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

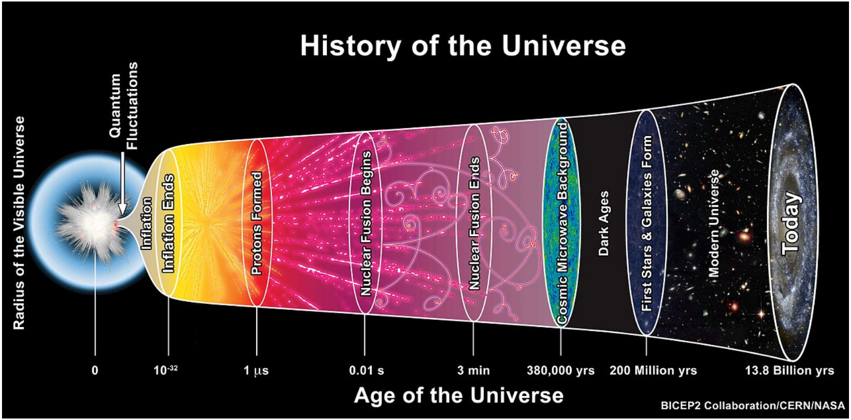
CERN LHC seminar

25th July 2023

Introduction to *CP* violation

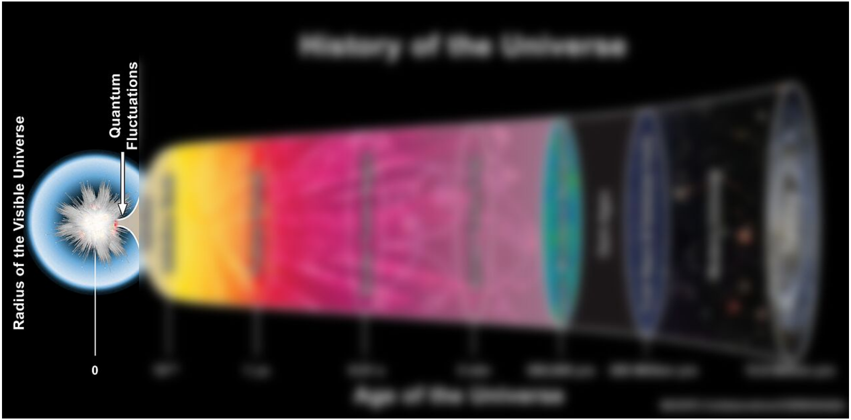
What is γ and why measure it?

Big Bang and matter-antimatter asymmetry



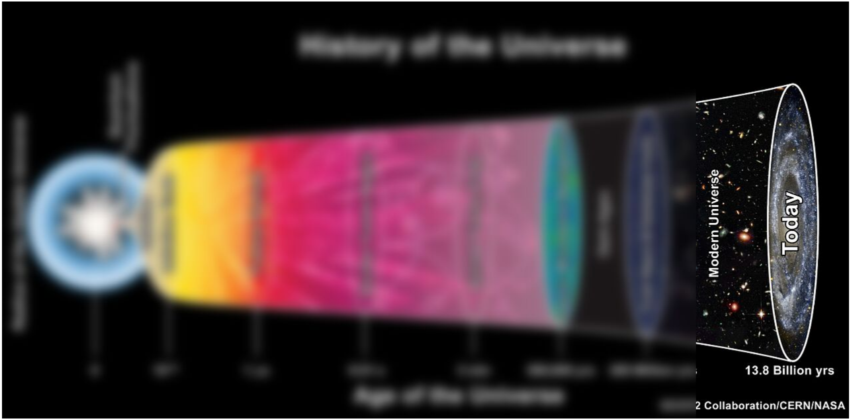
Where is the antimatter in the universe?

Big Bang and matter-antimatter asymmetry



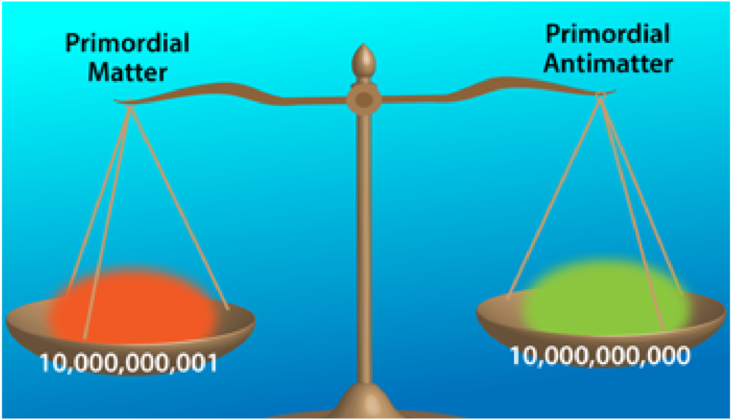
Initially equal amounts of matter and antimatter...

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

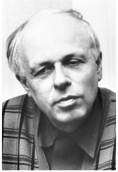


Photo from the Nobel Foundation archive.
Andrei Dmitrievich Sakharov
Prize share: 1/1

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

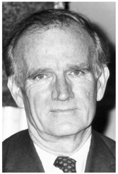


Photo from the Nobel Foundation archive.
Val Logsdon Fitch
Prize share: 1/2

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"

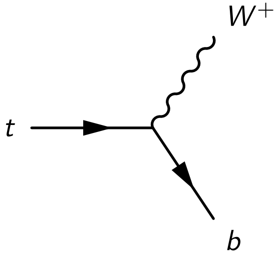
- CP violation discovery in 1964
- Phys. Rev. Lett. **13**, 138
- Observed $K_L^0 \to \pi^+\pi^-$
- Since, CP violation has also been observed in the B, B_s and D systems

