

The angle γ 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



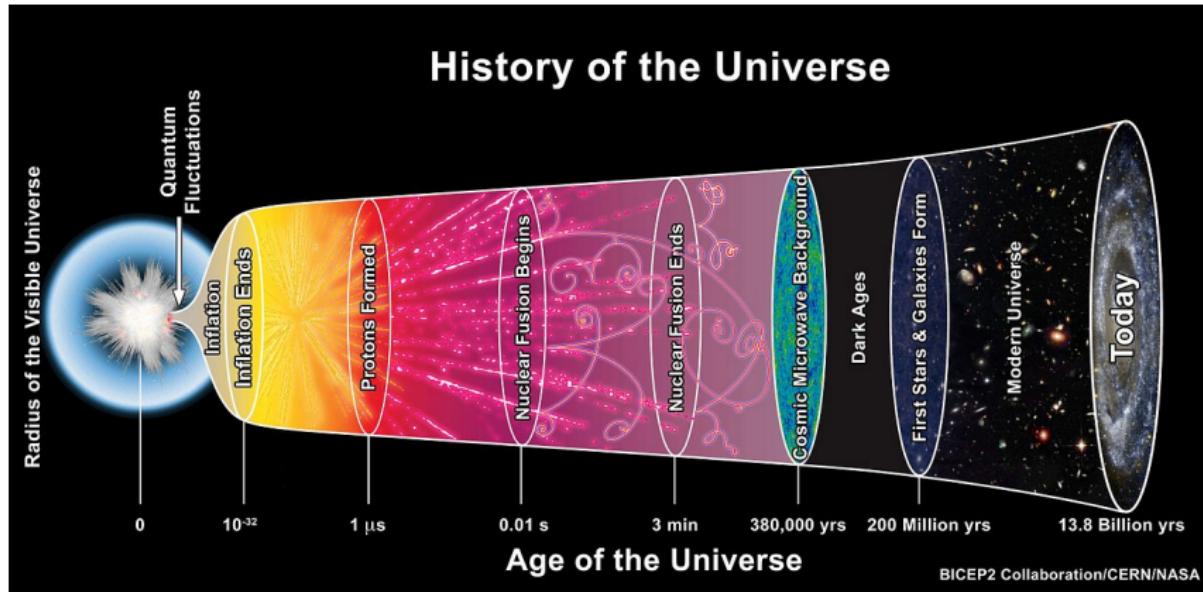
Plan for this seminar:

- ① Overview of LHCb's current γ determinations
- ② The combination of γ measurements to date (Run 1 and 2)
- ③ New Run 1 and 2 results:
 - $B^0 \rightarrow DK^*$, $D \rightarrow K_S^0 h^+ h^-$
 - $B^\pm \rightarrow D^* h^\pm$, $D \rightarrow K_S^0 h^+ h^-$
 - $B^\pm \rightarrow Dh^\pm$, $D \rightarrow K^+ K^- \pi^+ \pi^-$
- ④ Future prospects (Run 3 and beyond)

Introduction to CP violation

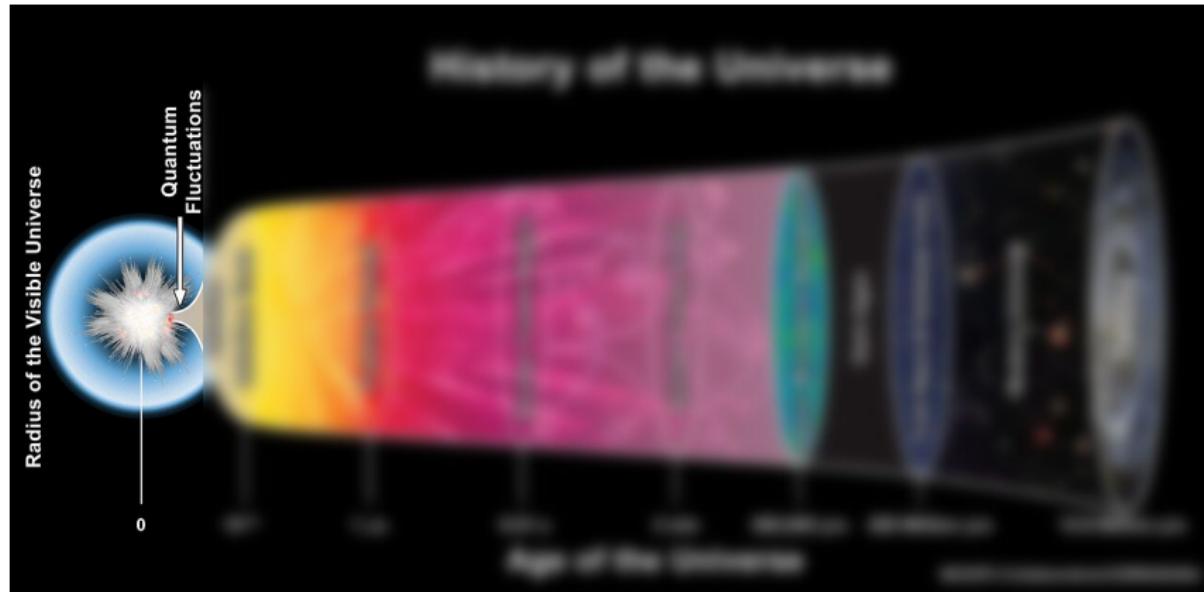
What is γ and why measure it?

Big Bang and matter-antimatter asymmetry



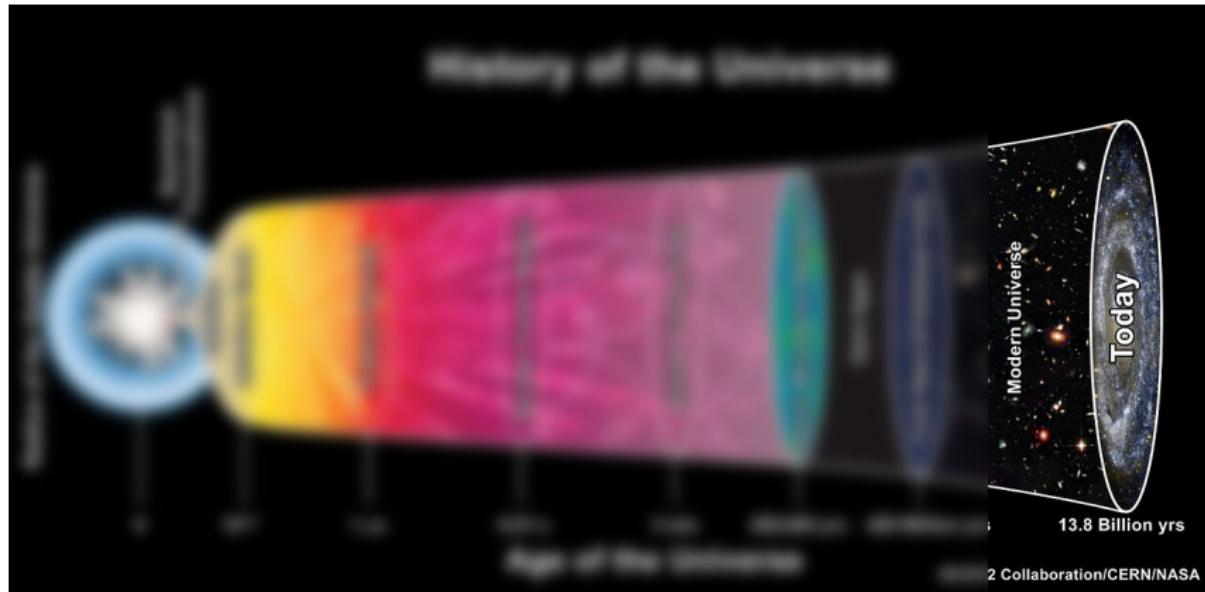
Where is the antimatter in the universe?

Big Bang and matter-antimatter asymmetry



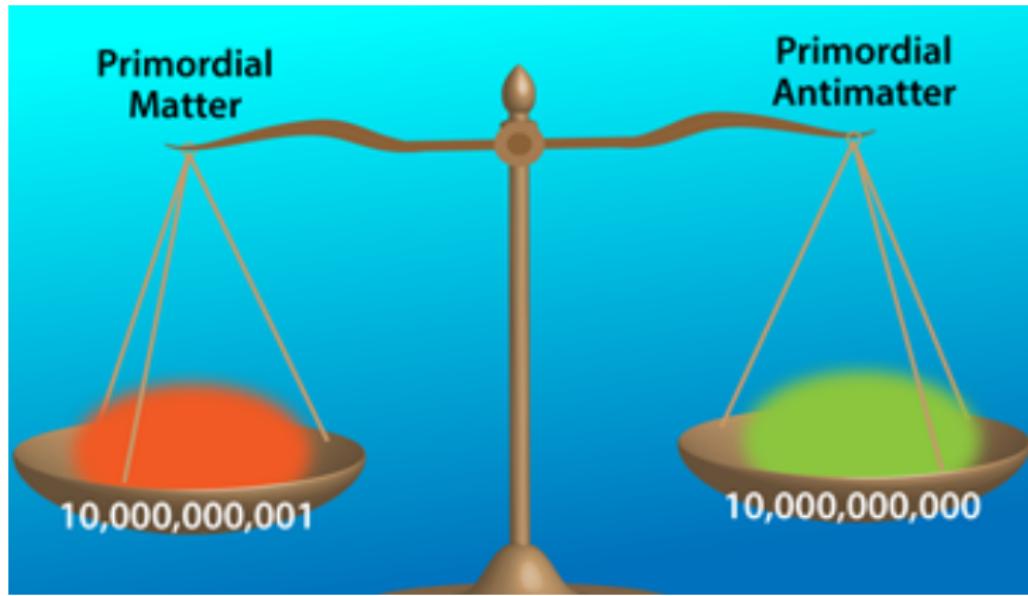
Initially equal amounts of matter and antimatter...

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

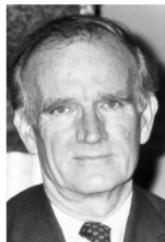


Photo from the Nobel Foundation archive.
Val Logsdon Fitch

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"

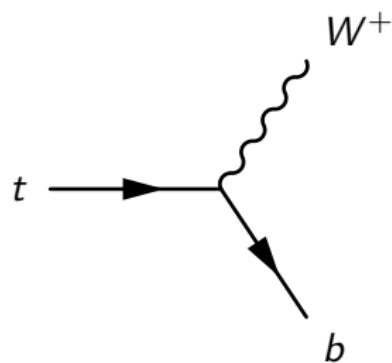
- CP violation discovery in 1964
- Phys. Rev. Lett. **13**, 138
- Observed $K_L^0 \rightarrow \pi^+ \pi^-$
- Since, CP violation has also been observed in the B , B_s and D systems

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

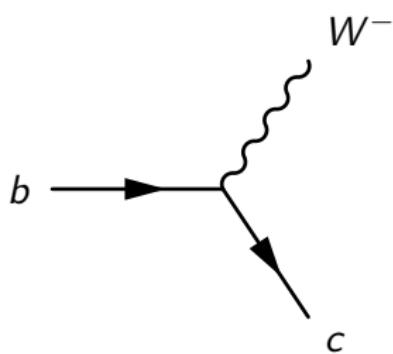
The CKM matrix and the Unitary Triangle

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_{CKM} has a single complex phase that is responsible for all CPV in SM

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

Expand V_{CKM} to first order in CPV terms: Wolfenstein parameterisation
Assume $\lambda \equiv \sin(\theta_c)$ is small

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

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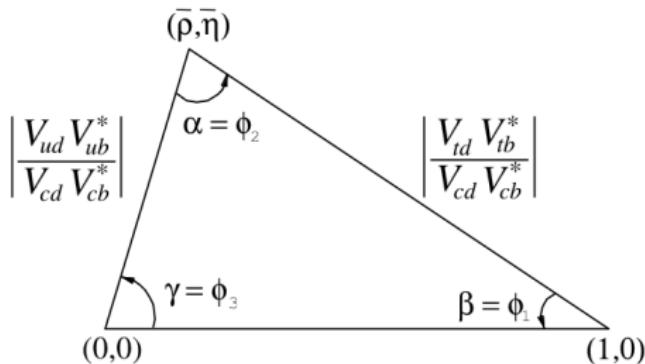
In SM, with only 3 generations of quarks, V_{CKM} must be unitary
This gives us 9 constraints, one of which is:

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

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 2×2 rotation matrix
- The additional complex phase in V_{CKM} matrix explains CPV in SM
- This also predicted the third generation of quarks, which were discovered later

We must verify if V_{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:
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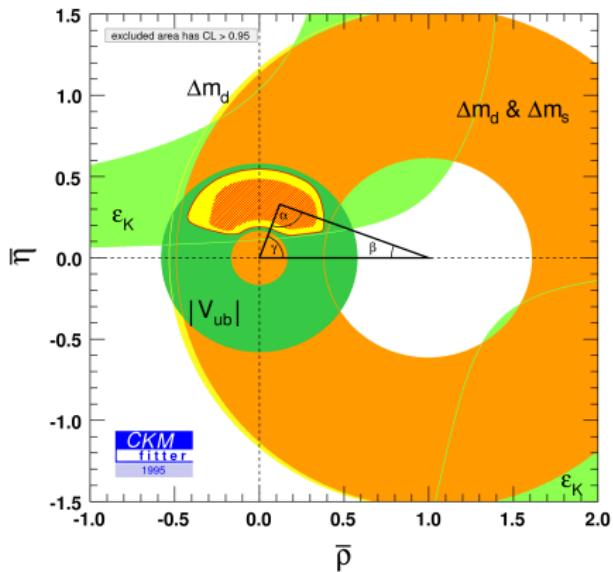
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Precise knowledge of quark interactions will help us search for new physics with CPV, which may not have the same CKM structure

The CKM matrix and the Unitary Triangle

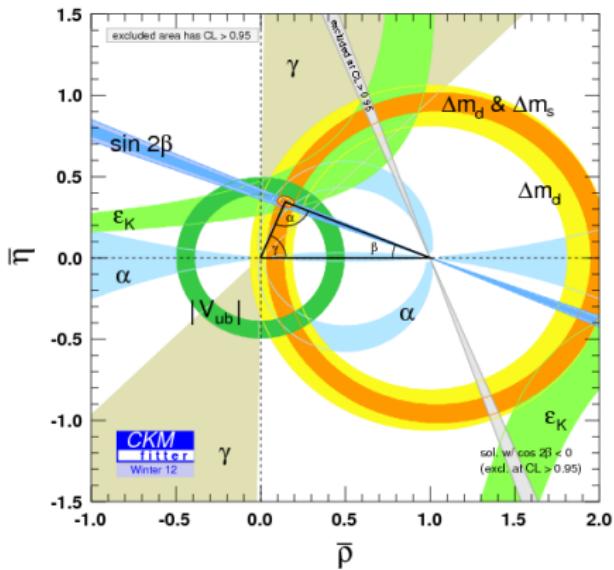
Before Belle and BaBar, the Unitary Triangle was poorly constrained



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

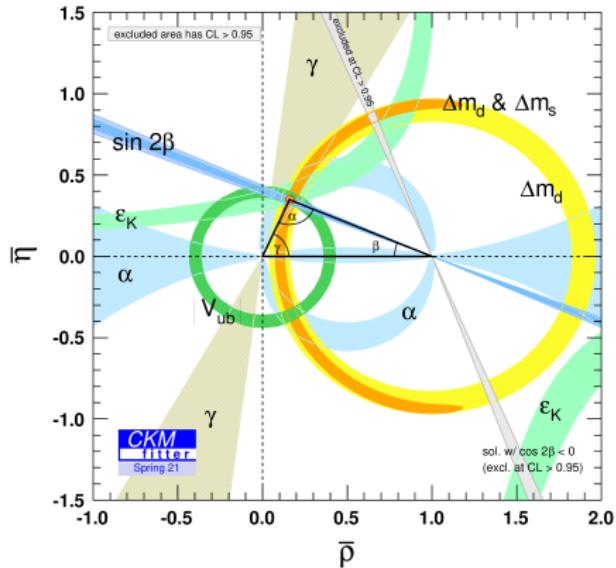
Huge progress by b-factories, but γ is the least precisely measured angle...



CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005), updated results and plots available at:
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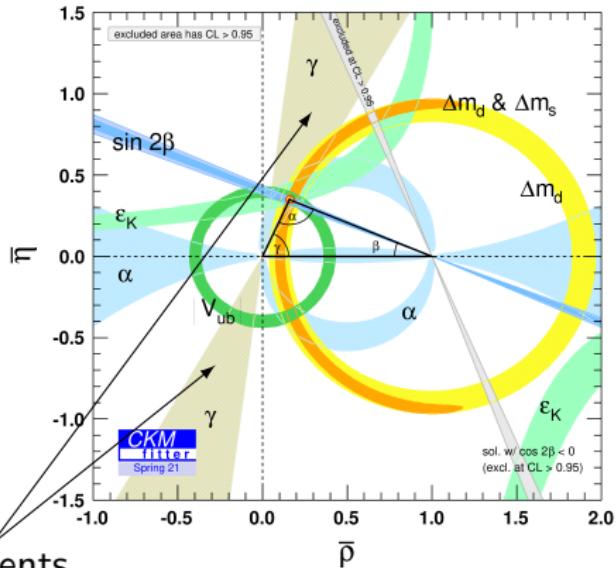
... but with LHCb, this is no longer the case!



