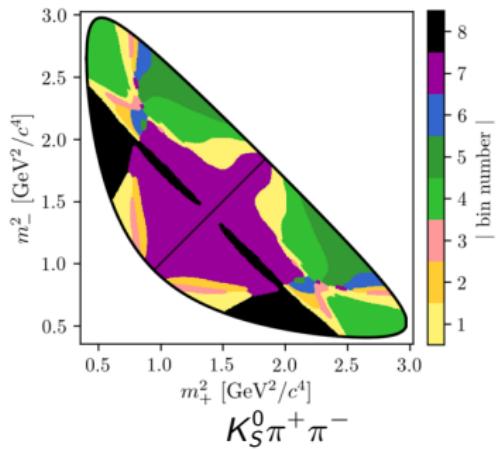
Binned four-body decay:  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$

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A journey through five dimensions

# Binned four-body decay: $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$

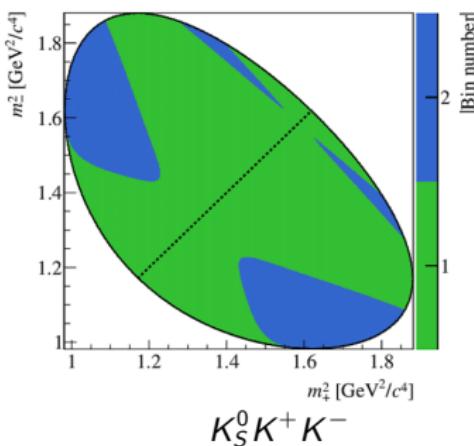
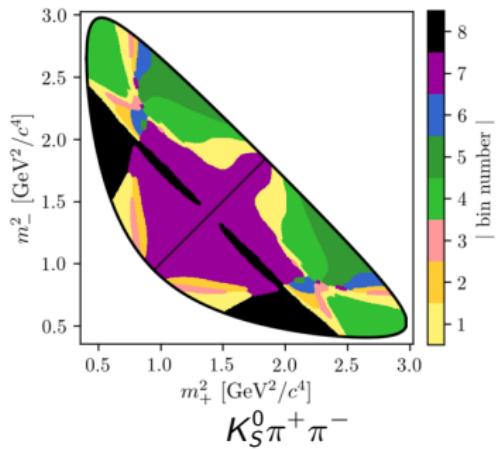
Back to  $D^0 \rightarrow K_S^0 h^+ h^-$  binning schemes, visualised on a Dalitz plot:



- Bin boundaries are optimised for sensitivity to  $\gamma$  by CLEO
- We would like to do this for  $D^0 \rightarrow K^+ K^- \pi^+ \pi^- \dots$

# Binned four-body decay: $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$

Back to  $D^0 \rightarrow K_S^0 h^+ h^-$  binning schemes, visualised on a Dalitz plot:



- Bin boundaries are optimised for sensitivity to  $\gamma$  by CLEO
- We would like to do this for  $D^0 \rightarrow K^+ K^- \pi^+ \pi^- \dots$
- ... but the four-body phase space is five-dimensional!

Binned four-body decay:  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$

But how do we navigate through a 5D space?



Use an amplitude model! JHEP **02** (2019) 126

Ultimately, the charm strong-phase differences will be measured directly at BESIII, and the  $\gamma$  measurement will be model independent

Binned four-body decay:  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$

A binning scheme must satisfy the following:

- Minimal dilution of strong phases when integrating over bins
- Enhance interference between  $B^\pm \rightarrow D^0 K^\pm$  and  $B^\pm \rightarrow \bar{D}^0 K^\pm$