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

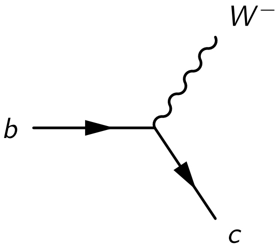
The CKM matrix and the Unitary Triangle

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

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



(a) $t \to bW^+$



(b) $b \to cW^-$

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

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

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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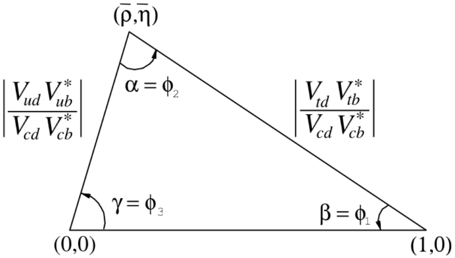

R. L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

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: U. Montan
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- Kobayashi and Maskawa extended Cabibbo's 2×2 rotation matrix
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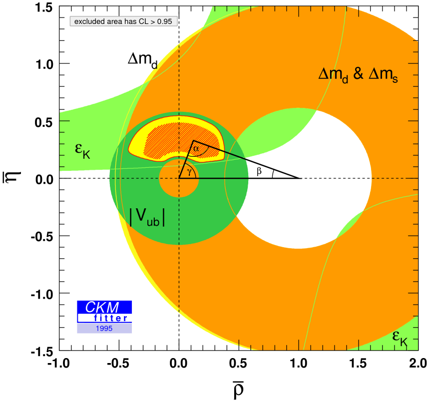
Precise knowledge of quark interactions will help us search for new physics with CPV, which may not have the same CKM structure

The CKM matrix and the Unitary Triangle

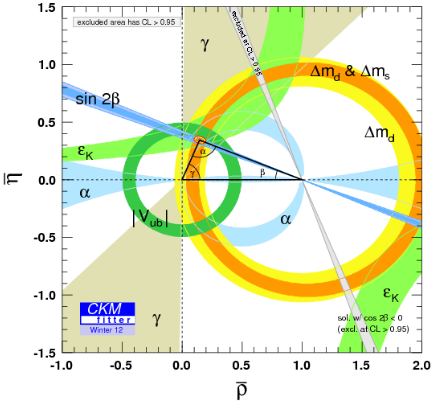
Before Belle and BaBar, the Unitary Triangle was poorly constrained



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



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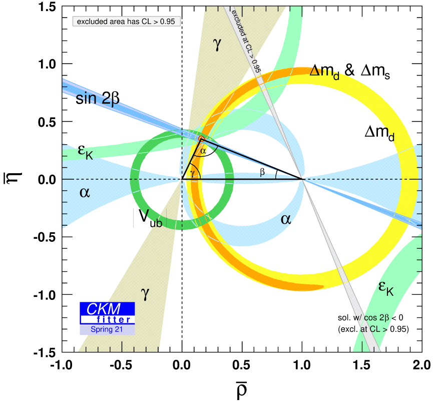
The CKM matrix and the Unitary Triangle

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



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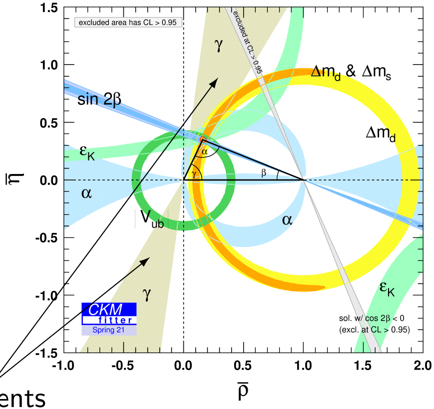

Direct γ measurements

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

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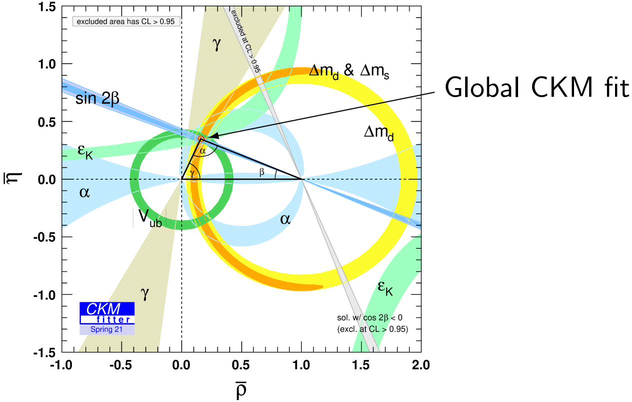
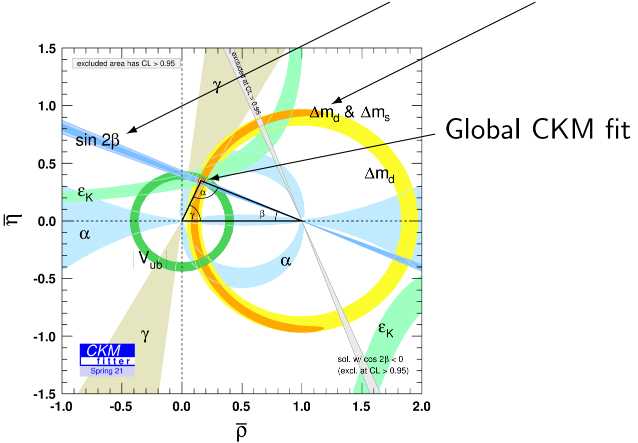


CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005), updated results and plots available at: http://ckmfitter.in2p3.fr