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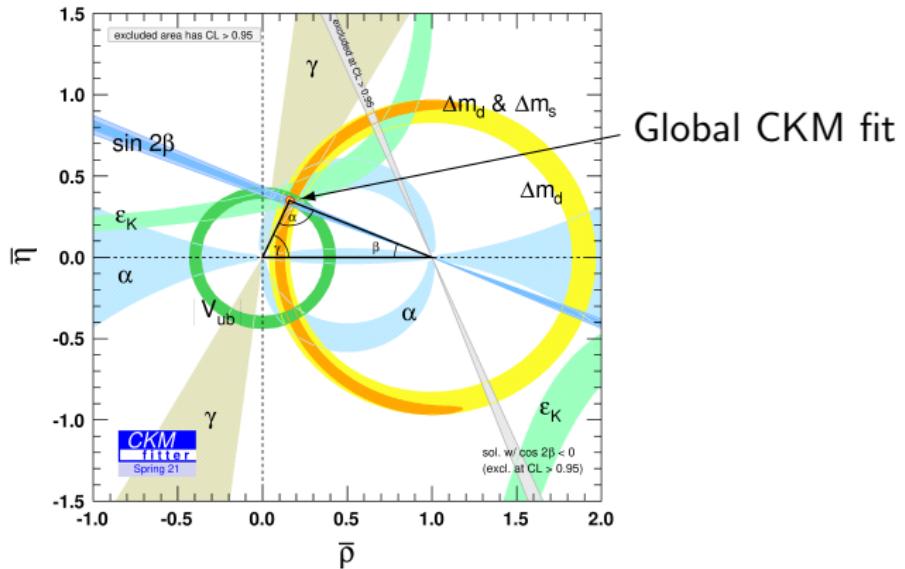


Direct γ measurements

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

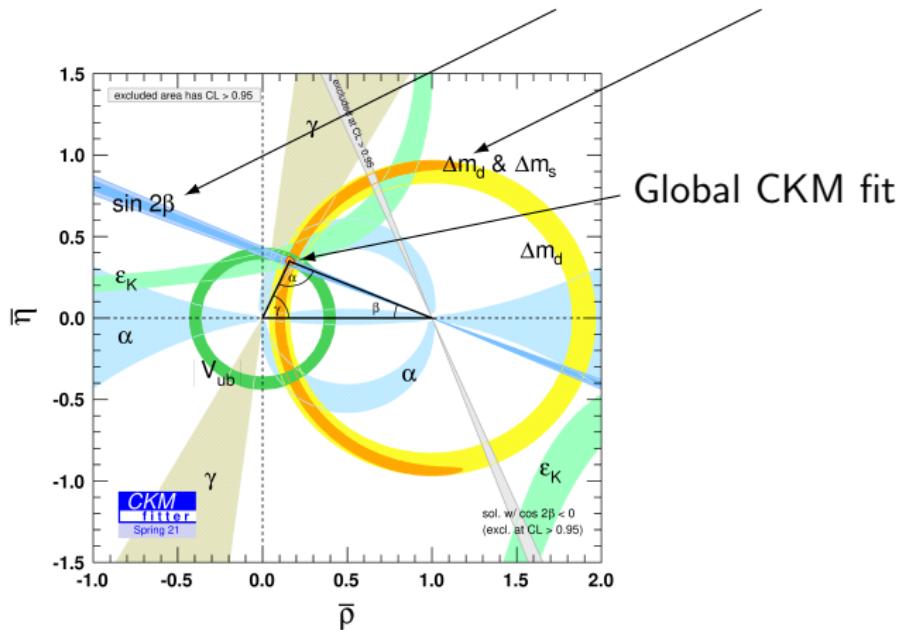
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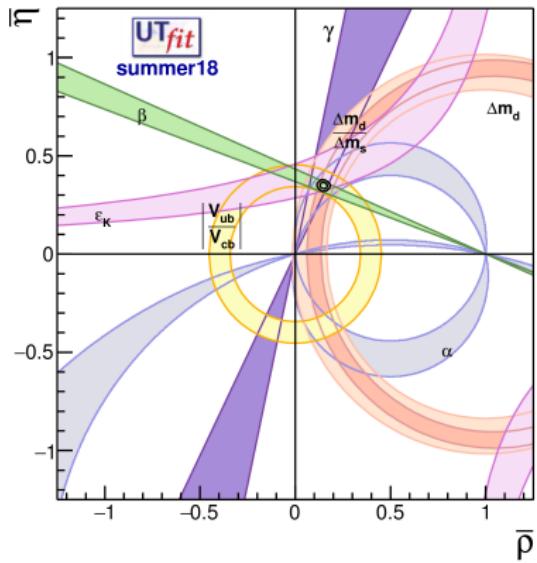
Loop level measurements of γ are dominated by $\sin(2\beta)$ and B^0/B_s^0 mixing



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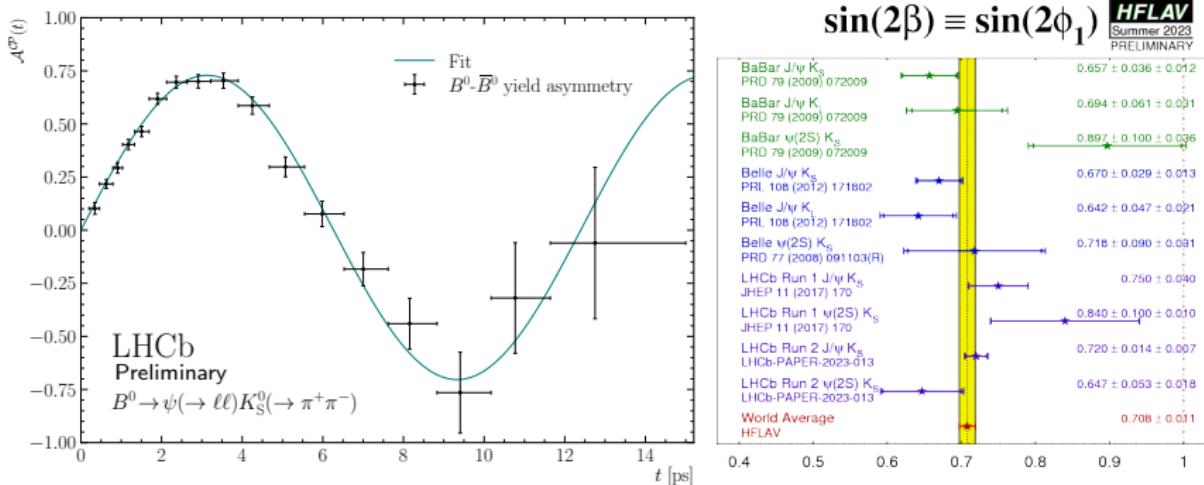
The CKM matrix and the Unitary Triangle

Similar global fits have also been performed by UTfit, with similar results



The CKM matrix and the Unitary Triangle

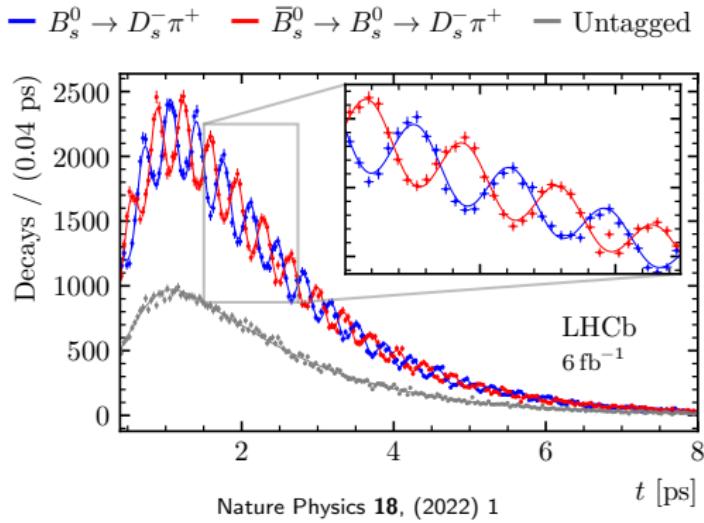
LHC seminar by P. Li and V. Jevtic on 13th June 2023:
Single most precise measurement of $\sin(2\beta)$



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:

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

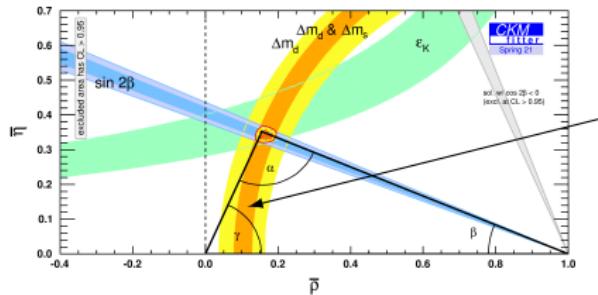
The CKM matrix and the Unitary Triangle

Why is the CKM angle γ 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

The CKM matrix and the Unitary Triangle

Why is the CKM angle γ of interest?



Dominated by
lattice QCD

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:
<http://ckmfitter.in2p3.fr>

With precise γ measurements, we can compare with the indirect loop level measurements, which assume unitarity ("SM prediction")

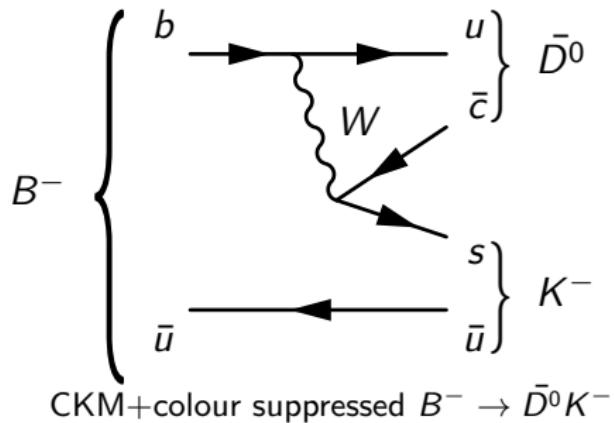
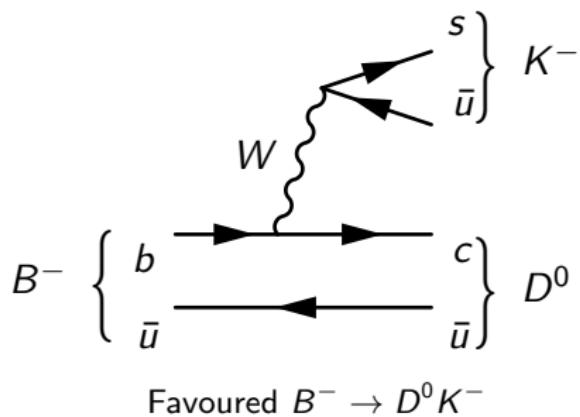
How to measure γ ?

How to measure γ ?

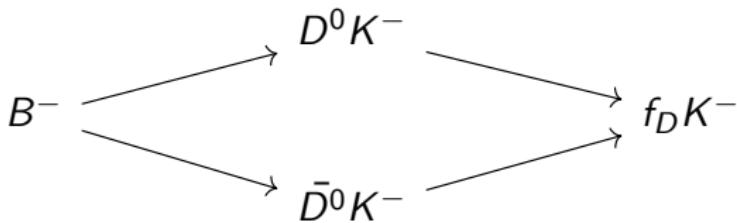
It's all about interferences!

Sensitivity through interference

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

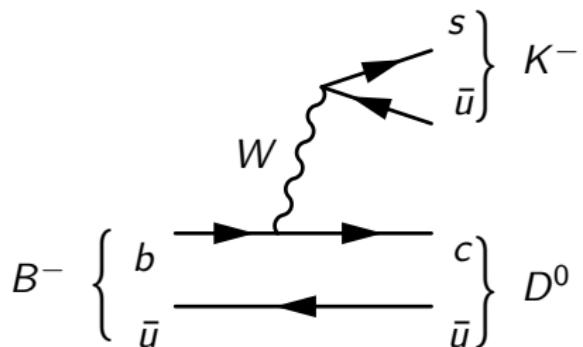


Interference when D^0 and \bar{D}^0 decay to a common final state f_D

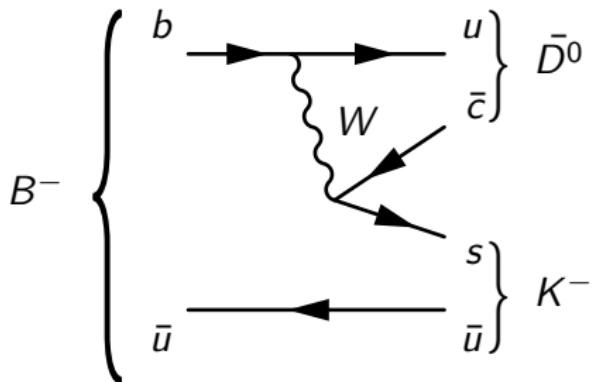


Sensitivity through interference

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



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



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

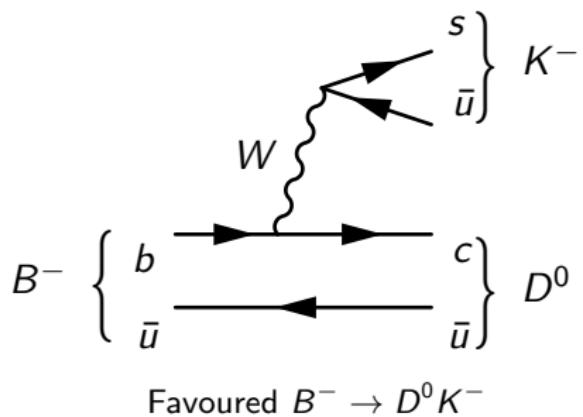
$b \rightarrow u\bar{c}s$ and $b \rightarrow c\bar{u}s$ interference \rightarrow Sensitivity to γ

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

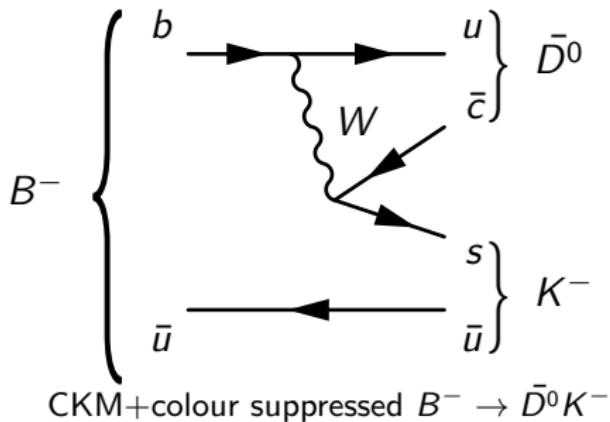
$$\mathcal{A}(B^+) = \mathcal{A}_B (\mathcal{A}_{\bar{D}^0} + r_B e^{i(\delta_B + \gamma)} \mathcal{A}_{D^0})$$

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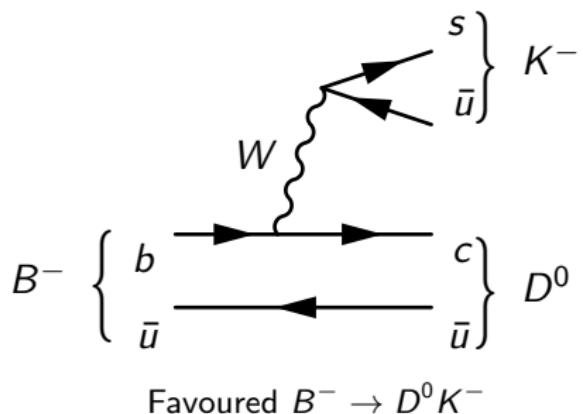
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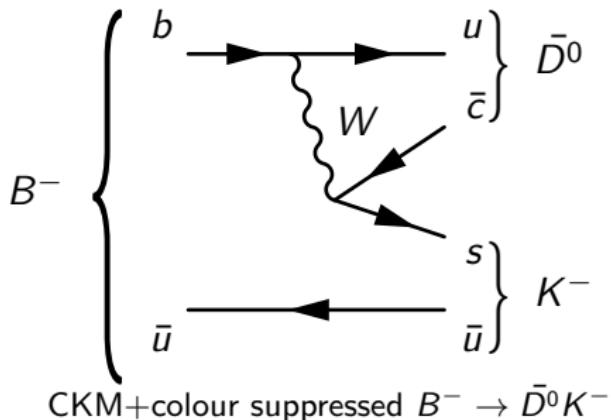
The magnitude of interference effects governed by $r_B \approx 0.1$

Sensitivity through interference

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



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

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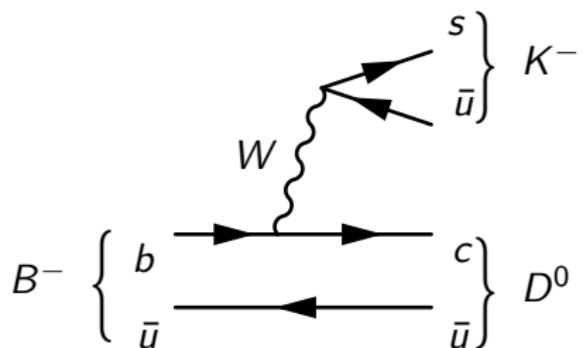
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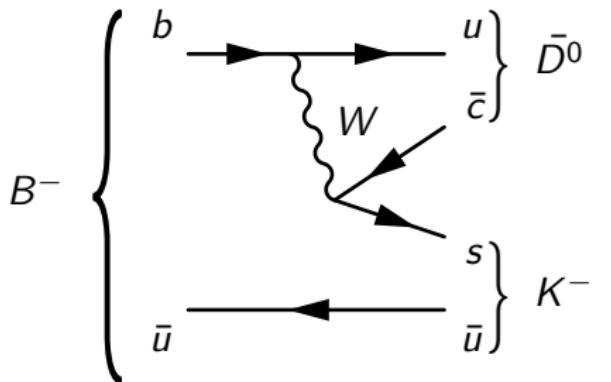
The strong-phase difference δ_B accounts for all unknown QCD phase shifts

Sensitivity through interference

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



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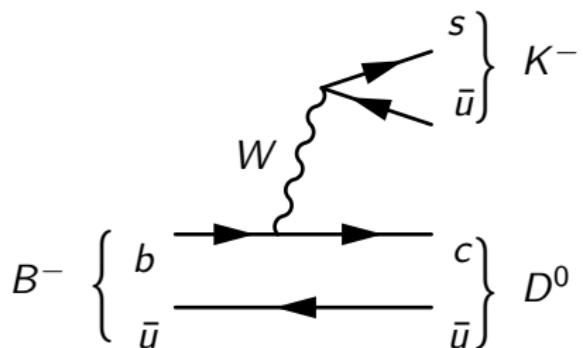
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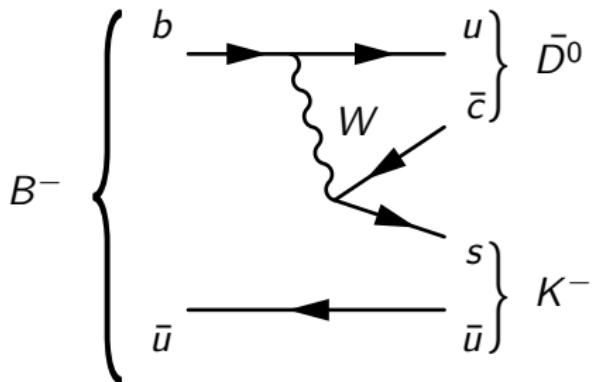
The weak phase γ swaps sign under CP

Sensitivity through interference

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



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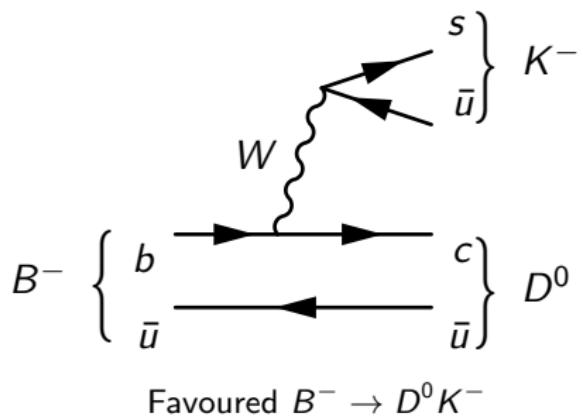
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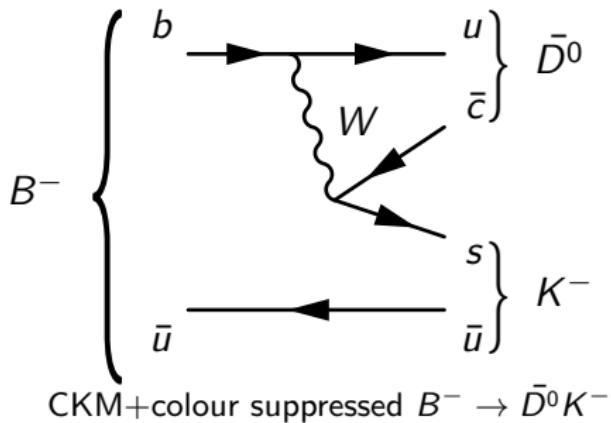
γ, r_B, δ_B are free parameters \implies No need for inputs from theory

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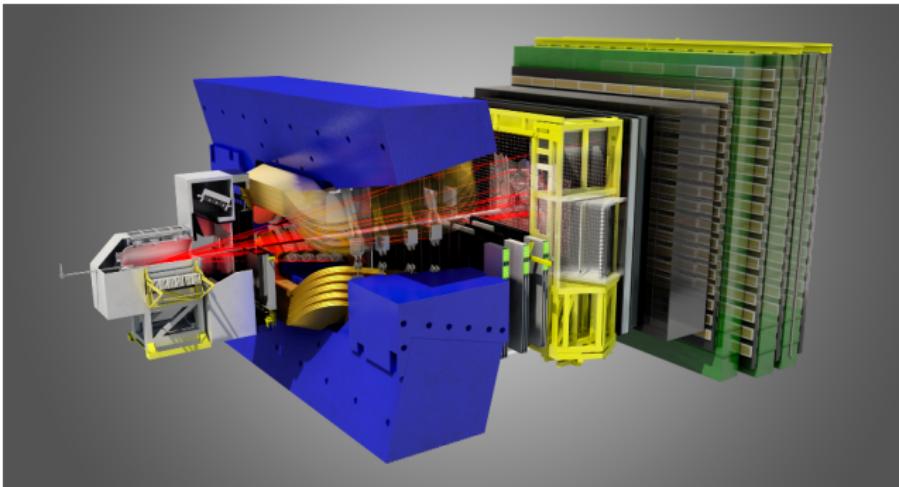
$$\mathcal{A}(B^+) = \mathcal{A}_B (\mathcal{A}_{\bar{D}^0} + r_B e^{i(\delta_B + \gamma)} \mathcal{A}_{D^0})$$

Note: Even at tree level, BF is $3.6 \times 10^{-4} \implies$ Very challenging!