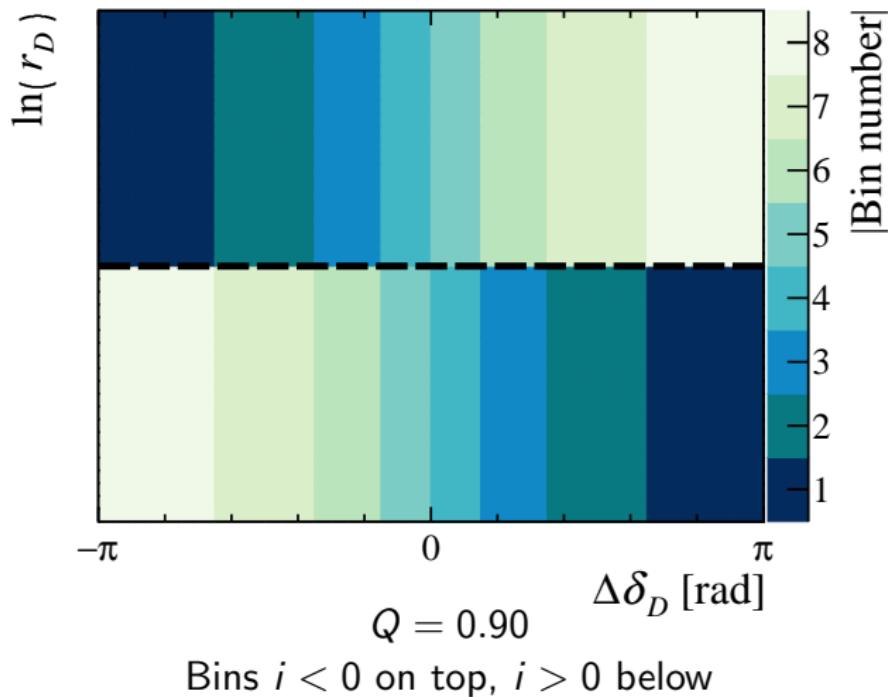
How to bin a 5-dimensional phase space?

- ① For each  $B^\pm$  candidate, use the amplitude model to calculate

$$\frac{\mathcal{A}(D^0)}{\mathcal{A}(\bar{D}^0)} = r_D e^{i\delta_D}$$

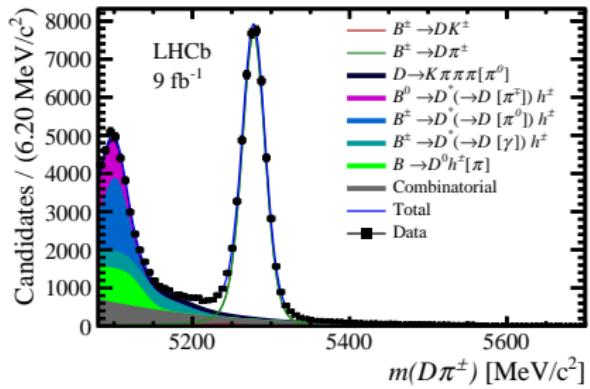
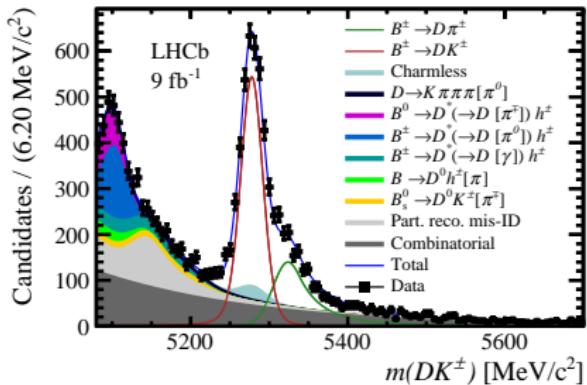
- ② Split  $\delta_D$  into uniformly spaced bins
- ③ Use the symmetry line  $r_D = 1$  to separate bin  $+i$  from  $-i$
- ④ Optimise the binning scheme by adjusting the bin boundaries in  $\delta_D$

# Binning scheme



# Phase-space binned $B^\pm \rightarrow [K^+ K^- \pi^+ \pi^-]_D K^\pm$

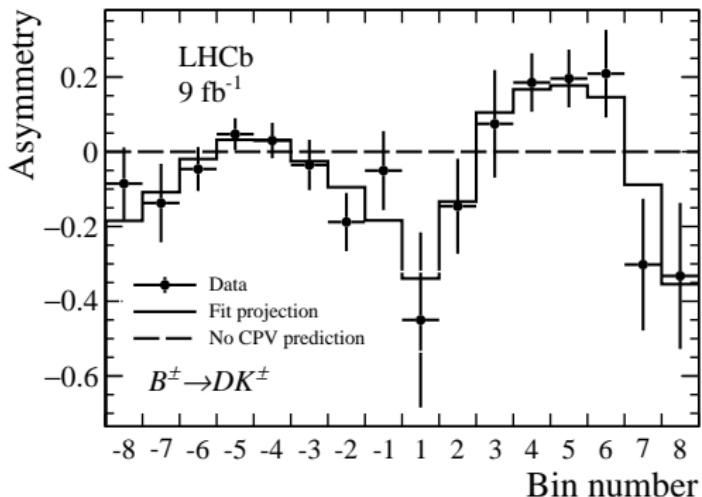
Fully charged final state  $\implies$  Highly suitable for LHCb