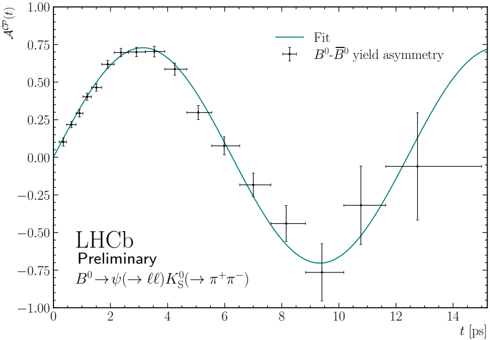
The CKM matrix and the Unitary Triangle

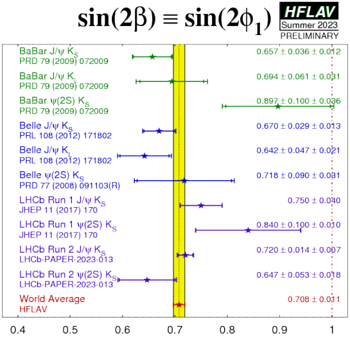
Loop level measurements of γ are dominated by $\sin(2\beta)$ and B^0/B^0_s mixing



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

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

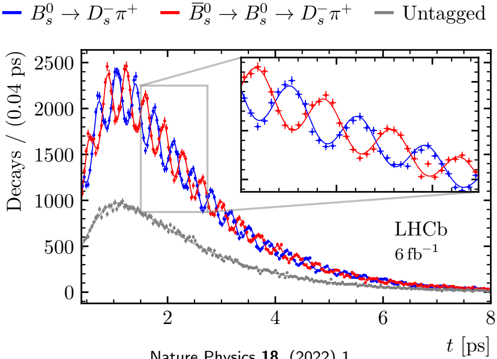




$$\text{World average: } \sin(2\beta) = 0.708 \pm 0.011$$
$$\beta = (22.5 \pm 0.4)^\circ$$

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



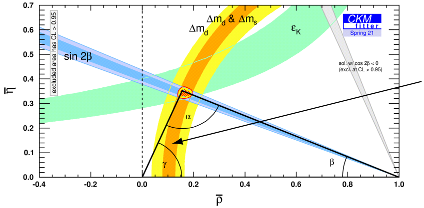
Nature Physics **18**, (2022) 1

HFLAV averages:

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

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



Dominated by lattice QCD

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

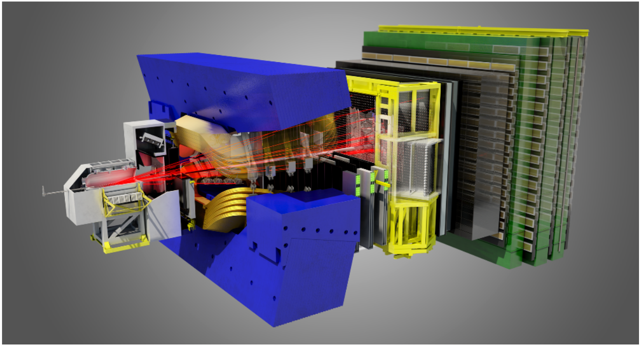
CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005), updated results and plots available at: http://ckmfitter.in2p3.fr

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

The LHCb detector

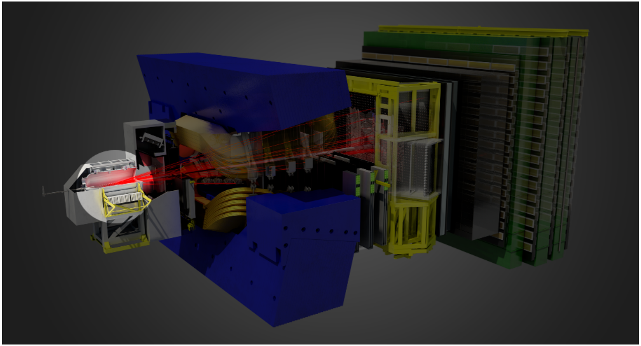
(Original Run 1 and 2 detector)

The LHCb detector



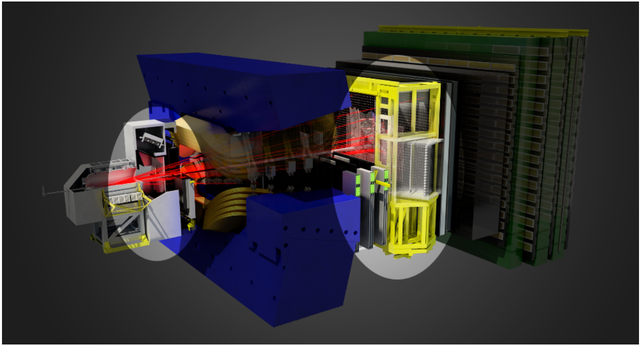
LHCb: A beauty experiment with a lot of charm

The LHCb detector



VELO: Vertex locator to reconstruct B and D vertices

The LHCb detector

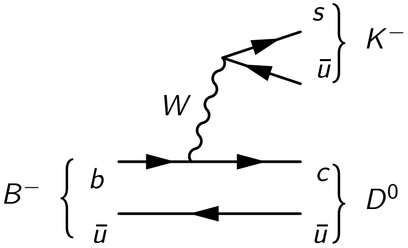


RICH: Identify particles from B and D

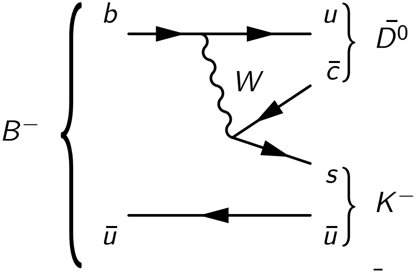
How to measure γ?

It's all about interferences!