The LHCb detector

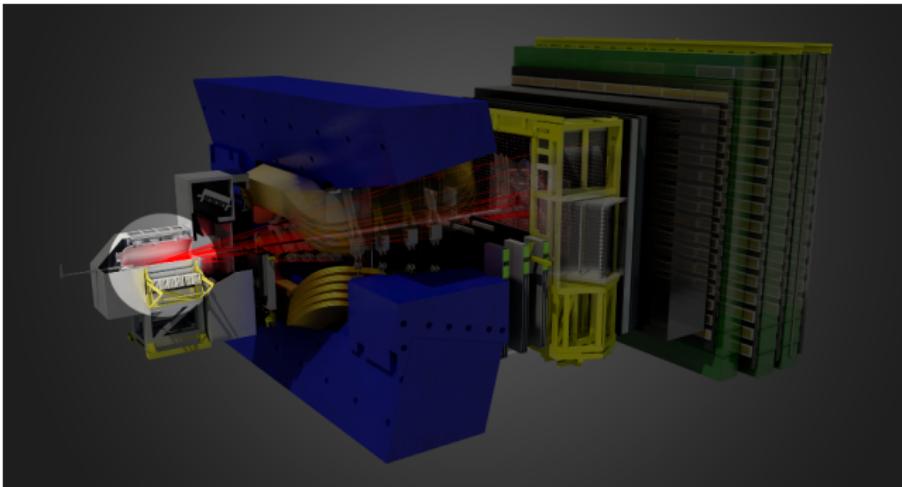
(Original Run 1 and 2 detector)

The LHCb detector



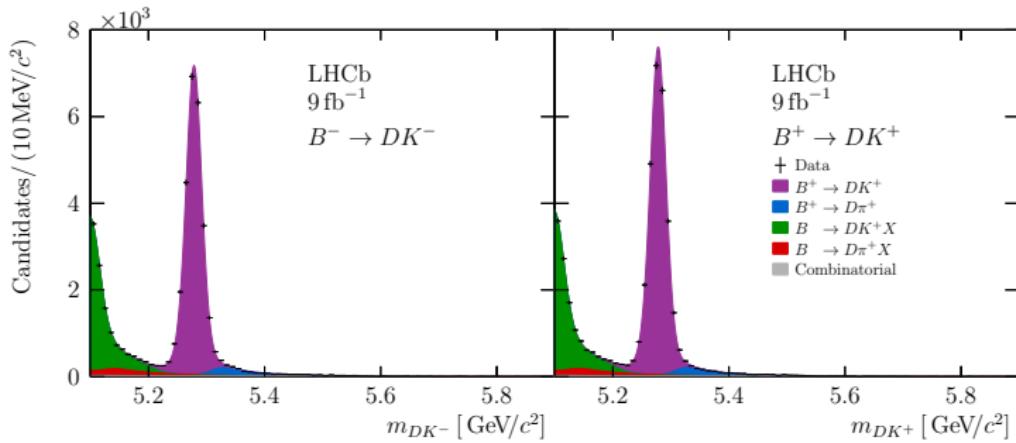
LHCb: A beauty experiment with a lot of charm

The LHCb detector



VELO: Vertex locator to reconstruct B and D vertices

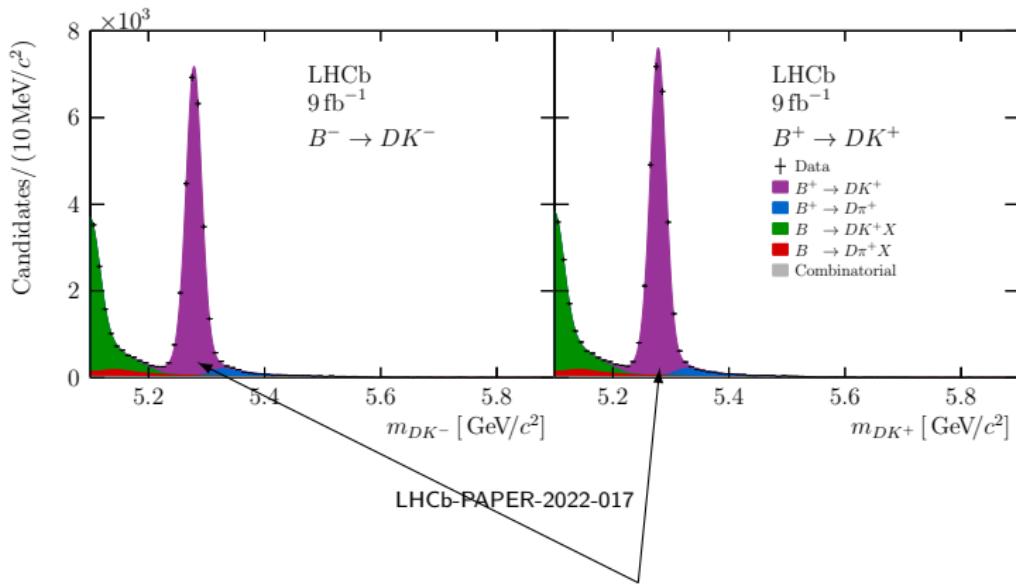
The LHCb detector



LHCb-PAPER-2022-017

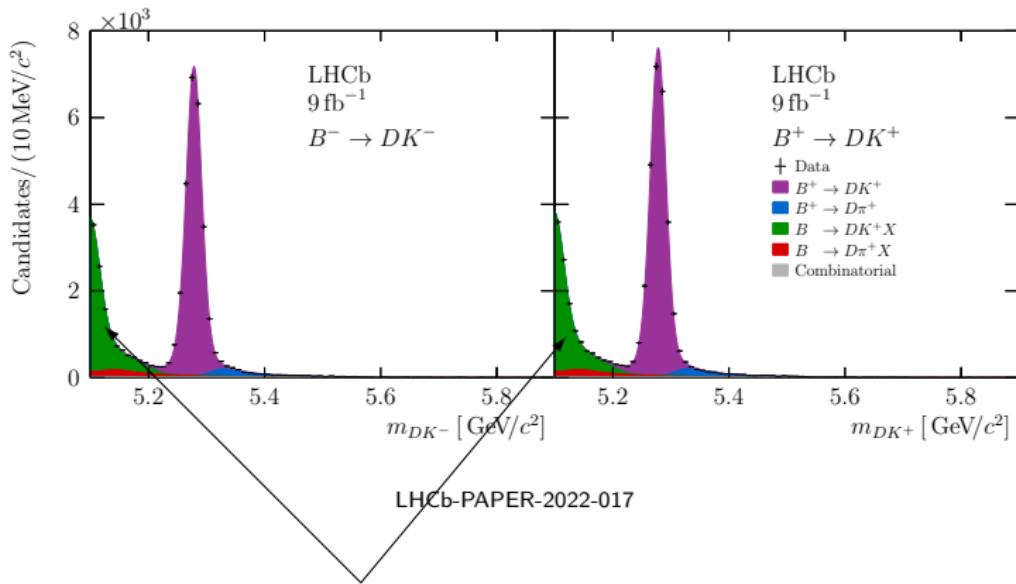
Example of $B^\pm \rightarrow DK^\pm$ selection
 $(D \rightarrow K^-\pi^+\pi^-\pi^+)$

The LHCb detector



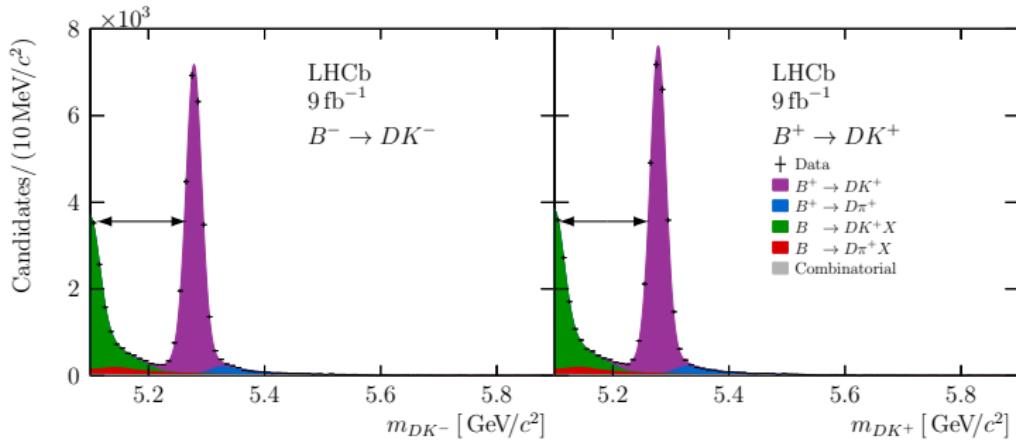
Correctly reconstructed B^\pm candidates
High signal efficiency

The LHCb detector



Partially reconstructed background
 B decays with missing pion or photon

The LHCb detector

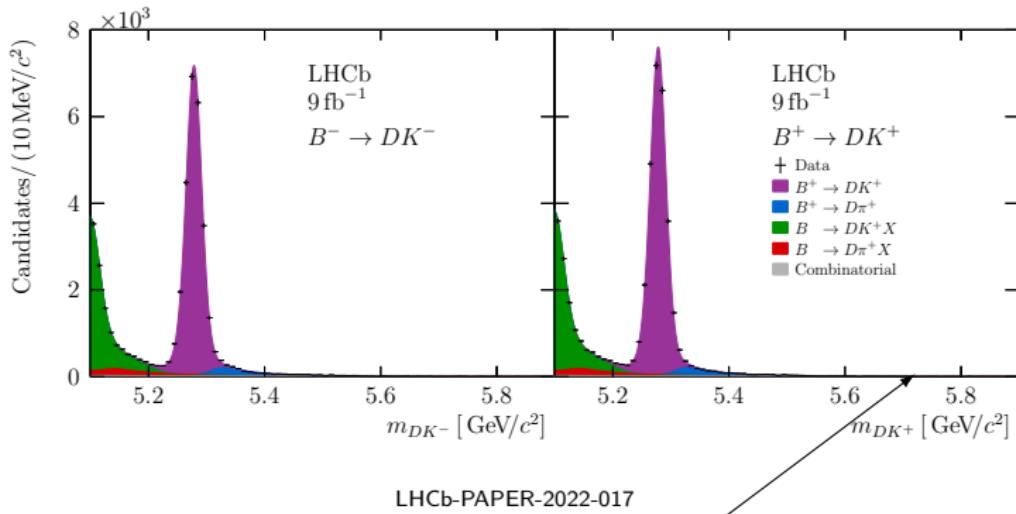


LHCb-PAPER-2022-017

Excellent mass resolution

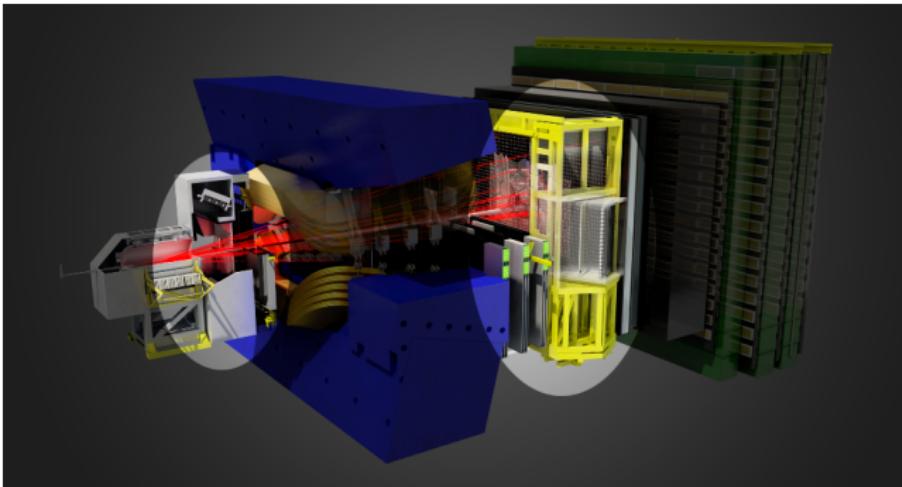
Signal is well separated from partially reconstructed background

The LHCb detector



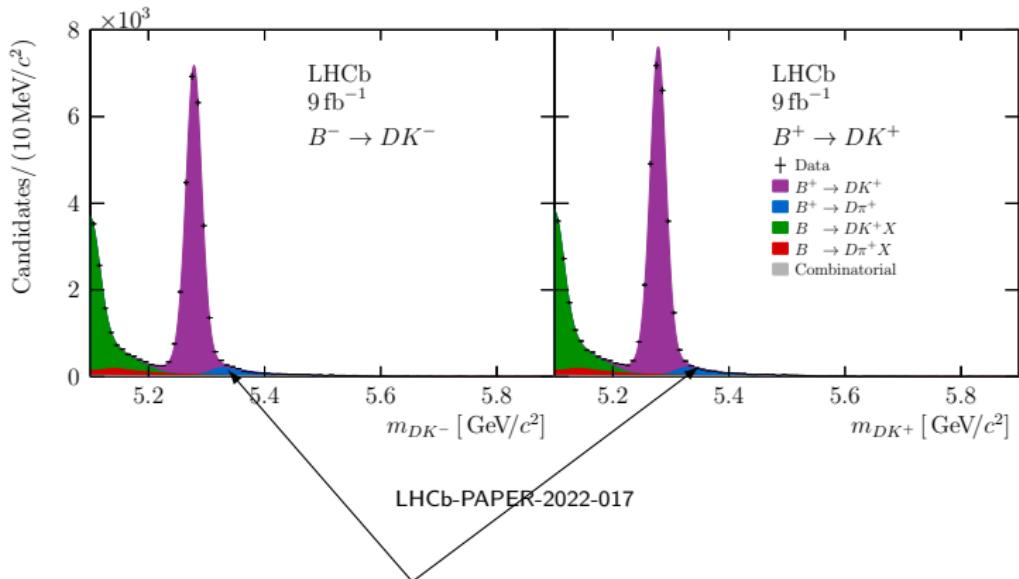
Extremely low combinatorial background
Clean environment at a hadron collider

The LHCb detector



RICH: Identify particles from B and D

The LHCb detector

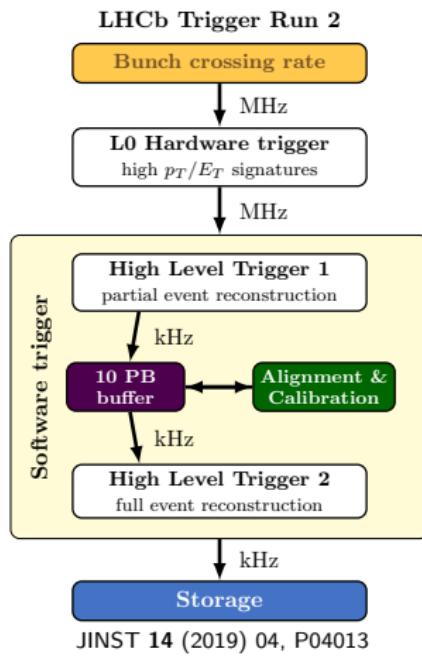


Mis-ID from $B^\pm \rightarrow D\pi^\pm \rightarrow DK^\pm$ is almost negligible
Without PID, this background would be 13 times larger!

The LHCb detector

Trigger: An important part of the LHCb detector

- Reduces rate of collisions saved by three orders of magnitude
- Online reconstruction with real-time calibration
- Turbo stream: Write compact event directly from trigger and discard raw event data
- High efficiency and high purity



Methods for measuring γ

How to interpret asymmetries?

What D final states?

Several methods are used to measure γ precisely

1

2

3

What D final states?

Several methods are used to measure γ precisely

① CP eigenstates (“GLW method”)

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

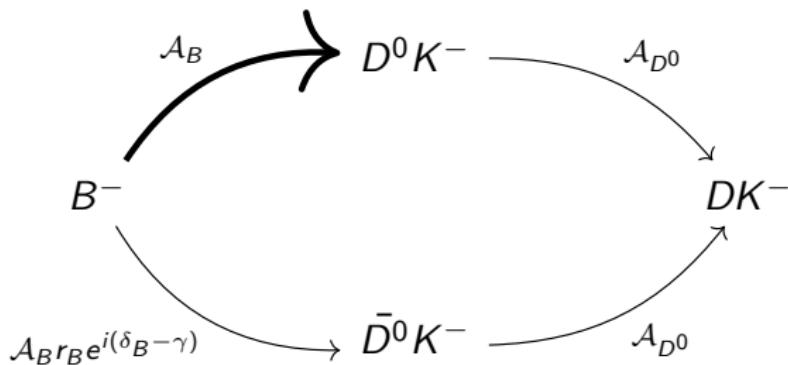
②

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

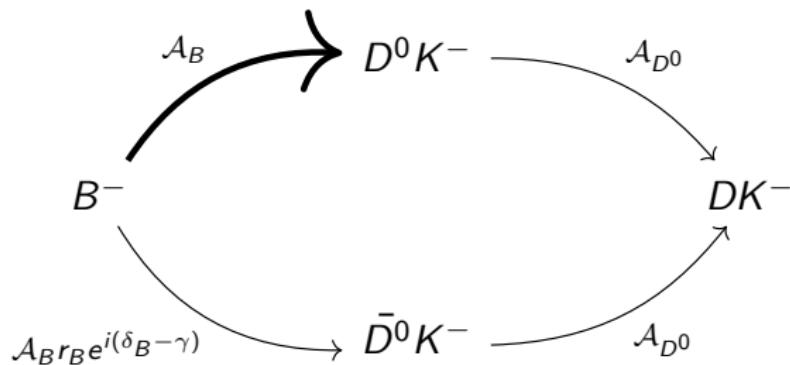


$$|\mathcal{A}(B^-)|^2 \propto 1 + r_B^2 + 2r_B \cos(\delta_B - \gamma)$$

D decays to a CP eigenstate

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

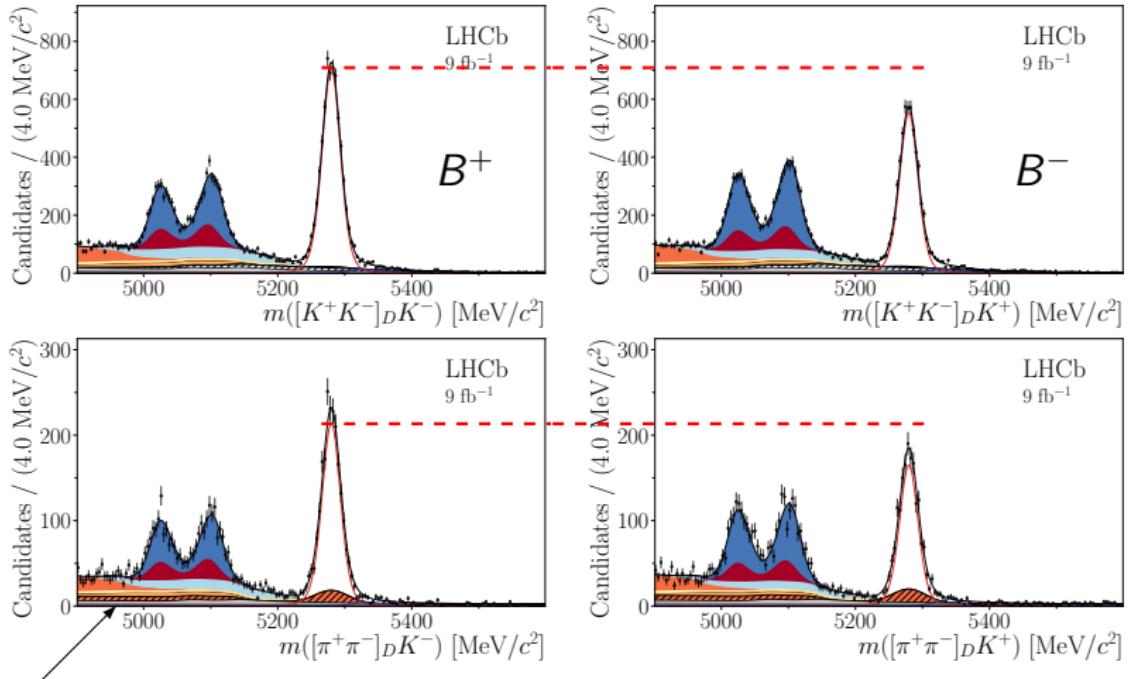
For CP eigenstates, $\mathcal{A}_{D^0} = \mathcal{A}_{\bar{D}^0}$



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

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

D decays to a CP eigenstate



Partially reconstructed background

JHEP 04 (2021) 081

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

What D final states?