Eur. Phys. J. C 83, 547 (2023)

- $B^\pm \rightarrow [K^+ K^- \pi^+ \pi^-]_D h^\pm$  signal yield:
  - $B^\pm \rightarrow DK^\pm$ :  $3026 \pm 38$
  - $B^\pm \rightarrow D\pi^\pm$ :  $44349 \pm 218$

# Phase-space binned $B^\pm \rightarrow [K^+ K^- \pi^+ \pi^-]_D K^\pm$



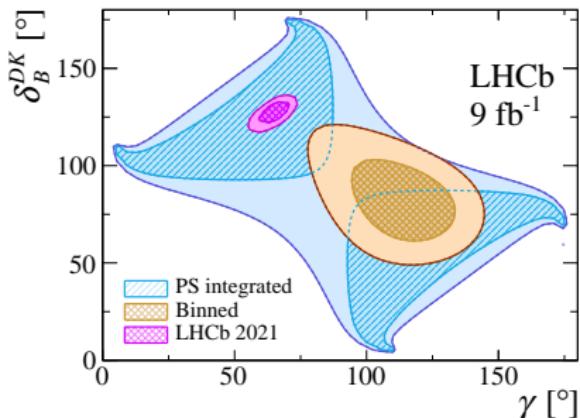
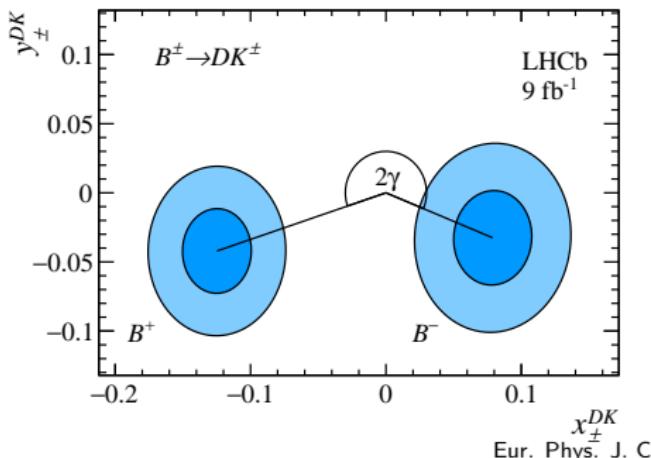
Eur. Phys. J. C 83, 547 (2023)

- Clear bin asymmetries are seen, and the non-trivial distribution is driven by the change in strong-phase differences across phase space
- While the interpretation of  $\gamma$  require charm inputs, the observed bin asymmetries are model independent

# Phase-space binned $B^\pm \rightarrow [K^+ K^- \pi^+ \pi^-]_D K^\pm$

From the phase-space binned asymmetries, we obtain:

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



These results are model dependent, and will be updated once BESIII  
strong-phase inputs are available

# The angle $\gamma$ of the Cabibbo-Kobayashi-Maskawa ansatz

Almost at the end of this seminar, but not the end of the journey!

# Future prospects

## Future prospects:

- The measurements presented today will make valuable improvements to future  $\gamma$  combinations
- Several interesting Run 1+2 results are in the pipeline:
  - ① Update of  $B^\pm \rightarrow [K^+ K^- \pi^+ \pi^-]_D h^\pm$  with charm inputs from BESIII
  - ② Two-body results from  $B^0 \rightarrow D K^{*0}$  could shed light on the (slight) tension between  $B^0$  and  $B^\pm$
  - ③ Time-dependent measurements, such as  $B_s^0 \rightarrow D_s^- K^+$  with Run 2, will be interesting to compare with results from  $B^\pm/B^0$
- LHCb, during Run 3 and 4, anticipates to collect five times more data
  - $\gamma$  is still dominated by statistical uncertainties!

# Summary and future prospects

## In summary:

- ① Long journey towards a precise determination of  $\gamma$
- ② Two recent results of  $B^\pm \rightarrow D^* h^\pm$  and  $B^0 \rightarrow DK^{*0}$  with  $D \rightarrow K_S^0 h^+ h^-$ , using external inputs from BESIII
  - Unique synergy between beauty and charm factories
- ③ A binned measurement with the channel  $B^\pm \rightarrow [K^+ K^- \pi^+ \pi^-]_D K^\pm$  has been performed for the first time
  - Need external inputs for charm strong-phases from BESIII
- ④ LHCb is on track to reach a  $1^\circ$  precision after Run 3 and 4!

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Thanks for your attention!