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



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



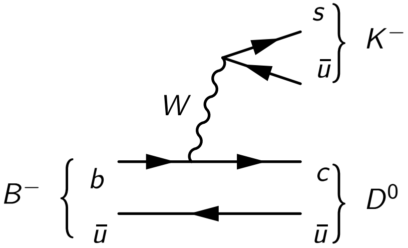
CKM+colour suppressed $B^- \to \bar{D}^0 K^-$

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

$$\begin{tikzcd} & D^0 K^- \arrow[dr] & \\ B^- \arrow[ur] \arrow[dr] & & f_D K^- \\ & \bar{D}^0 K^- \arrow[ur] & \end{tikzcd}$$

Sensitivity through interference

Measure γ through interference effects in $B^{\pm} \to DK^{\pm}$



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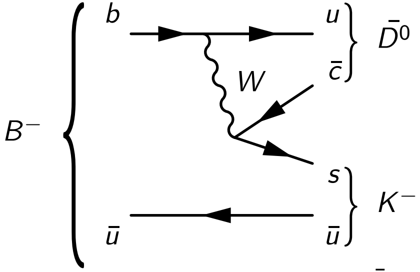


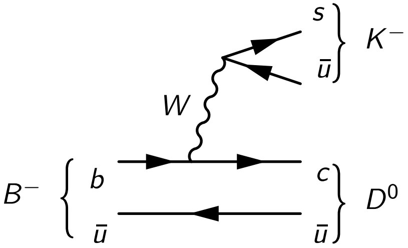
CKM+colour suppressed $B^- \to \bar{D}^0 K^-$

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

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

Sensitivity through interference

Measure γ through interference effects in $B^{\pm} \to DK^{\pm}$



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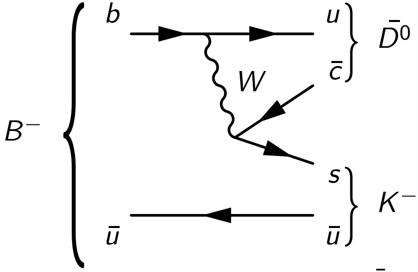

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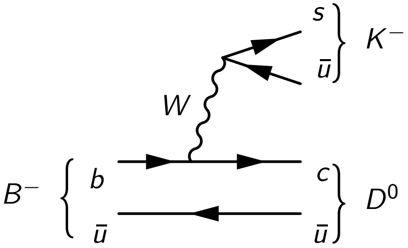
$$\mathcal{A}(B^-) = \mathcal{A}_B \left(\mathcal{A}_{D^0} + r_B e^{i(\delta_B - \gamma)} \mathcal{A}_{\bar{D}^0}\right)$$
$$\mathcal{A}(B^+) = \mathcal{A}_B \left(\mathcal{A}_{\bar{D}^0} + r_B e^{i(\delta_B + \gamma)} \mathcal{A}_{D^0}\right)$$

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

Sensitivity through interference

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



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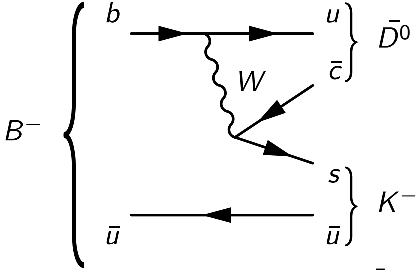

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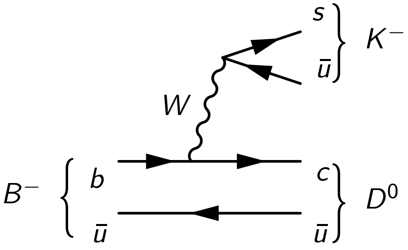
$$\mathcal{A}(B^+) = \mathcal{A}_B\left(\mathcal{A}_{\bar{D}^0} + r_B\, e^{i(\delta_B + \gamma)}\mathcal{A}_{D^0}\right)$$

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

Measure γ through interference effects in $B^{\pm} \to DK^{\pm}$



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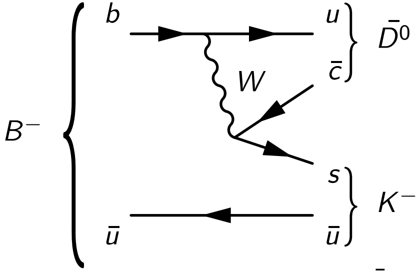

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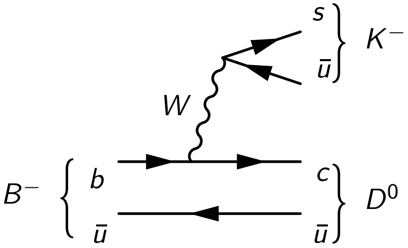
$$\mathcal{A}(B^+) = \mathcal{A}_B\left(\mathcal{A}_{\bar{D}^0} + r_B\, e^{i(\delta_B + \gamma)}\mathcal{A}_{D^0}\right)$$

The weak phase γ swaps sign under CP

Sensitivity through interference

Measure γ through interference effects in $B^{\pm} \to DK^{\pm}$



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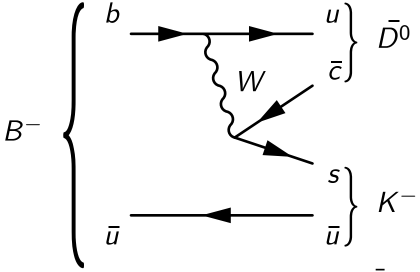

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$$\mathcal{A}(B^+) = \mathcal{A}_B\left(\mathcal{A}_{\bar{D}^0} + \boxed{r_B}\, e^{i(\boxed{\delta_B} + \boxed{\gamma})}\mathcal{A}_{D^0}\right)$$

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

What D final states should we consider?

No single method is sufficient to determine γ precisely!