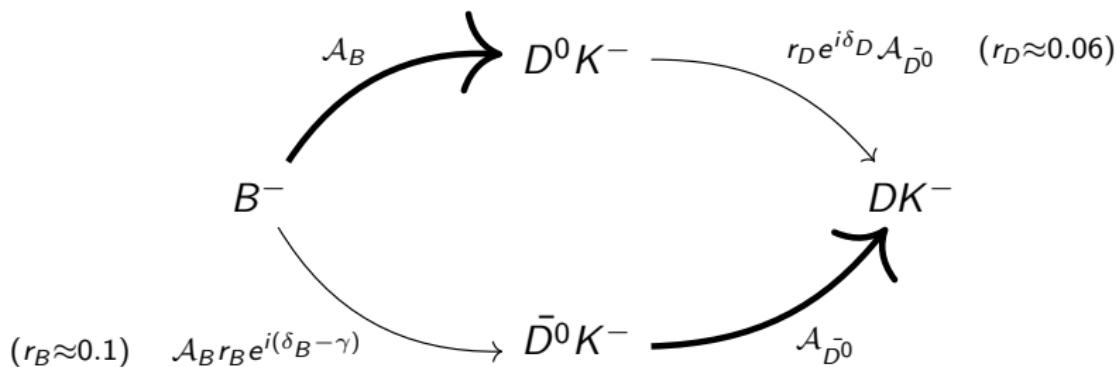
Several methods are used to measure γ precisely

- 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

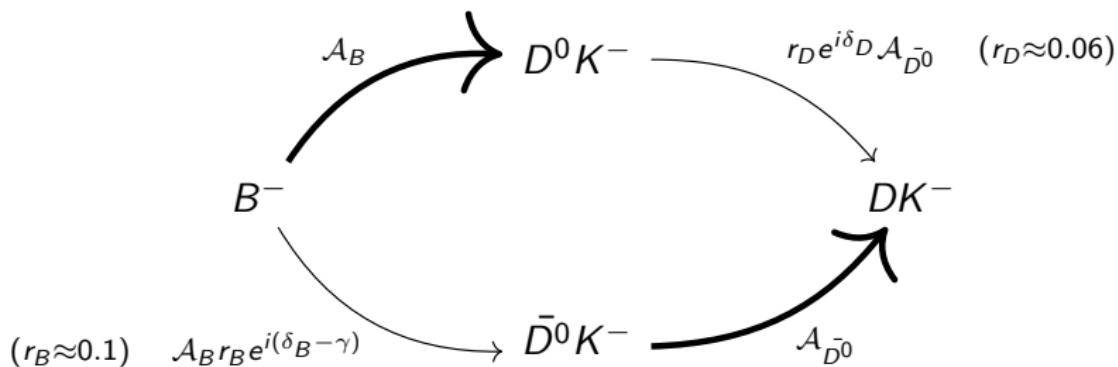


$$|\mathcal{A}(B^-)|^2 \propto r_D^2 + r_B^2 + 2r_B r_D \cos(\delta_B - \gamma + \delta_D)$$

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



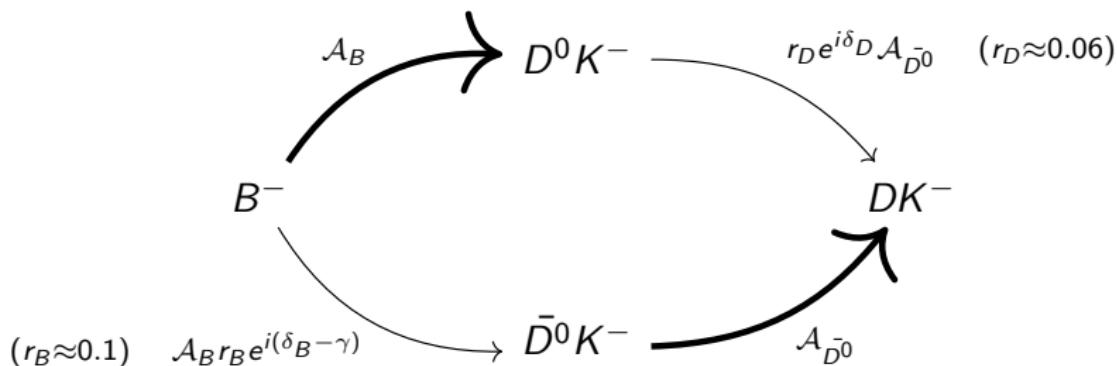
$$|\mathcal{A}(B^-)|^2 \propto r_D^2 + r_B^2 + 2r_B r_D \cos(\delta_B - \gamma + \delta_D)$$

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

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



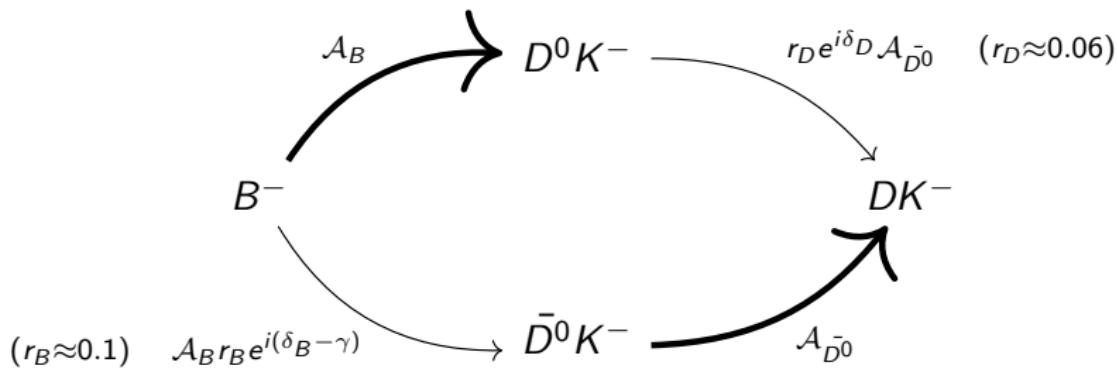
$$|\mathcal{A}(B^-)|^2 \propto r_D^2 + r_B^2 + 2r_B r_D \cos(\delta_B - \gamma + \delta_D)$$

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

Doubly Suppressed Cabibbo D decays

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

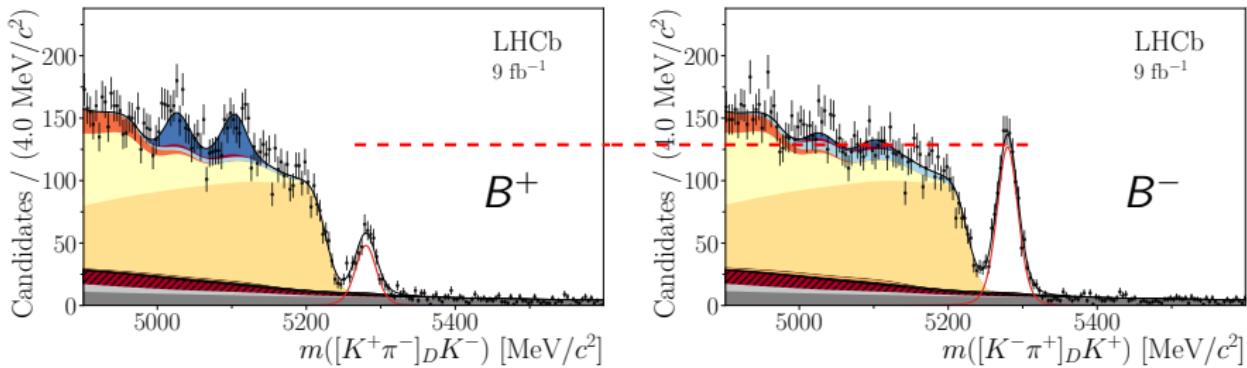
Interference between CF and DCS decays



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

r_D and δ_D can be measured in charm mixing or directly at charm factories

Doubly Suppressed Cabibbo D decays

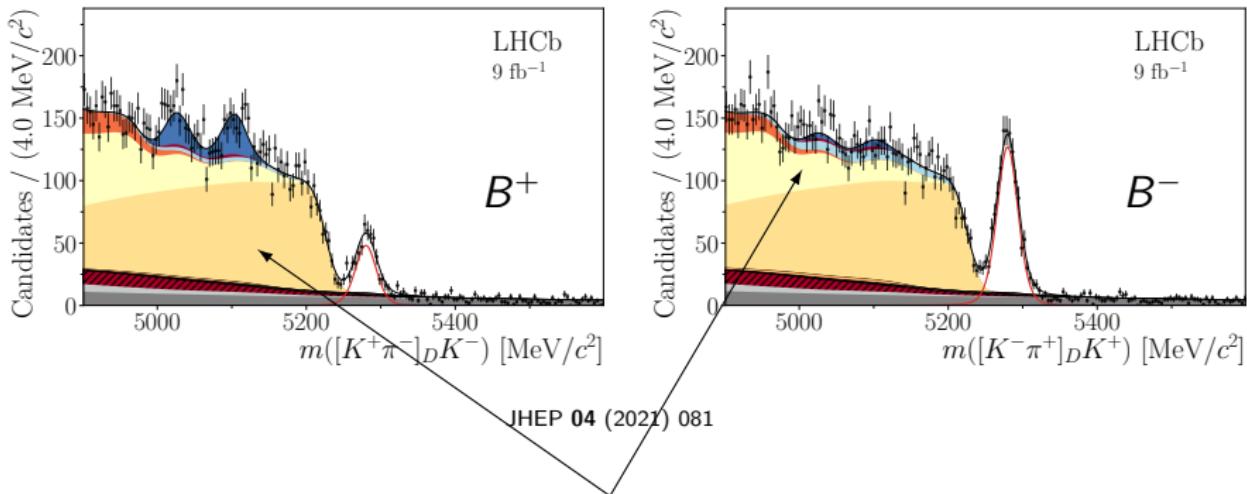


JHEP 04 (2021) 081

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

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

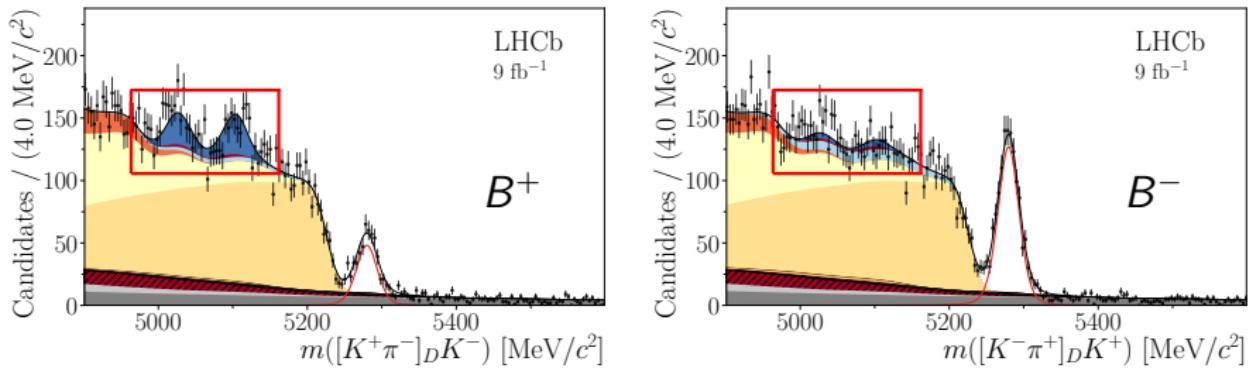
Doubly Suppressed Cabibbo D decays



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

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

Doubly Suppressed Cabibbo D decays

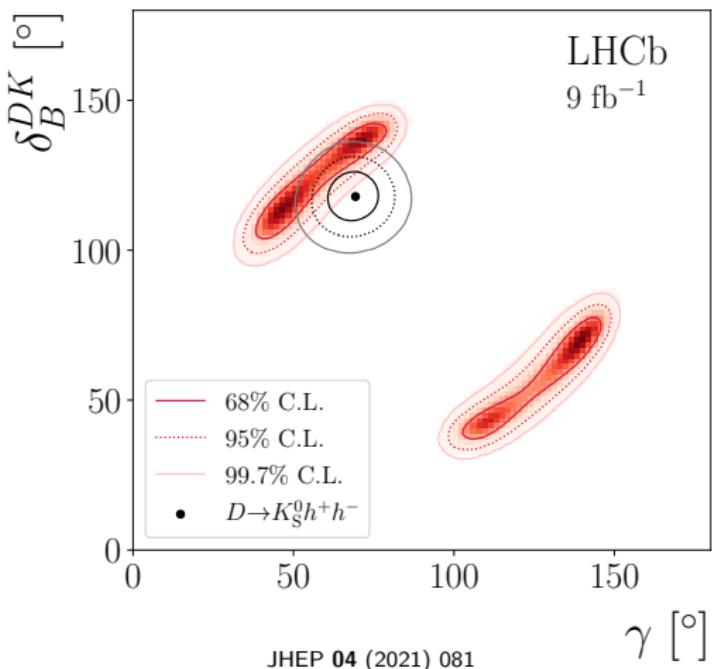


JHEP 04 (2021) 081

Asymmetry is also seen in the double-peaked background

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

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 γ 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

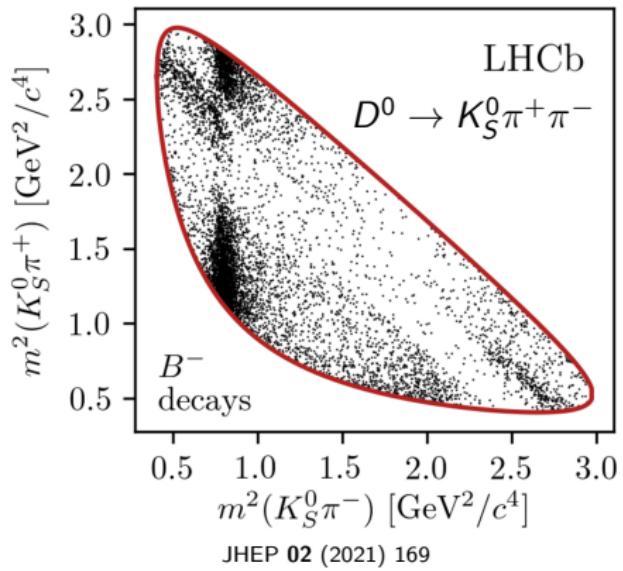
- Multi-body decays can have many intermediate resonances
- Decay amplitudes therefore vary across “phase space”

Degrees of freedom for an N -body decay

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

Multi-body D decays

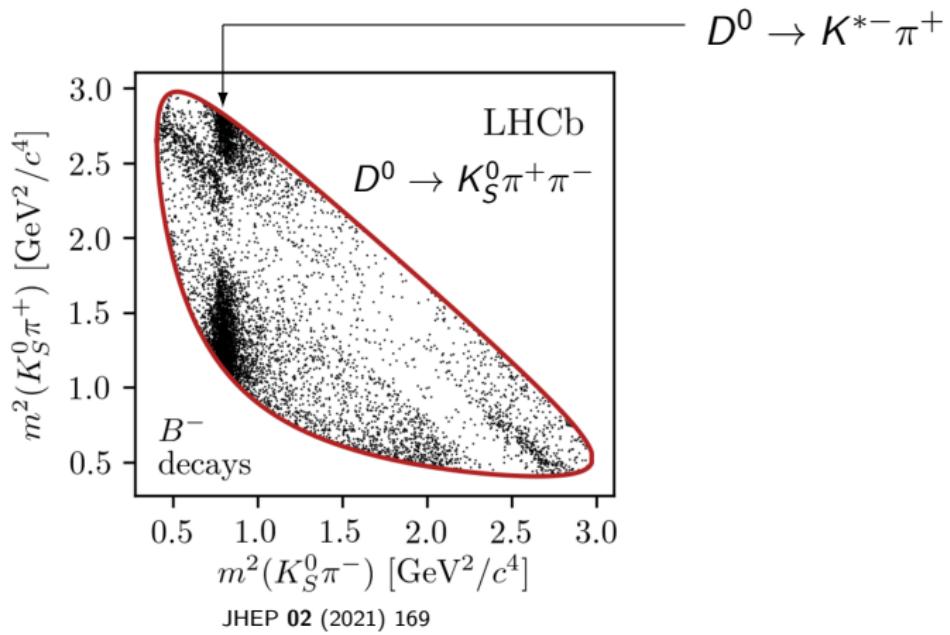
For 3-body decays, phase space is two-dimensional: Dalitz plots



JHEP 02 (2021) 169

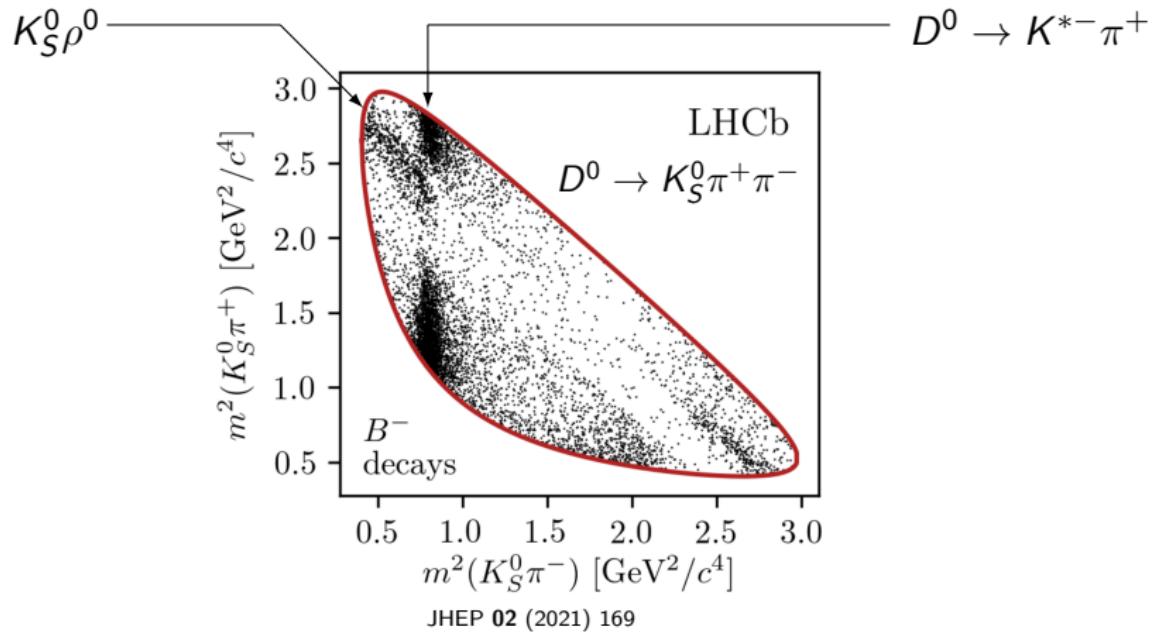
Multi-body D decays

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



Multi-body D decays

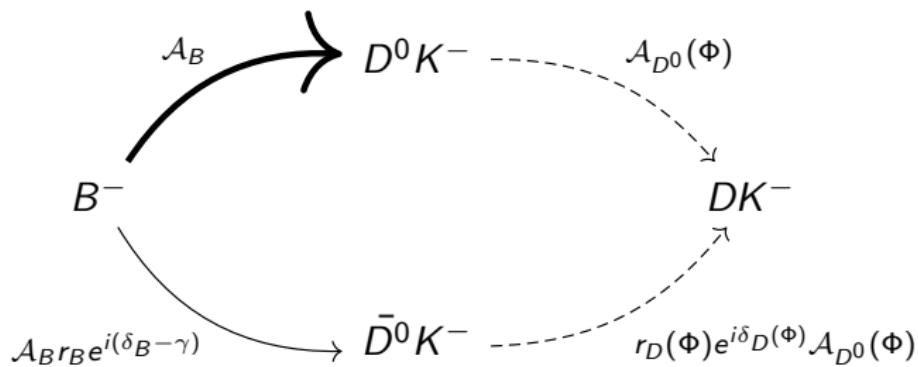
For 3-body decays, phase space is two-dimensional: Dalitz plots