1. GLW method: CP eigenstates
   - $D \to K^+K^-$, $\pi^+\pi^-$, ...
2.
3.

D decays to a CP eigenstate

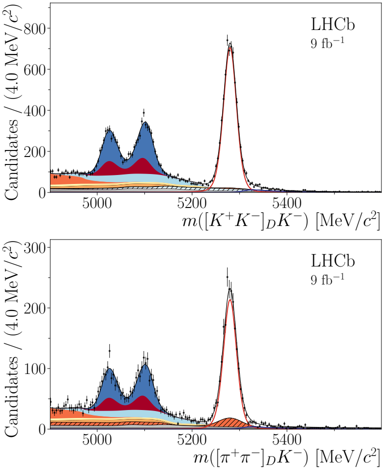
Naively, we expect the size of CPV effects to be around $r_B \approx 10\%$

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

$$
\begin{tikzcd}
 & D^0 K^- \arrow[dr, bend left, "\mathcal{A}_{D^0}"] & \\
B^- \arrow[ur, bend left, "\mathcal{A}_B"] \arrow[dr, bend right, "\mathcal{A}_B r_B e^{i(\delta_B - \gamma)}"'] & & DK^- \\
 & \bar{D}^0 K^- \arrow[ur, bend right, "\mathcal{A}_{D^0}"'] &
\end{tikzcd}
$$

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

D decays to a CP eigenstate



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

What D final states?

What D final states should we consider?

No single method is sufficient to determine γ precisely!

1. GLW method: CP eigenstates
   - $D \to K^+K^-$, $\pi^+\pi^-$, ...
2. ADS method: Doubly-Cabibbo Suppressed decays
   - $D \to K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, ...
3.

Doubly Suppressed Cabibbo D decays

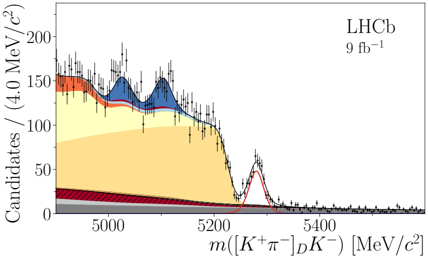
Interference effects can be greatly enhanced

Use a Doubly Suppressed Cabibbo decay: $\mathcal{A}_{D^0} = r_D e^{i\delta_D} \mathcal{A}_{\bar{D}^0}$

$$\begin{tikzcd}
 & D^0 K^- \arrow[dr, bend left, "r_D e^{i\delta_D} \mathcal{A}_{\bar{D}^0}"] & \\
B^- \arrow[ur, bend left, "\mathcal{A}_B"] \arrow[dr, bend right, "\mathcal{A}_B r_B e^{i(\delta_B - \gamma)}"'] & & DK^- \\
 & \bar{D}^0 K^- \arrow[ur, bend right, "\mathcal{A}_{\bar{D}^0}"'] &
\end{tikzcd}$$

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

Doubly Suppressed Cabibbo D decays



JHEP **04** (2021) 081

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

Additionally, the partially reconstructed background has an equal but opposite asymmetry

What D final states should we consider?

No single method is sufficient to determine γ precisely!

1. GLW method: CP eigenstates
   - $D \to K^+K^-$, $\pi^+\pi^-$, ...
2. ADS method: Doubly-Cabibbo Suppressed decays
   - $D \to K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, ...
3. BPGGSZ method: Multi-body final states
   - $D \to K_S^0\pi^+\pi^-$, $K_S^0K^+K^-$, ...

Multi-body D decays

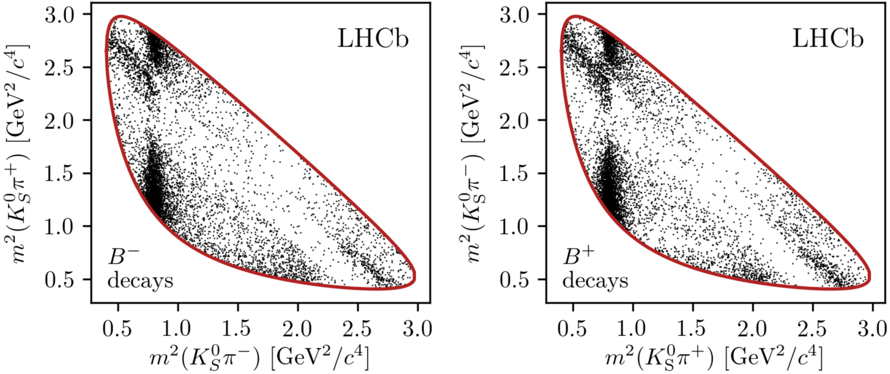
The three-body D-decay phase space is two-dimensional $\implies$ Dalitz plot

$B^{\pm}$ decay rate depends on the D^0 and $\bar{D}^0$ strong-phase difference

$$\begin{tikzcd}
 & D^0 K^- \arrow[dr, dashed, "\mathcal{A}_{D^0}(\Phi)"] & \\
B^- \arrow[ur, bend left, "\mathcal{A}_B"] \arrow[dr, bend right, "\mathcal{A}_B r_B e^{i(\delta_B - \gamma)}"'] & & DK^- \\
 & \bar{D}^0 K^- \arrow[ur, dashed, "r_D(\Phi) e^{i\delta_D(\Phi)} \mathcal{A}_{D^0}(\Phi)"'] &
\end{tikzcd}$$

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

Multi-body D decays

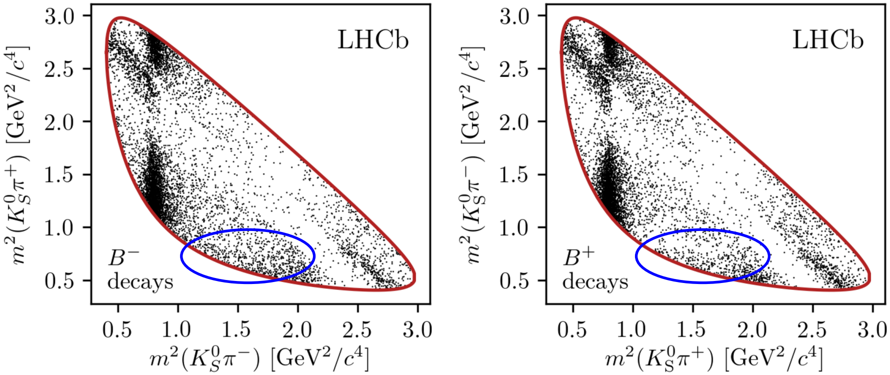


$B^- \to [K_S^0\pi^+\pi^-]_D K^-$ $B^+ \to [K_S^0\pi^+\pi^-]_D K^+$

JHEP **02** (2021) 169

Can you find the asymmetries?