Multi-body D decays

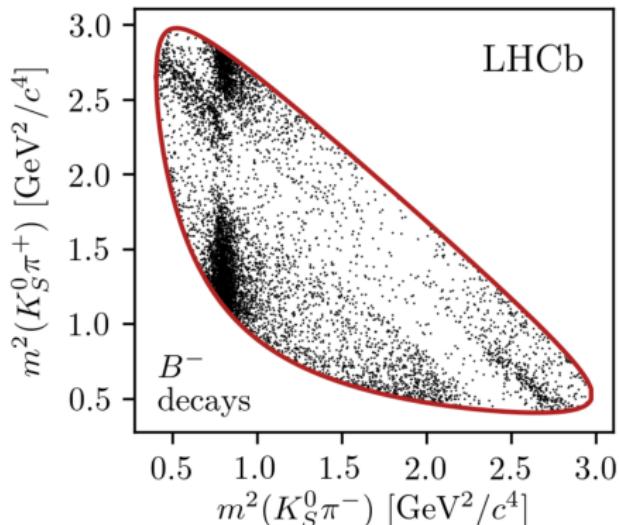
B^\pm decay rate depends on the phase space position Φ

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

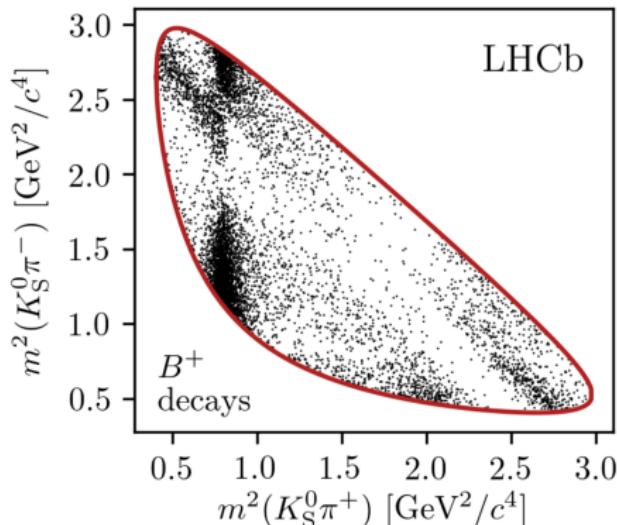


$$|A(B^-)|^2 \propto 1 + r_B^2 r_D^2(\Phi) + 2r_B r_D(\Phi) \cos(\delta_B - \gamma + \delta_D(\Phi))$$

Multi-body D decays



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

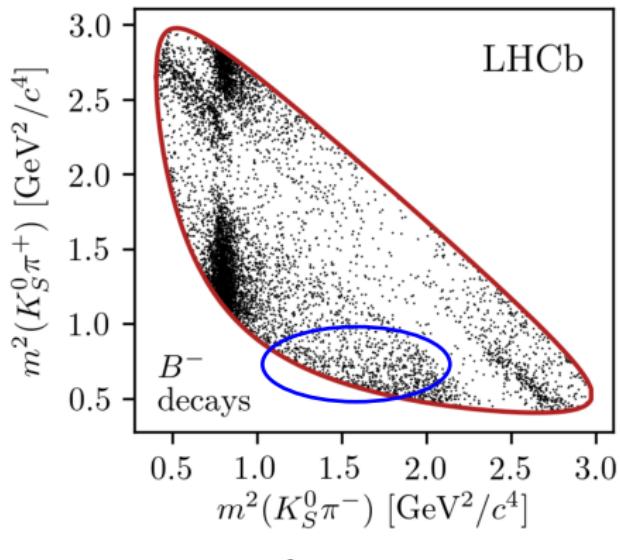


$$B^+ \rightarrow [K_S^0 \pi^+ \pi^-]_D K^+$$

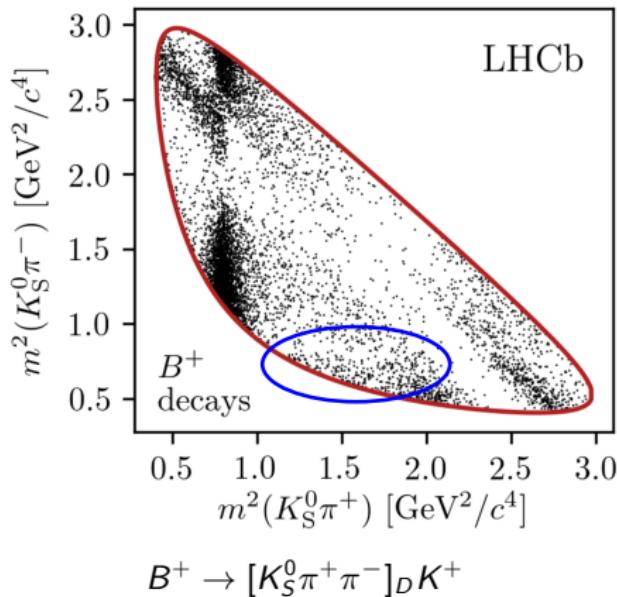
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Can you find the asymmetries?

Multi-body D decays



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

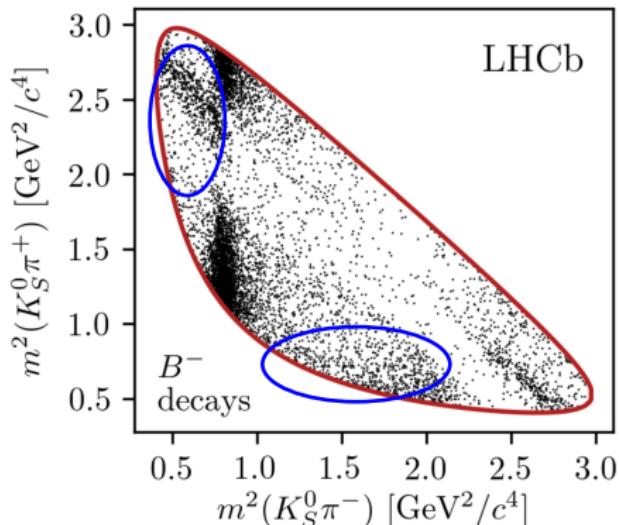


$$B^+ \rightarrow [K_S^0 \pi^+ \pi^-]_D K^+$$

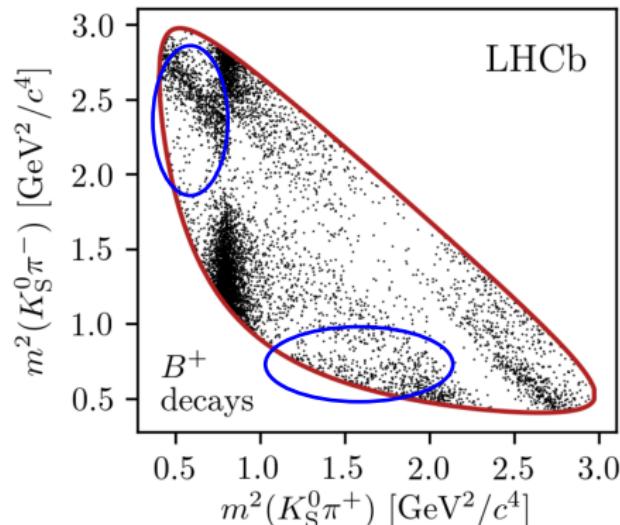
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Can you find the asymmetries?

Multi-body D decays



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



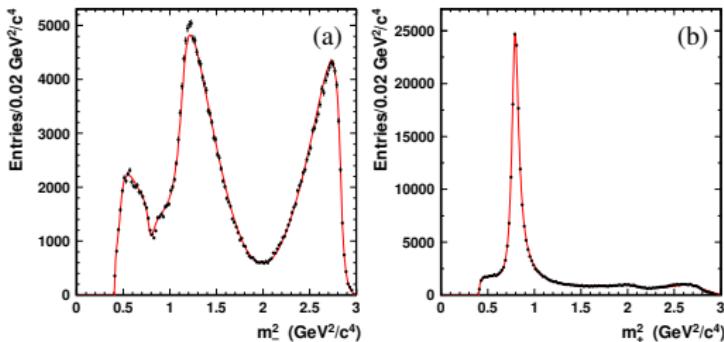
$$B^+ \rightarrow [K_S^0\pi^+\pi^-]_D K^+$$

JHEP 02 (2021) 169

Can you find the asymmetries?

Multi-body D decays

- Interpretation of γ from the multi-body charm decays requires knowledge of $\delta_D(\Phi)$, which vary across phase space
- This can be modelled:
 - ① Decay amplitude takes the form $\mathcal{A}(\Phi) = \sum_i a_i \mathcal{F}_i$
 - ② Lineshapes \mathcal{F}_i can be Breit-Wigner, etc.
 - ③ Fit $|\mathcal{A}|^2$ to data to determine the complex coefficients a_i

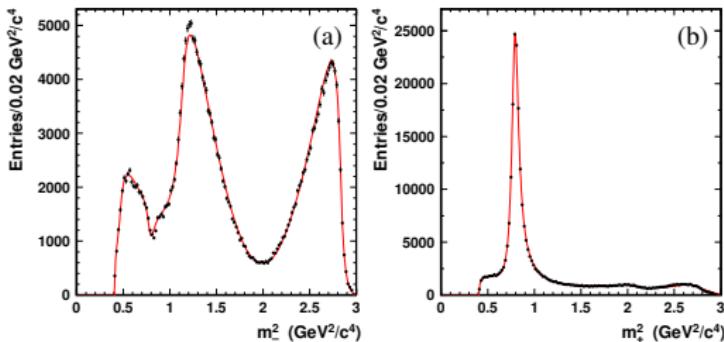


Phys. Rev. D 73 (2006) 112009

Use $\mathcal{A}(\Phi)$ to predict $\delta_D(\Phi)$

Multi-body D decays

- Interpretation of γ from the multi-body charm decays requires knowledge of $\delta_D(\Phi)$, which vary across phase space
- This can be modelled:
 - ① Decay amplitude takes the form $\mathcal{A}(\Phi) = \sum_i a_i \mathcal{F}_i$
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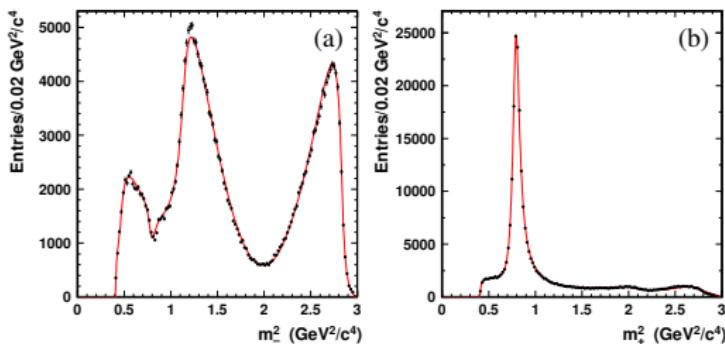


Phys. Rev. D 73 (2006) 112009

Problem: How do we know the model prediction of $\delta_D(\Phi)$ is correct?

Multi-body D decays

- Interpretation of γ from the multi-body charm decays requires knowledge of $\delta_D(\Phi)$, which vary across phase space
- This can be modelled:
 - ① Decay amplitude takes the form $\mathcal{A}(\Phi) = \sum_i a_i \mathcal{F}_i$
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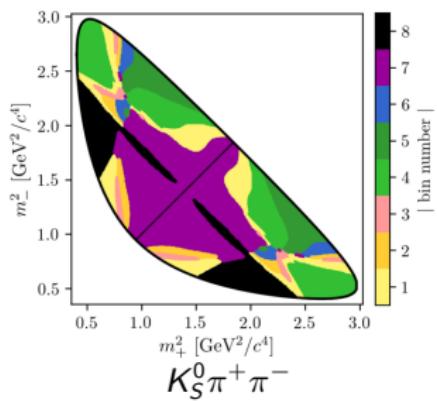
Phys. Rev. D 73 (2006) 112009

Serious problem: No reliable method for evaluating the $\delta_D(\Phi)$ uncertainty!

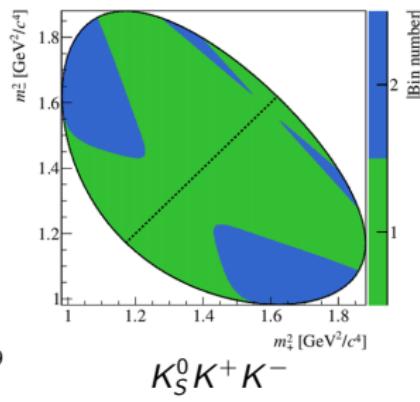
Multi-body D decays

Solution: Measure $\delta_D(\Phi)$ directly at charm factories

- ➊ Divide phase space into “bins” using the amplitude model
- ➋ Bins should encompass regions with similar $\delta_D(\Phi)$
 - Avoid diluting the sensitivity to γ
- ➌ Measure the average $\delta_D(\Phi)$ in each bin



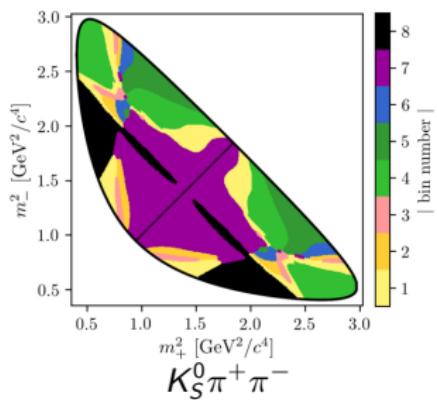
JHEP 02 (2021) 169



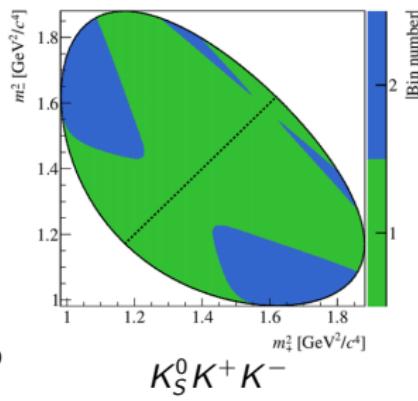
Multi-body D decays

Solution: Measure $\delta_D(\phi)$ directly at charm factories

- Interpretation of γ becomes model independent
 - γ is theoretically clean \implies Avoid introducing any theory uncertainties
- In fact, the LHCb γ combination is completely model independent!



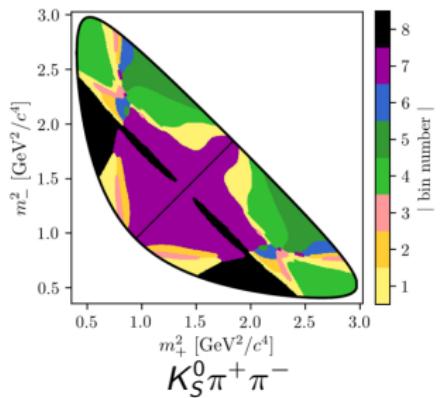
JHEP 02 (2021) 169



Multi-body D decays

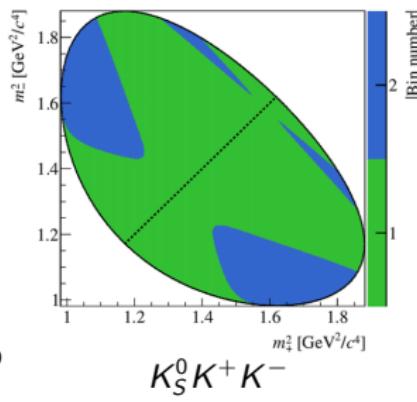
Solution: Measure $\delta_D(\Phi)$ directly at charm factories

- Interpretation of γ becomes model independent
 - γ is theoretically clean \implies Avoid introducing any theory uncertainties
- In fact, the LHCb γ combination is completely model independent!
- Furthermore, the interpretation of γ only uses relative bin yields \implies No dependence on production or detection asymmetries



JHEP 02 (2021) 169

$K_S^0 \pi^+ \pi^-$



$K_S^0 K^+ K^-$

Multi-body D decays

Quick digression: Charm factories 101

Consider charm production at threshold: $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$

- $\psi(3770) \rightarrow D^0\bar{D}^0$ decay conserves $\mathcal{C} = -1$



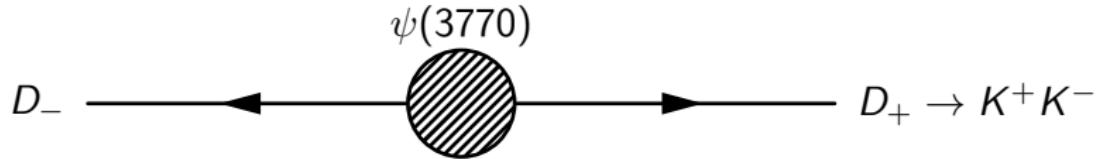
- $D\bar{D}$ pair are entangled, or quantum correlated
- Decay properties, such as branching fractions, are correlated

Multi-body D decays

Quick digression: Charm factories 101

Consider charm production at threshold: $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$

- $\psi(3770) \rightarrow D^0\bar{D}^0$ decay conserves $\mathcal{C} = -1$



- If, for example, the tag is CP-even, $D_+ \rightarrow K^+K^-$, the other D meson is forced into an CP-odd state

Multi-body D decays

Quick digression: Charm factories 101

Consider charm production at threshold: $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$

- CP-odd wave function and decay rate:

$$\mathcal{A}(D_-) = \mathcal{A}(D^0) - \mathcal{A}(\bar{D}^0) \implies$$

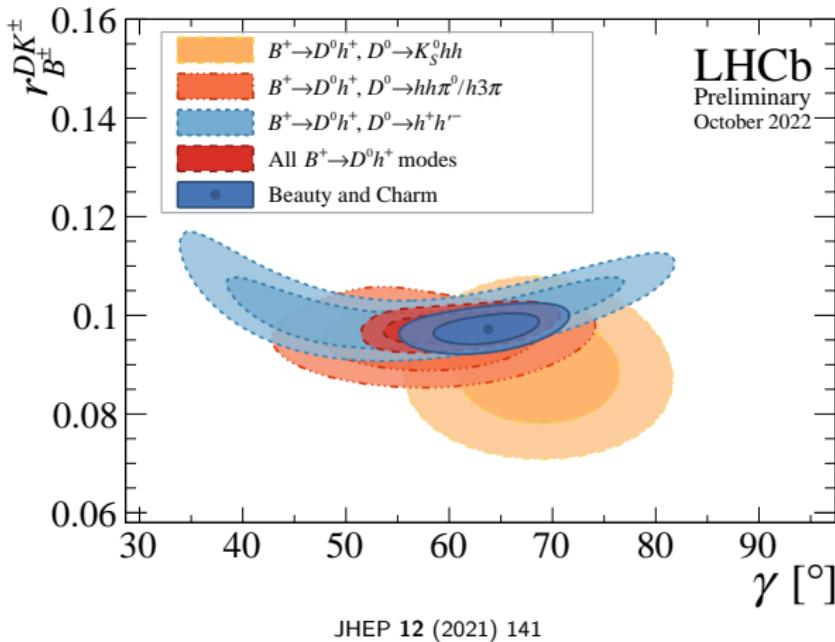
$$|\mathcal{A}(D_-)|^2 = |\mathcal{A}(D^0)|^2 + |\mathcal{A}(\bar{D}^0)|^2 - 2|\mathcal{A}(D^0)||\mathcal{A}(\bar{D}^0)| \cos(\delta_D)$$