Multi-body D decays

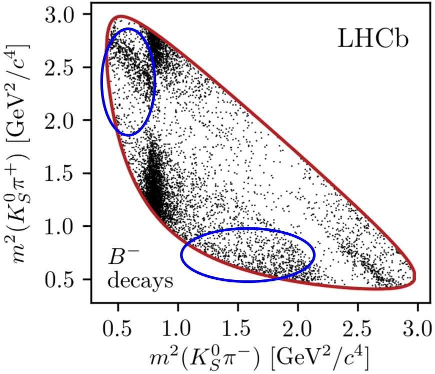


$B^- \to [K_S^0\pi^+\pi^-]_D K^-$ $\qquad$ $B^+ \to [K_S^0\pi^+\pi^-]_D K^+$

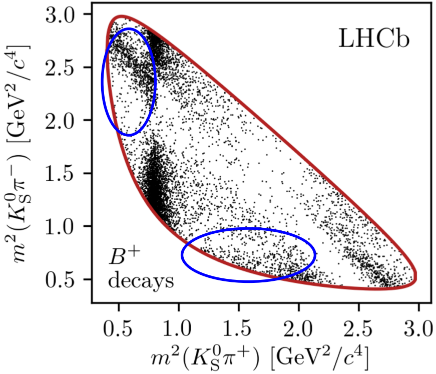
JHEP **02** (2021) 169

Can you find the asymmetries?

Multi-body D decays



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



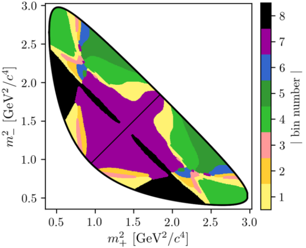
$B^+ \to [K_S^0\pi^+\pi^-]_D K^+$

JHEP **02** (2021) 169

Can you find the asymmetries?

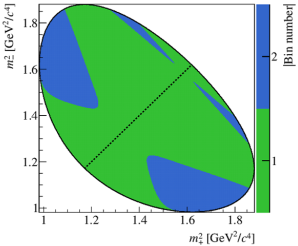
Multi-body D decays

- Interpretation of γ from the multi-body charm decays require external inputs of the charm strong-phase differences
- The three-body decays $D \to K_S^0 h^+ h^-$ 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 γ becomes model independent



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

JHEP **02** (2021) 169

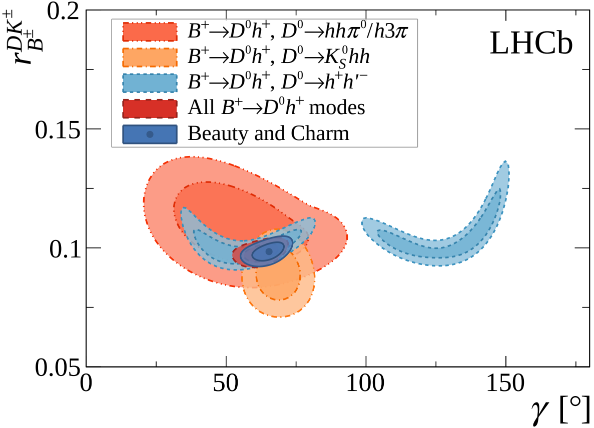


$K_S^0 K^+ K^-$

The LHCb γ and charm combination

Lots of beauty in charm!