Charm factories have direct access to δ_D

The LHCb γ combination

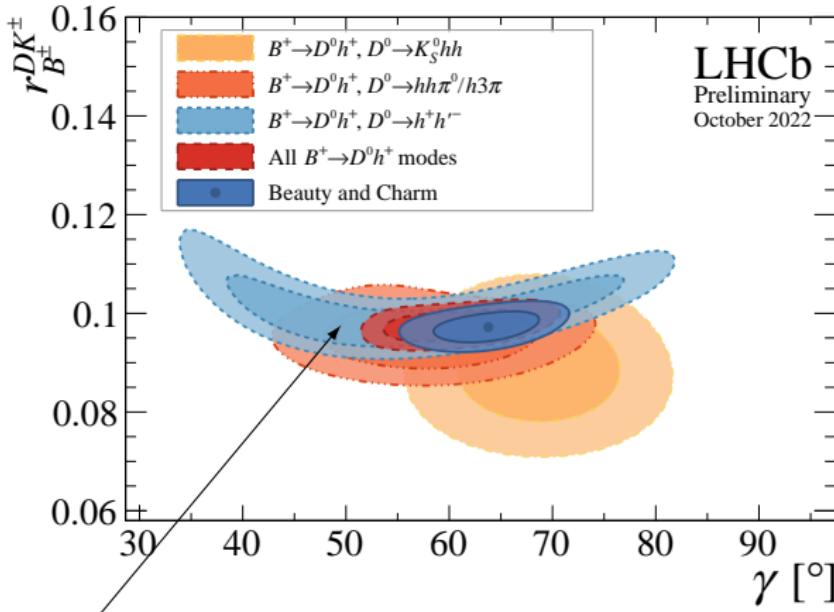
How to combine a decade of γ measurements

The LHCb γ combination



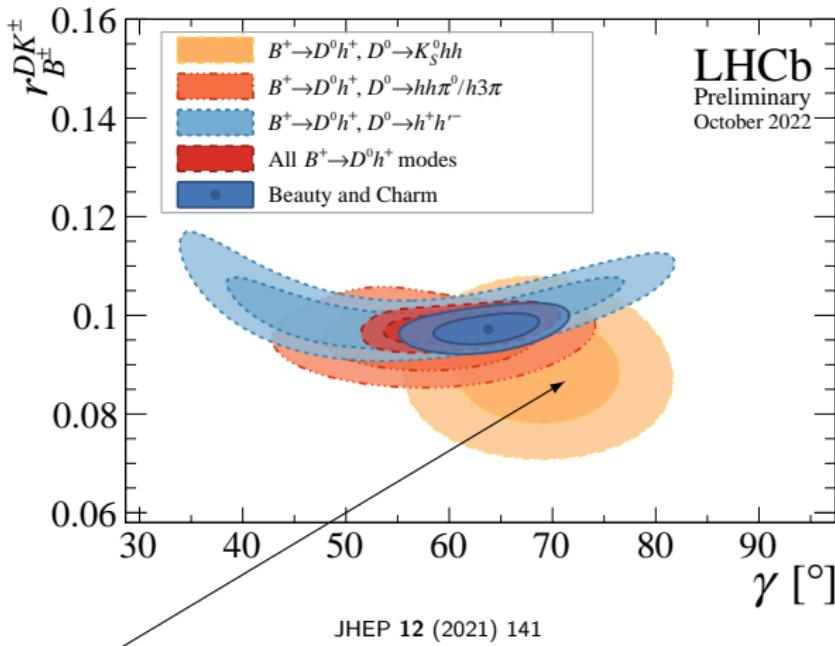
Currently, γ measurements are dominated by $B^\pm \rightarrow Dh^\pm$

The LHCb γ combination



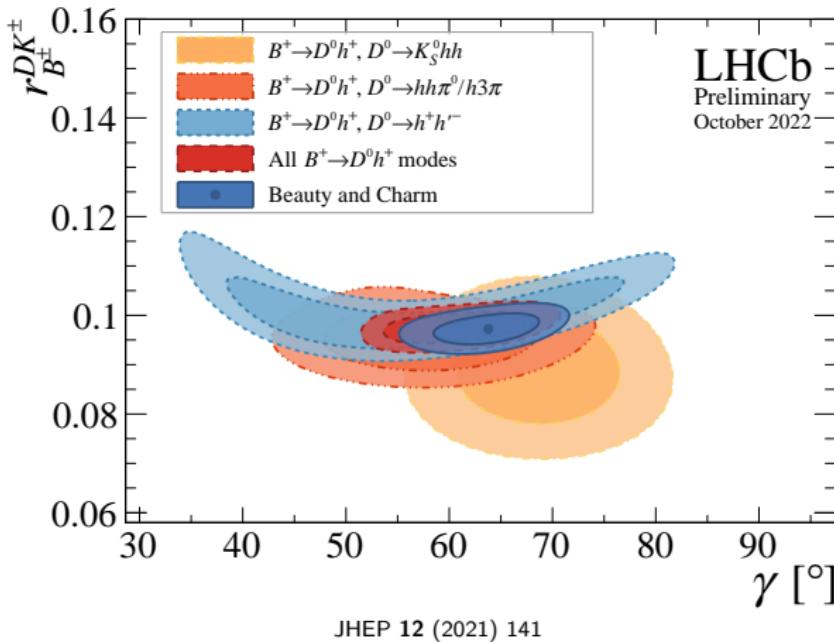
CP eigenstates and DCS decays: Narrow bands of degenerate solutions

The LHCb γ combination



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

The LHCb γ combination



A combination of direct γ measurements is necessary!

The LHCb γ combination

Other B decays are also interesting for γ measurements:

- 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 γ combination

Other B decays are also interesting for γ 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 γ combination

Other B decays are also interesting for γ 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 γ combination

Other B decays are also interesting for γ 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 γ combination

Other B decays are also interesting for γ 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	χ^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

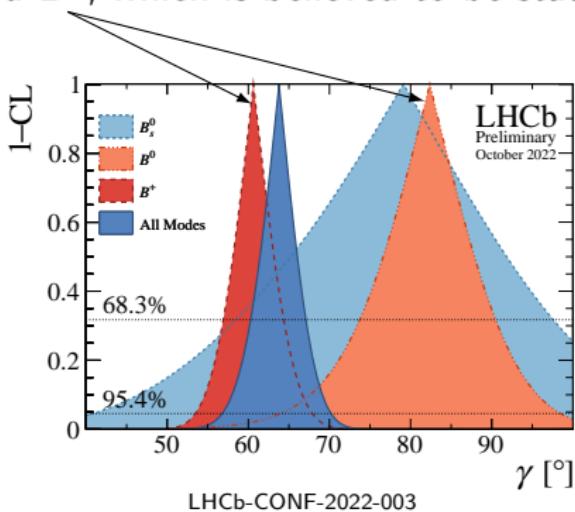
LHCb-CONF-2022-003

The LHCb γ combination

Other B decays are also interesting for γ measurements:

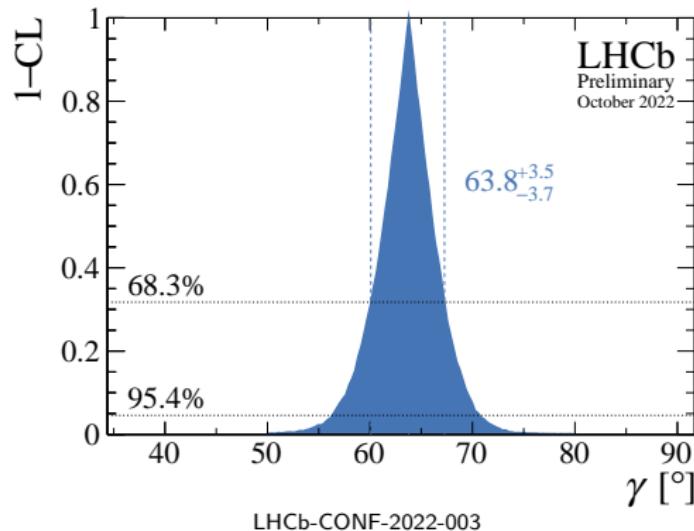
Small (2.2σ) tension between B^\pm and B^0 , which is believed to be statistical

- 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 γ combination

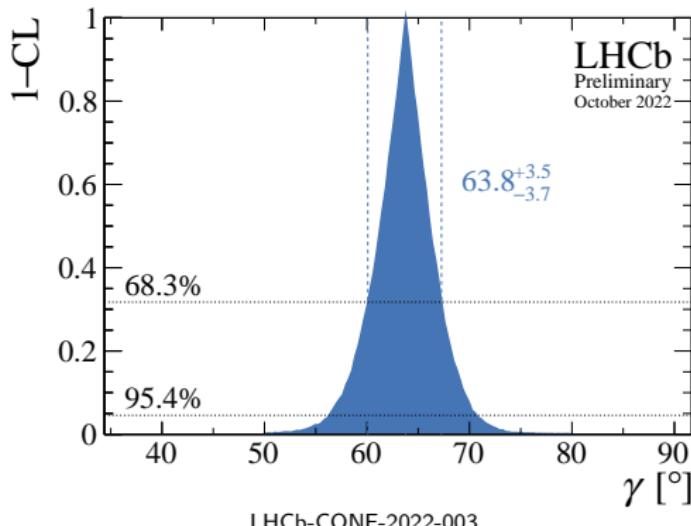
Our most precise knowledge of γ comes from the combination measurements



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

The LHCb γ combination

Our most precise knowledge of γ comes from the combination measurements

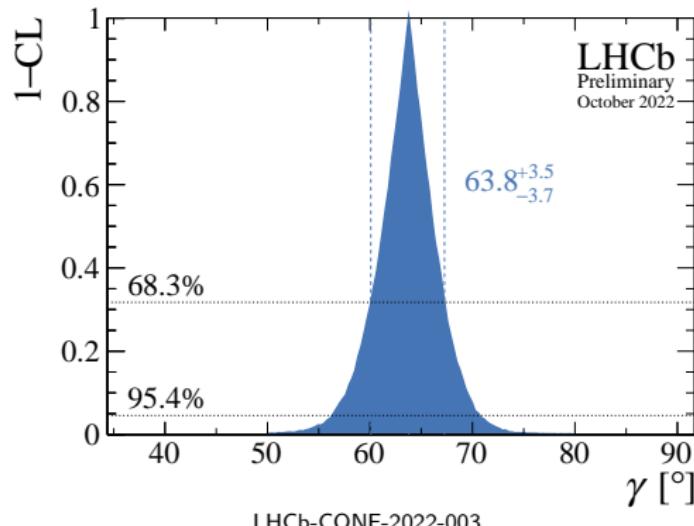


Combined result: $\gamma = (63.8^{+3.5}_{-3.7})^{\circ}$

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

The LHCb γ combination

Our most precise knowledge of γ comes from the combination measurements

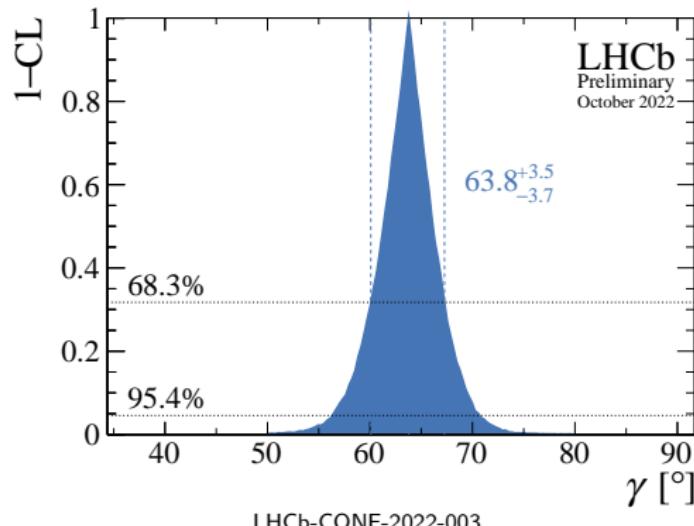


Combined result: $\gamma = (63.8^{+3.5}_{-3.7})^\circ$

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

The LHCb γ combination

Our most precise knowledge of γ 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

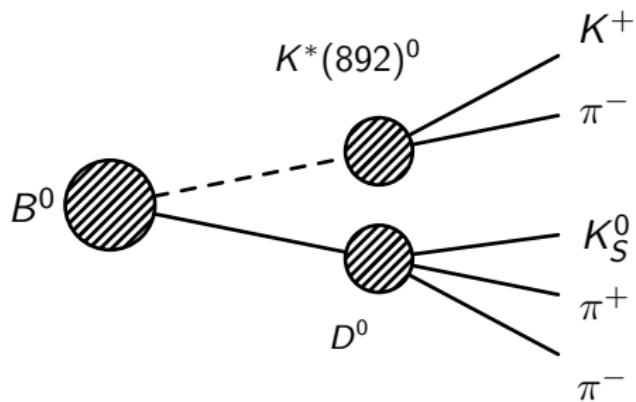
Neutral B decays

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!

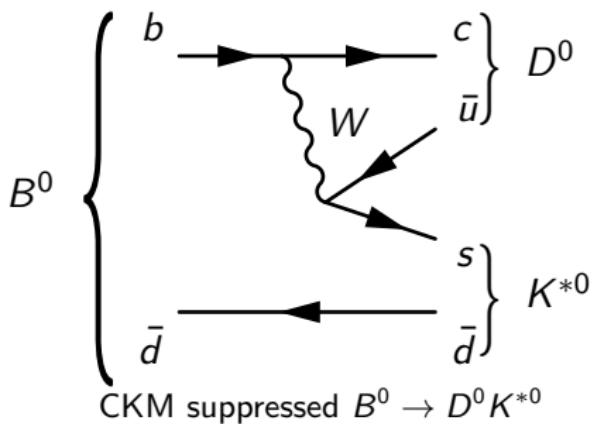
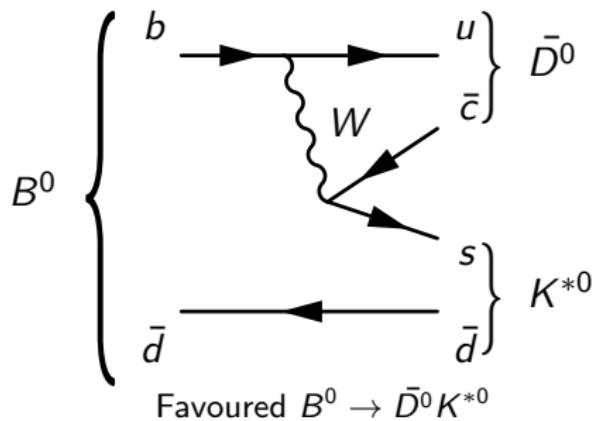


$$B^0 \rightarrow (K_S^0 h^+ h^-)_D (K^+ \pi^-)_{K^*}$$

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

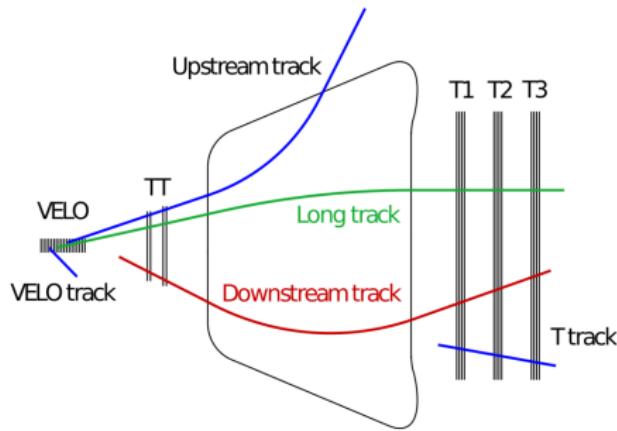
Neutral B decays

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



The interference is therefore expected to be ~ 3 times larger

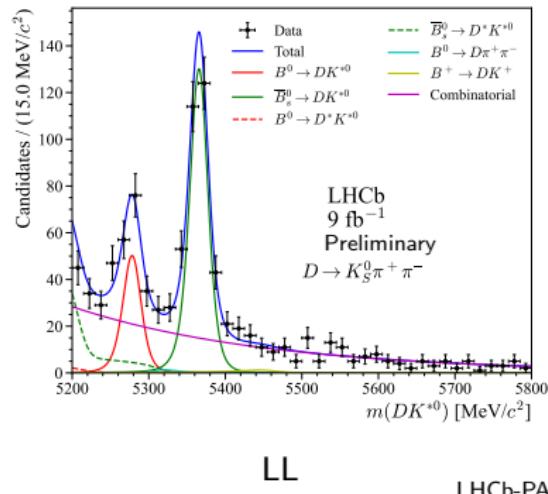
Neutral B decays



Tracking and vertexing in LHCb, PoS VERTEX2018 (2019) 039

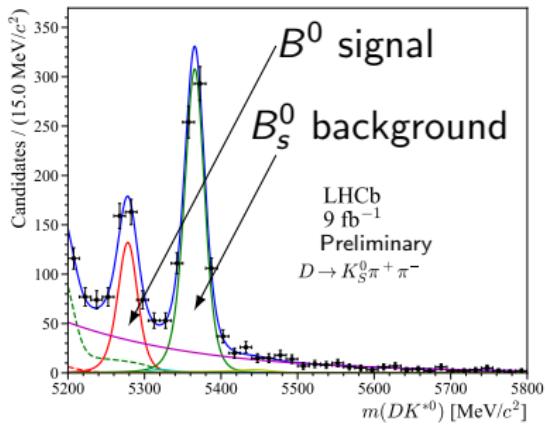
- Two separate selections of K_S^0 :
 - ➊ LL (**Long track**): K_S^0 decays in the VELO
 - ➋ DD (**Downstream track**): K_S^0 decays downstream of the VELO

Neutral B decays



LL

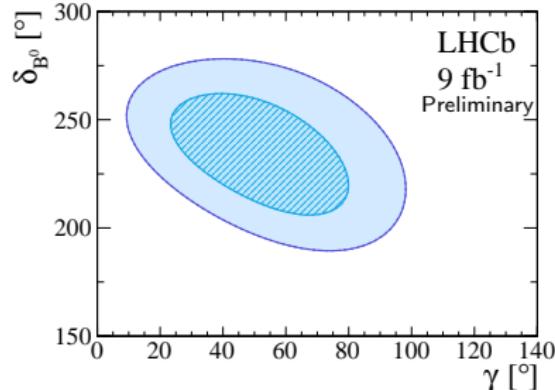
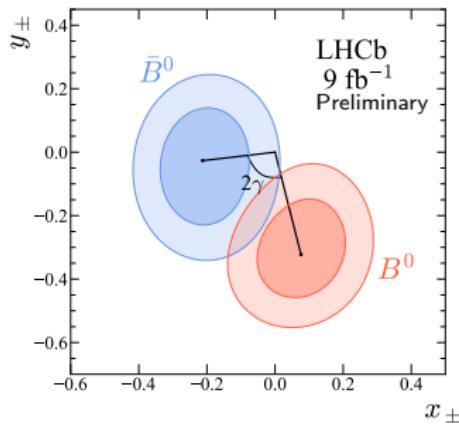
LHCb-PAPER-2023-009



DD

- $B^0 \rightarrow DK^{*0}$ candidates with $D \rightarrow K_S^0 \pi^+ \pi^-$ ($D \rightarrow K_S^0 K^+ K^-$):
 - ➊ LL: 102 ± 17 (12 ± 6)
 - ➋ DD: 288 ± 25 (32 ± 8)

Neutral B decays



LHCb-PAPER-2023-009

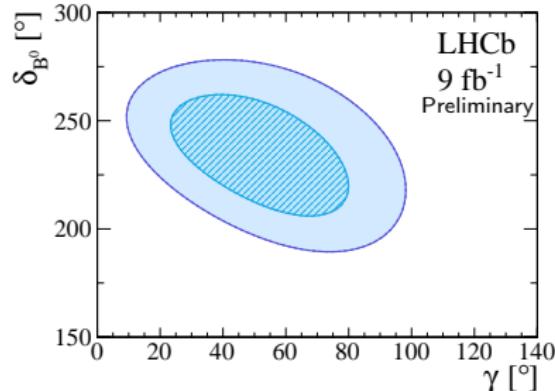
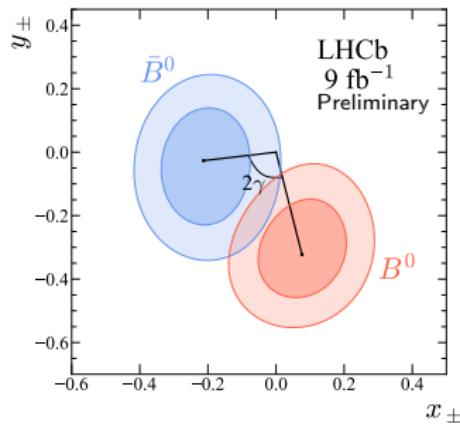
- Measured CP -violating observables:

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

- Measured value of γ is consistent with world average:

- $\gamma = (49 \pm 20)^\circ$
- $\delta_{B^0} = (236 \pm 19)^\circ$
- $r_{B^0} = 0.27 \pm 0.07$

Neutral B decays



LHCb-PAPER-2023-009

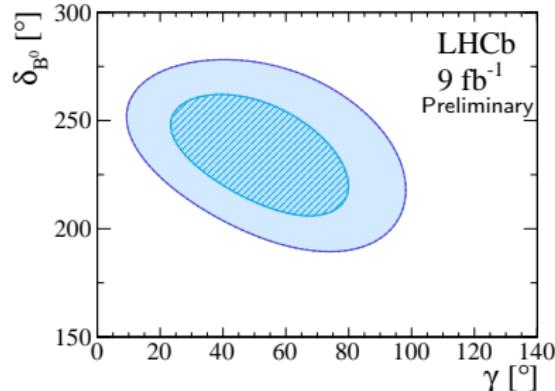
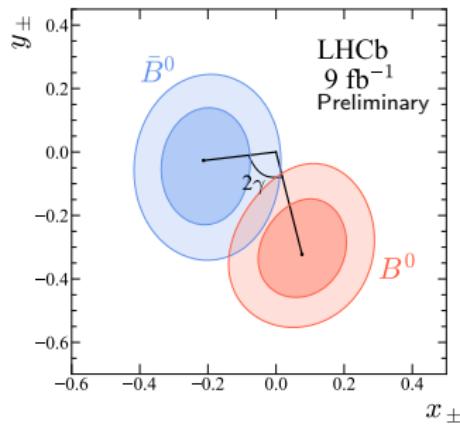
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Neutral B decays



LHCb-PAPER-2023-009

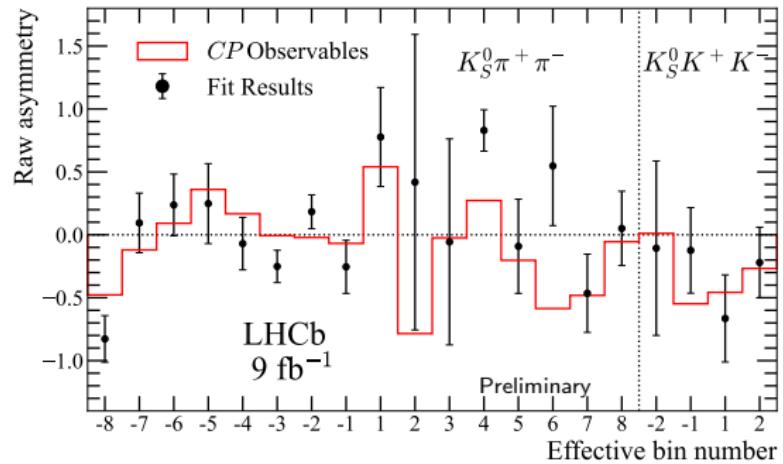
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$$x_{\pm} \equiv r_{B^0} \cos(\delta_{B^0} \pm \gamma) \text{ and } y_{\pm} \equiv r_{B^0} \sin(\delta_{B^0} \pm \gamma)$$

- Measured value of γ is consistent with world average:

- $\gamma = (49 \pm 20)^\circ \leftarrow$ This will reduce tension between B^0 and B^{\pm}
- $\delta_{B^0} = (236 \pm 19)^\circ$
- $r_{B^0} = 0.27 \pm 0.07 \leftarrow$ Compatible with expectation: $r_{B^0} \approx 3r_{B^{\pm}}$

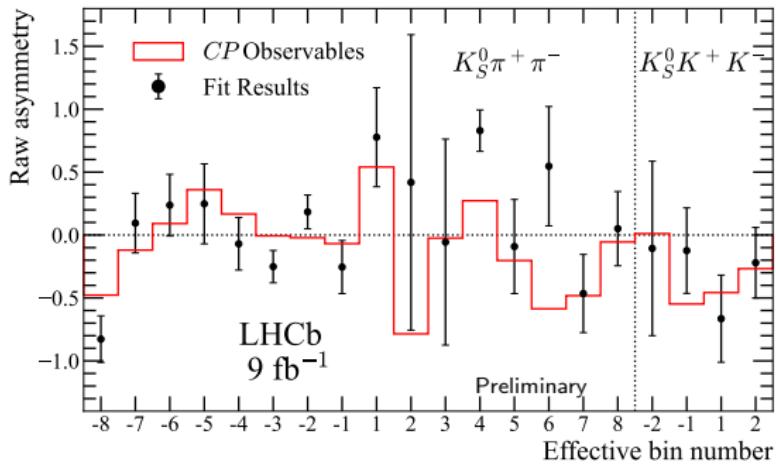
Neutral B decays



LHCb-PAPER-2023-009

- Compare relative bin yields between B^0 (\bar{B}^0) bin pairs
- Expect asymmetries to change in sign/magnitude across different bins

Neutral B decays



LHCb-PAPER-2023-009

- Red line:
 - ① Bin asymmetries are predicted from fitted parameters (x_{\pm}, y_{\pm})
 - ② A good agreement between fit and individual asymmetries is found

B decays to excited D^* final states

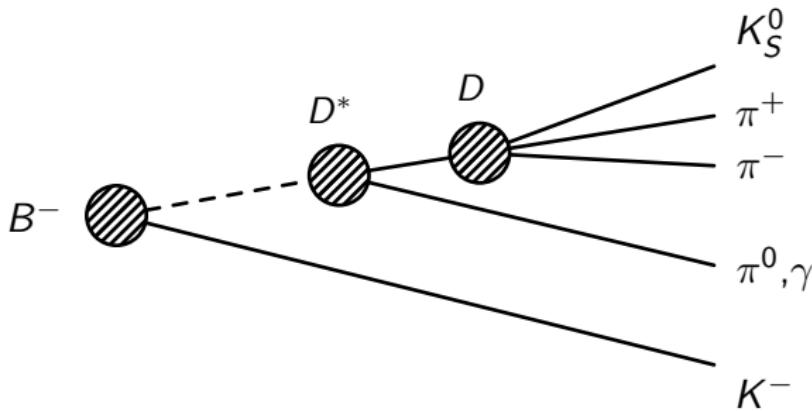
B decays to excited D^* final states

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!**



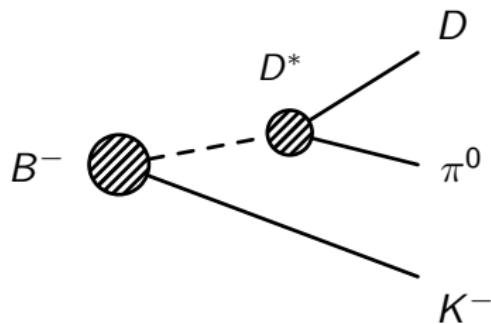
$$B^- \rightarrow [D\gamma, \pi^0]_{D^*} K^-, D \rightarrow K_S^0 \pi^+ \pi^-$$

Analysis is similar to $B^\pm \rightarrow DK^\pm$

Requires additional reconstruction of $D^* \rightarrow D\pi^0$ and $D^* \rightarrow D\gamma$

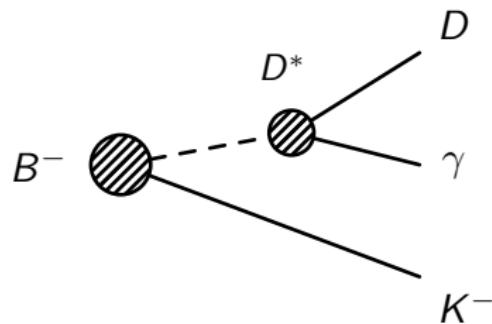
B decays to excited D^* final states

CP of the $D^* \rightarrow D\pi^0$ and $D^* \rightarrow D\gamma$ decays must be considered carefully



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

Angular momentum conservation



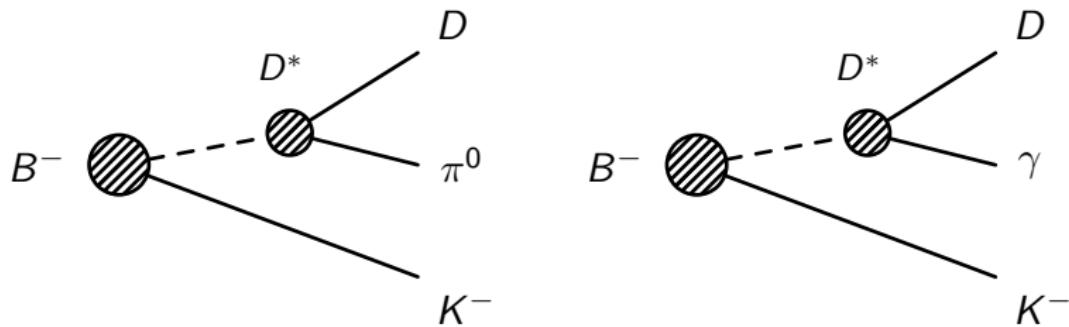
$$B^- \rightarrow [D\gamma]_{D^*} K^-$$

Parity conservation

Both decays must proceed with $l = 1$ due to conservation laws

B decays to excited D^* final states

CP of the $D^* \rightarrow D\pi^0$ and $D^* \rightarrow D\gamma$ decays must be considered carefully



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

$$\pi^0: \text{CP} = -1$$

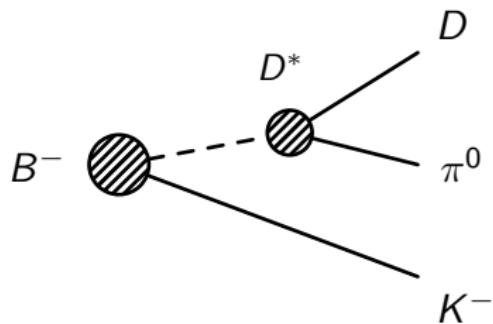
$$B^- \rightarrow [D\gamma]_{D^*} K^-$$

$$\gamma: \text{CP} = +1$$

However, π^0 and γ have opposite intrinsic CP

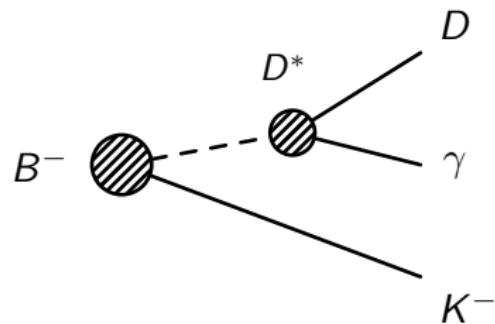
B decays to excited D^* final states

CP of the $D^* \rightarrow D\pi^0$ and $D^* \rightarrow D\gamma$ decays must be considered carefully



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

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



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

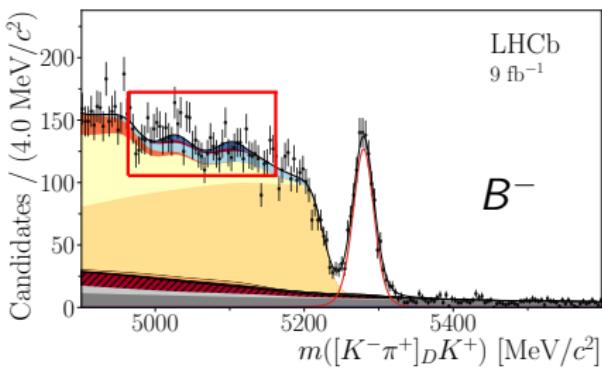
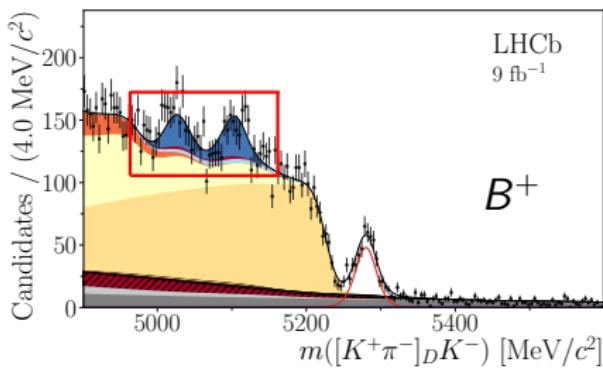
$$\mathcal{A}(D^0) - r_B e^{i(\delta_B - \gamma)} \mathcal{A}(\bar{D}^0)$$

Due to the opposite CP, asymmetries of $D\pi^0$ and $D\gamma$ are expected to be equal and opposite (Phys. Rev. D **70** (2004) 091503(R))

B decays to excited D^* final states

Reminder: Partially reconstructed background decays

Asymmetries previously measured for CP eigenstates and DCS decays

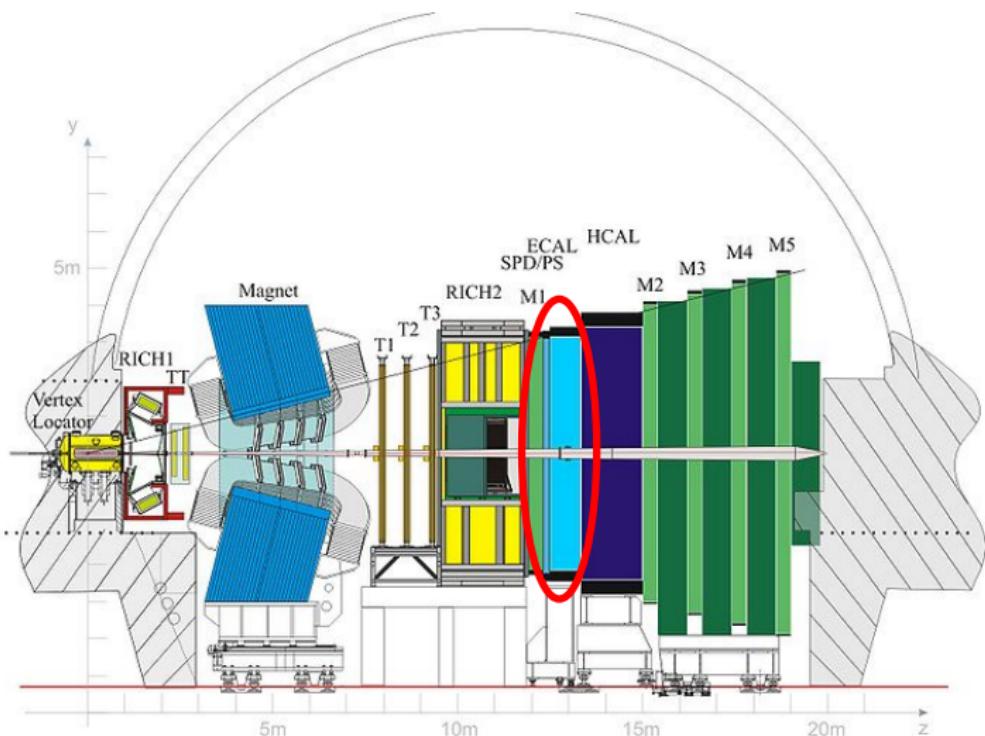


JHEP 04 (2021) 081

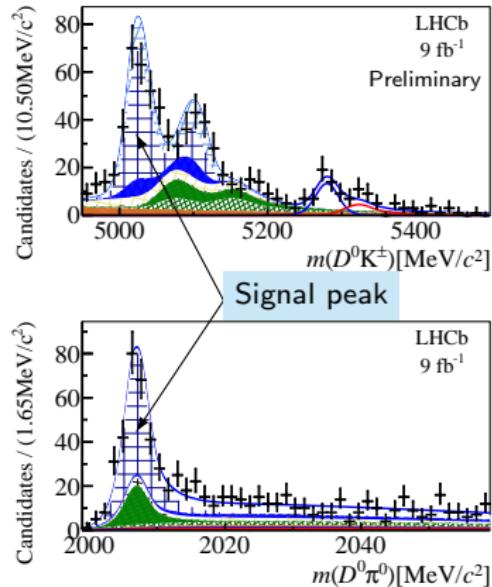
This analysis aims to fully reconstruct the $D^* \rightarrow D\pi^0$, $D\gamma$ decays,
with $D \rightarrow K_S^0 h^+ h^-$, in bins of phase space

B decays to excited D^* final states

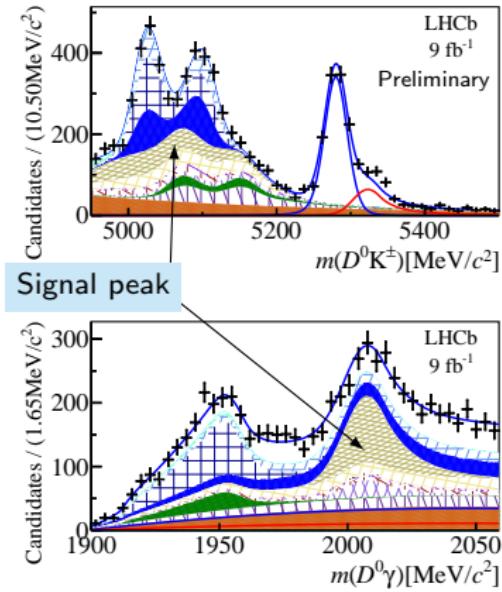
Small aside: reconstruct γ and $\pi^0 \rightarrow \gamma\gamma$ in the ECAL



B decays to excited D^* final states



Signal peak



Signal peak

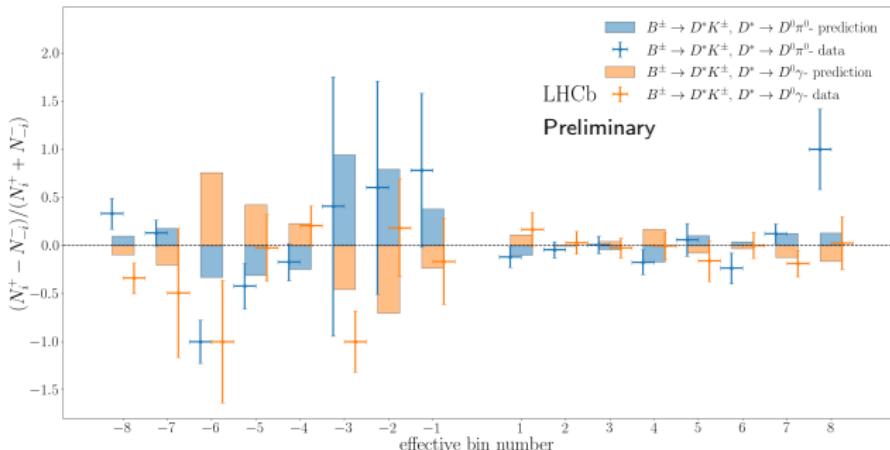
$$D^* \rightarrow D\pi^0$$

LHCb-PAPER-2023-012

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

A 2D fit is necessary to separate signal from background

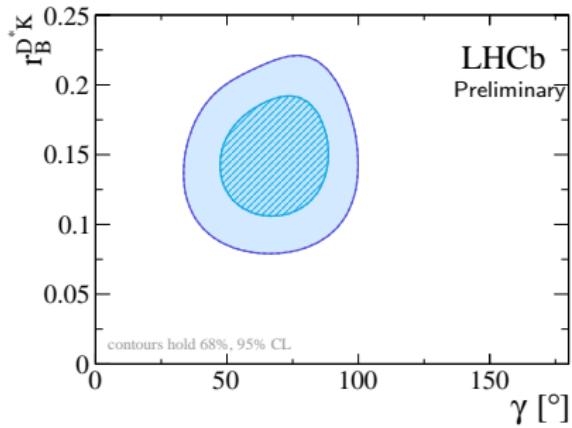
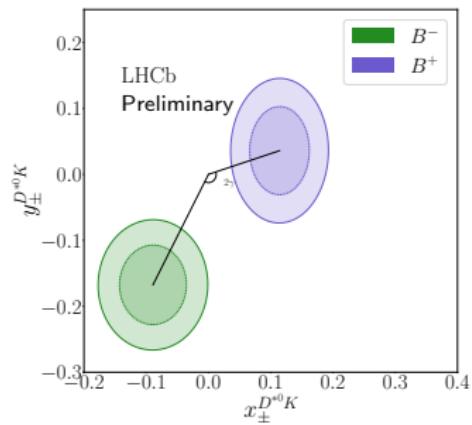
B decays to excited D^* final states