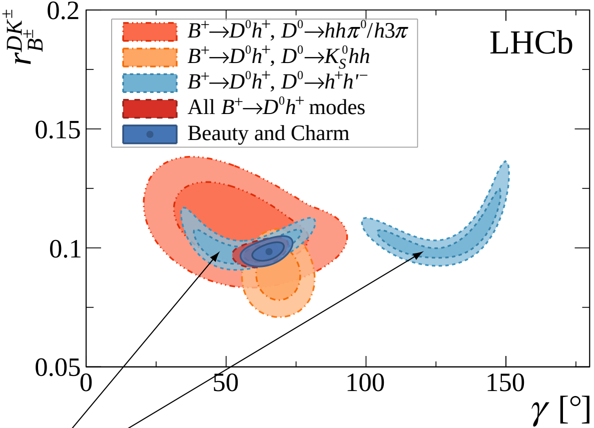
The LHCb γ and charm combination



JHEP **12** (2021) 141

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

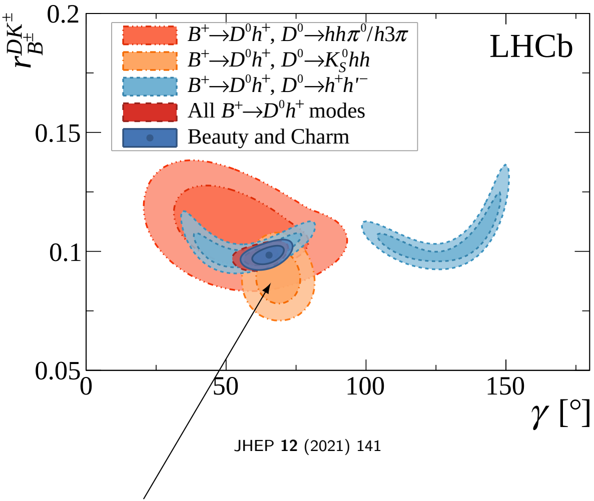
The LHCb γ and charm combination



JHEP **12** (2021) 141

GLW+ADS: Narrow bands, but many degenerate solutions

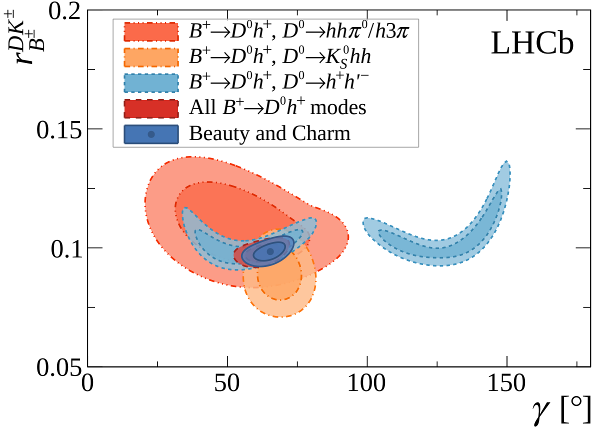
The LHCb γ and charm combination



JHEP **12** (2021) 141

BPGGSZ: Wider, but unqiue solution

The LHCb γ and charm combination



JHEP **12** (2021) 141

A combination of direct γ measurements is necessary!

Other B decays are also interesting for γ measurements:

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

- And many more...

The LHCb γ and charm combination

Other B decays are also interesting for γ measurements:

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

- And many more...

Other B decays are also interesting for γ measurements:

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

- And many more...

The LHCb γ and charm combination

Other B decays are also interesting for γ measurements:

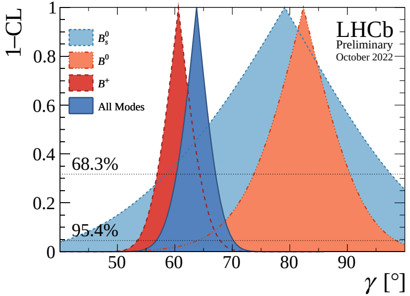
1. $B^{\pm} \to DK^{\pm} \leftarrow$ Golden mode
2. $B^{\pm} \to D^{*0}K^{\pm} \leftarrow$ New results!
3. $B^{0} \to DK^{*0} \leftarrow$ New results!
4. $B_s^{0} \to D_s^{-}K^{+} \leftarrow$ Not covered today

- And many more...

Other B decays are also interesting for γ measurements:

1. $B^{\pm} \to DK^{\pm}$
2. $B^{\pm} \to D^{*0}K^{\pm}$
3. $B^{0} \to DK^{*0}$
4. $B^{0}_{s} \to D^{-}_{s}K^{+}$

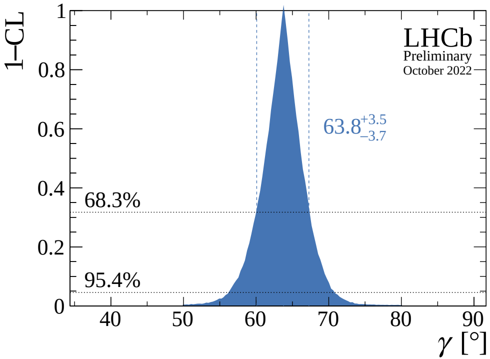
- And many more...



LHCb-CONF-2022-003

The LHCb γ and charm combination

Our most precise knowledge of γ comes from the combination of γ and charm mixing parameters



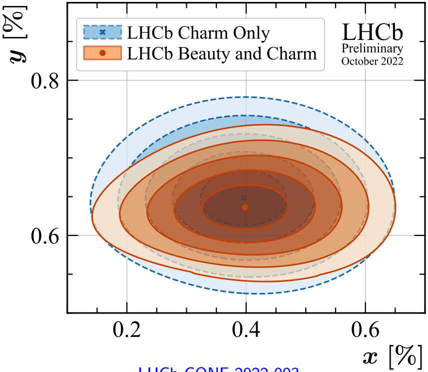
LHCb-CONF-2022-003

This is the most precise determination of γ by a single experiment!

Charged $B^{\pm}$ modes dominate, but all measurements are consistent

The LHCb γ and charm combination

Our most precise knowledge of γ comes from the combination of γ and charm mixing parameters



LHCb-CONF-2022-003

Mixing effects to γ measurements are approaching the statistical sensitivity

Knowledge of y is significantly improved through correlations with $\delta_D^{K\pi}$

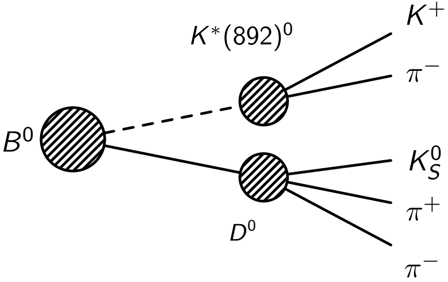
Neutral B decays

More interference with less statistics

Neutral B decays

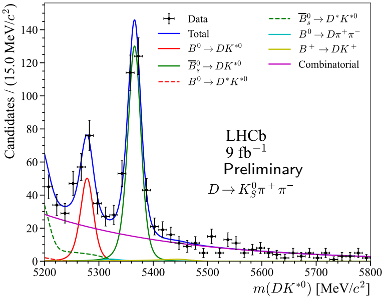
Neutral B decays are analysed with an identical strategy:

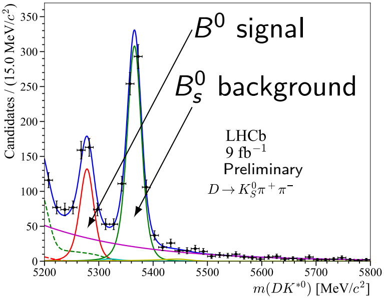
LHCb-PAPER-2023-009 (in preparation) New results!