LHCb-PAPER-2023-012

- 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 γ :

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

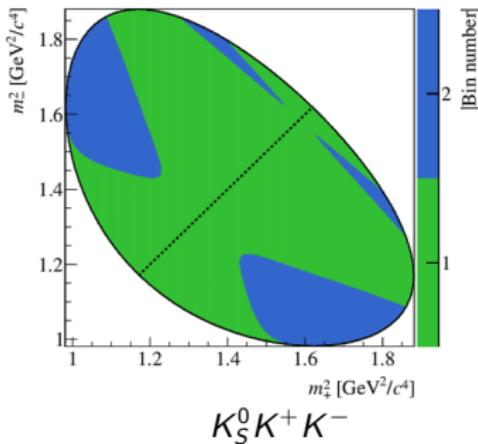
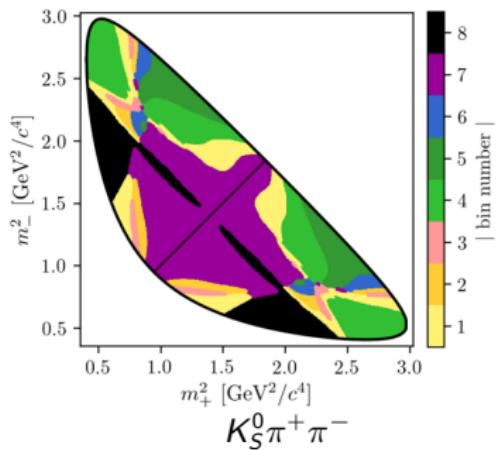
Binned four-body decay: $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$

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

A journey through five dimensions

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

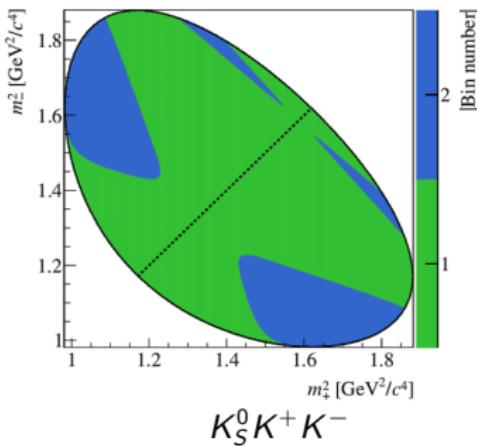
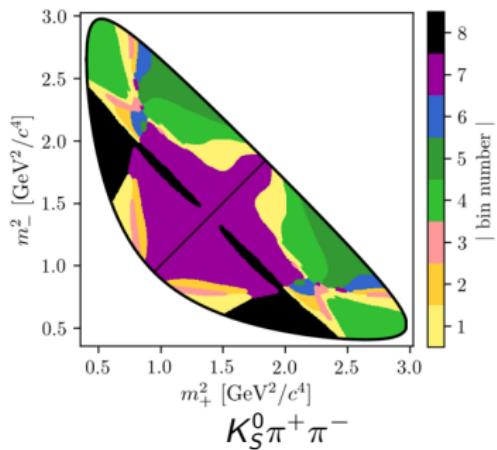
Back to $D^0 \rightarrow K_S^0 h^+ h^-$ binning schemes, visualised on a Dalitz plot:



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

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

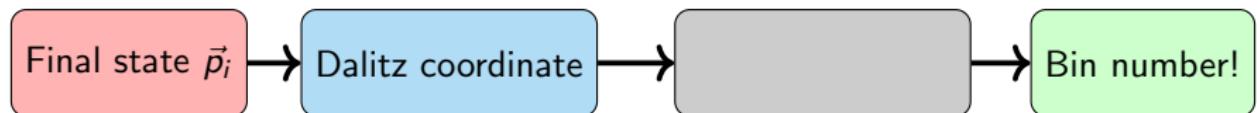
Back to $D^0 \rightarrow K_S^0 h^+ h^-$ binning schemes, visualised on a Dalitz plot:



- ... but for a four-body decay, phase space is five-dimensional
- Much more difficult to visualise!

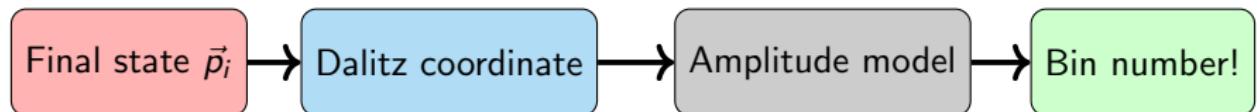
Binned four-body decay: $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$

But how do we define a binning scheme (in 5D)?



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

But how do we define a binning scheme (in 5D)?



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

The model can predict the strong-phase difference, allowing us to decide where to put bin boundaries

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 $B^\pm \rightarrow \bar{D}^0 K^\pm$

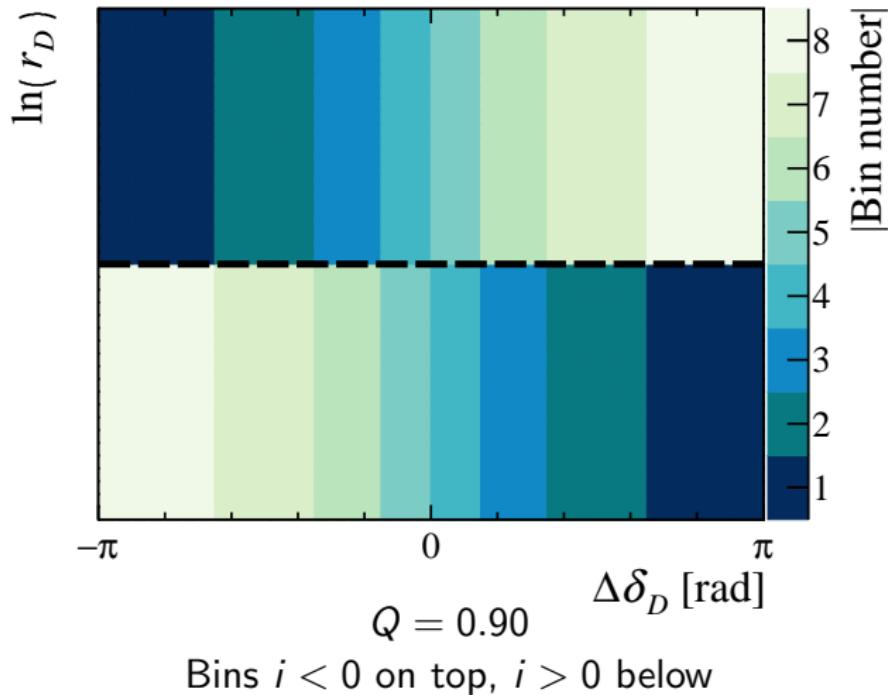
How to bin a 5-dimensional phase space?

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

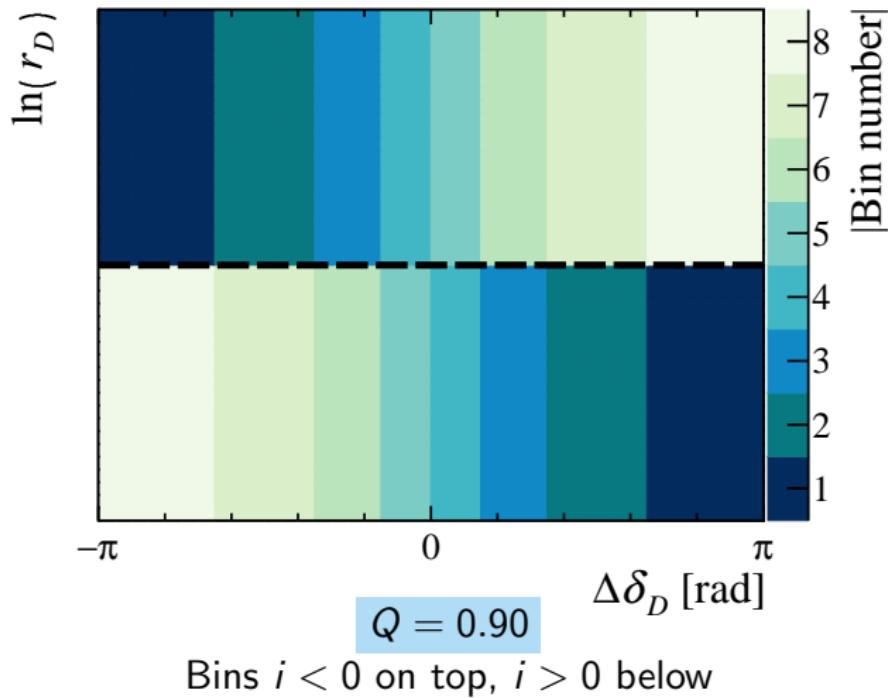
$$\frac{\mathcal{A}(D^0)}{\mathcal{A}(\bar{D}^0)} = r_D e^{i\delta_D}$$

- ② Split δ_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 δ_D

Binning scheme

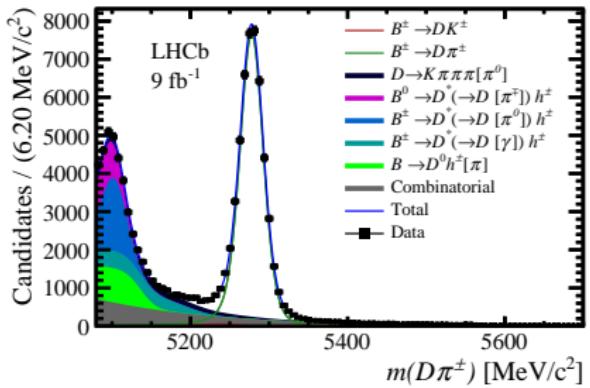
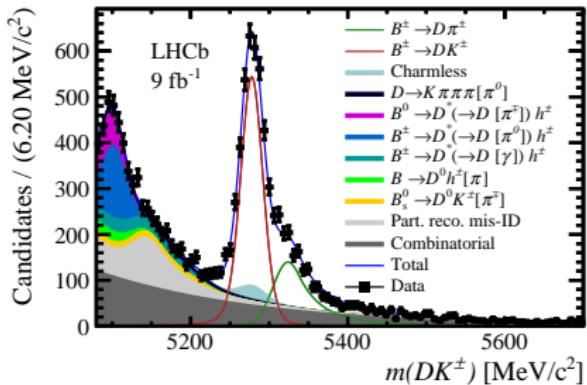


Binning scheme



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

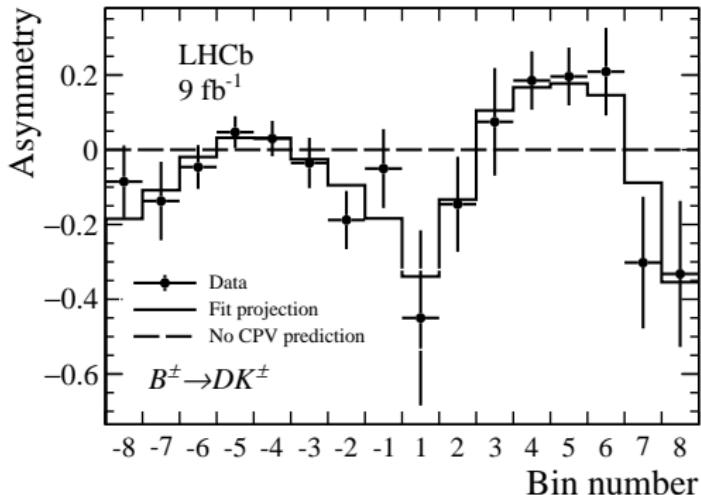
Fully charged final state \implies Highly suitable for LHCb



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 ± 38
 - $B^\pm \rightarrow D\pi^\pm$: 44349 ± 218

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



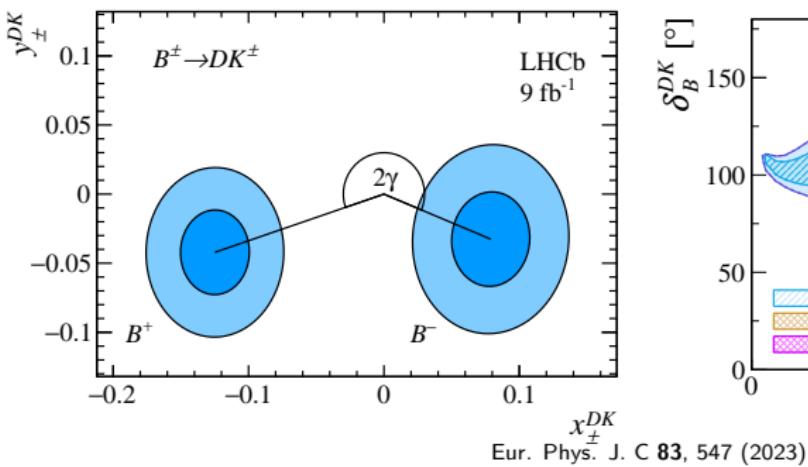
Eur. Phys. J. C 83, 547 (2023)

- 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 γ require inputs from charm threshold, 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:

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



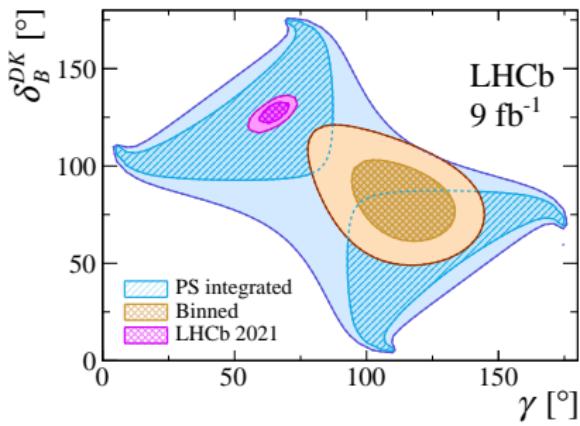
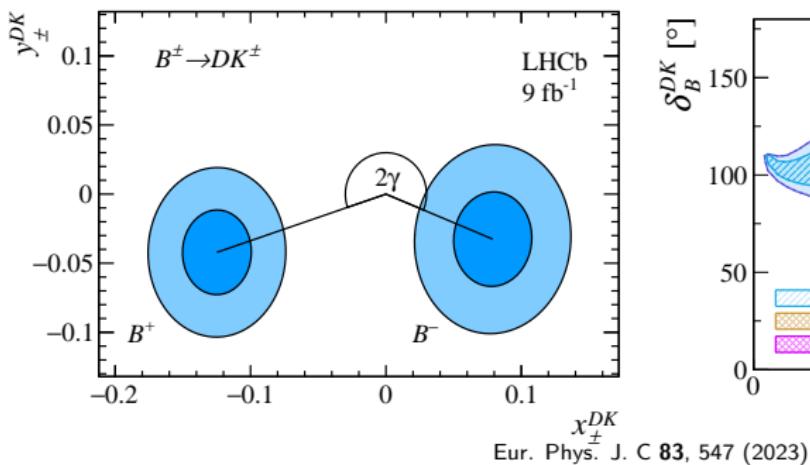
Eur. Phys. J. C 83, 547 (2023)

These results are model dependent, and show an almost 3σ tension with the γ combination

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

From the phase-space binned asymmetries, we obtain:

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

The angle γ of the Cabibbo-Kobayashi-Maskawa ansatz

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

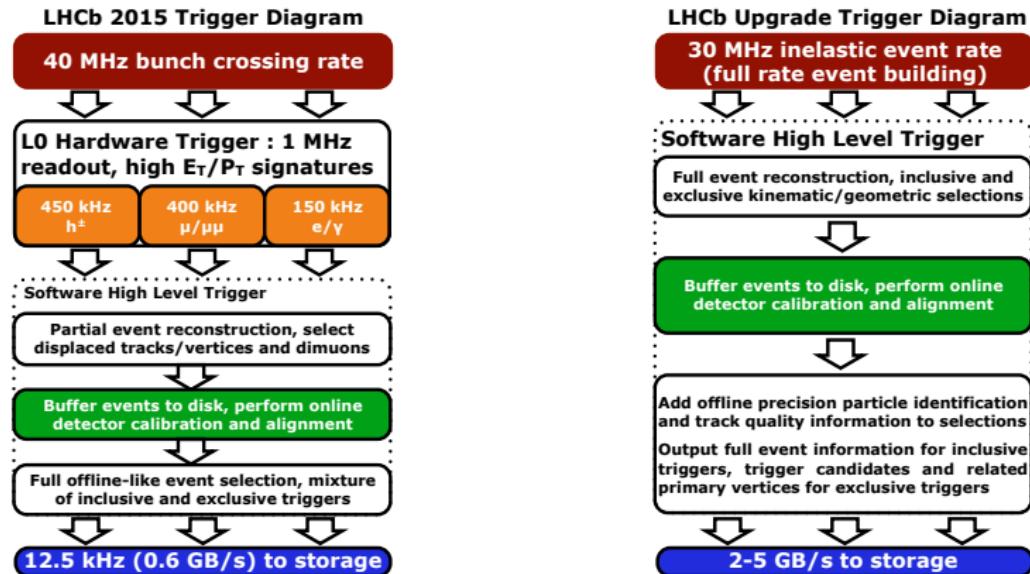
Future prospects

Future prospects:

- The measurements presented today will make valuable improvements when added to future γ combinations
 - Current average: $\gamma = 63.8^{+3.5}_{-3.7}$
- 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 Results with CP eigenstates and DCS decays from $B^0 \rightarrow D K^{*0}$ will bring the γ precision in B^0 closer to that in the B^\pm system
 - ③ Partially reconstructed analysis of $B^\pm \rightarrow D^* h^\pm$, with $D \rightarrow K_S^0 h^+ h^-$, will be complementary to the analysis presented today
 - ④ 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

Future prospects

Exciting times ahead with fully software-based trigger:



LHCb-FIGURE-2020-016

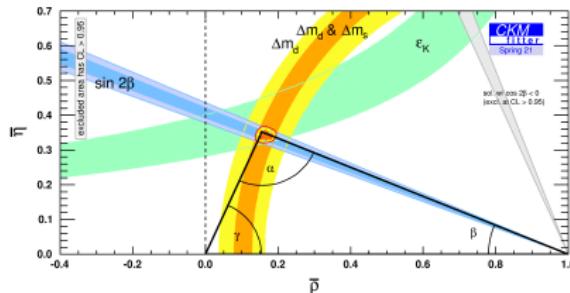
Key details of LHCb Upgrade I (arXiv:2305.10515):

- ① HLT1 will be run on GPU
- ② HLT2 will perform full event reconstruction
- ③ Much higher rate of interesting physics events
- ④ LHCb, during Run 3 and 4, anticipates to collect five times more data

γ is dominated by statistical uncertainties, and will therefore greatly benefit from the higher efficiencies with the new software trigger

Future prospects

We expect to reach 1° precision after Run 4



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

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

We may finally be able to match the indirect precision on γ !

However, we also expect results from lattice QCD to improve

Summary and future prospects

In summary:

- ① Long journey towards a precise determination of γ
- 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
- 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° precision on γ after Run 3 and 4
 - With Upgrade II, we hope to bring this down further to 0.4°

Summary and future prospects

In summary:

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Thanks for your attention!