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

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





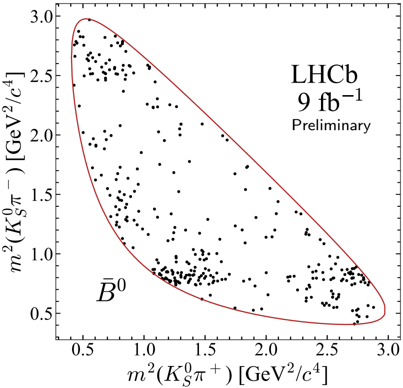
LL

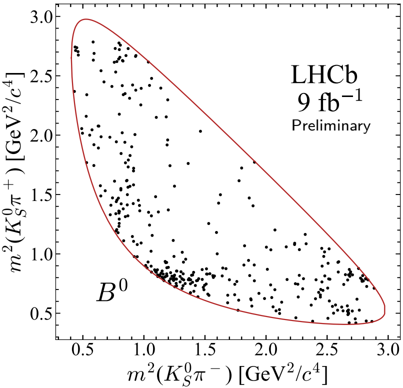
DD

LHCb-PAPER-2023-009

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

Neutral B decays



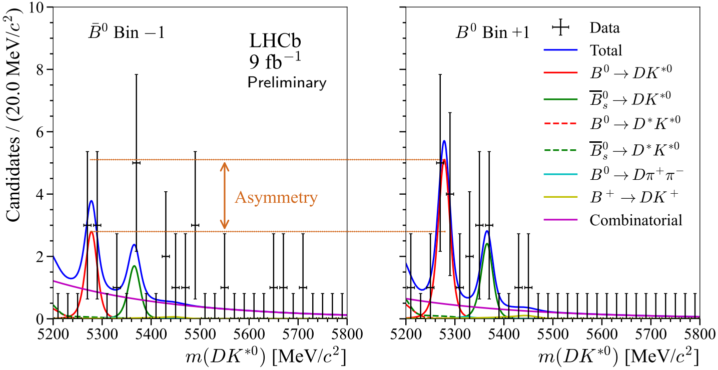


$\bar{B}^0$ B^0

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

Can you find the asymmetries?

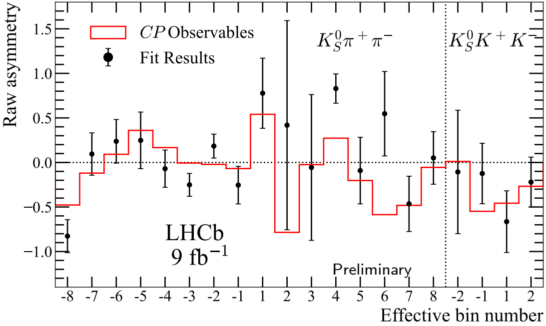
Neutral B decays



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^0_s decays, and these are not looked for

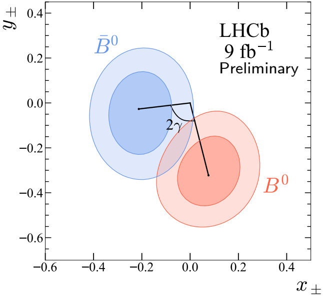
Neutral B decays

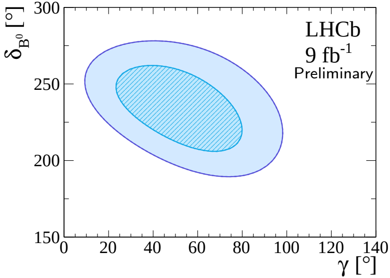


LHCb-PAPER-2023-009

- 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:

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

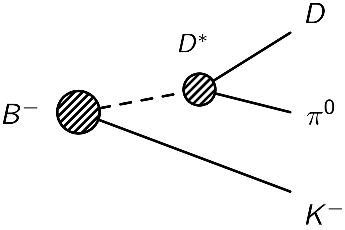
- Measured value of γ is consistent with world average:
  - $\gamma = (49 \pm 20)^\circ$
  - $\delta_{B^0} = (236 \pm 19)^\circ$
  - $r_{B^0} = 0.27 \pm 0.07 \leftarrow$ 3 times larger than the $B^\pm$ modes!

B decays to excited D^* final states

A measurement with neutral particles

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

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



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

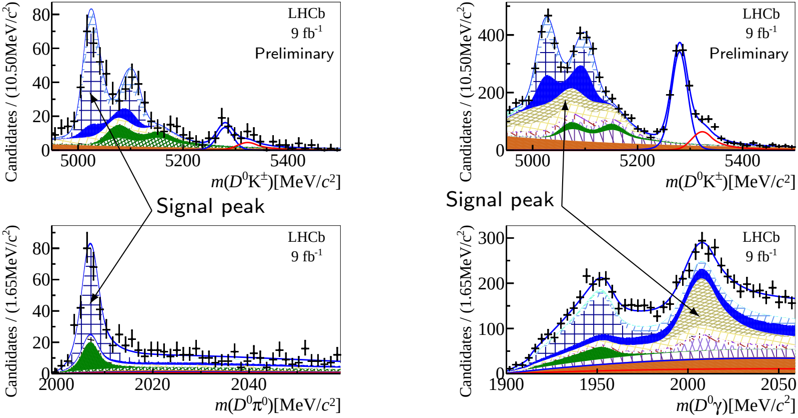
$$\mathcal{A}(D^0) + r_B e^{i(\delta_B - \gamma)} \mathcal{A}(\bar{D}^0)$$

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

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

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

B decays to excited D^* final states

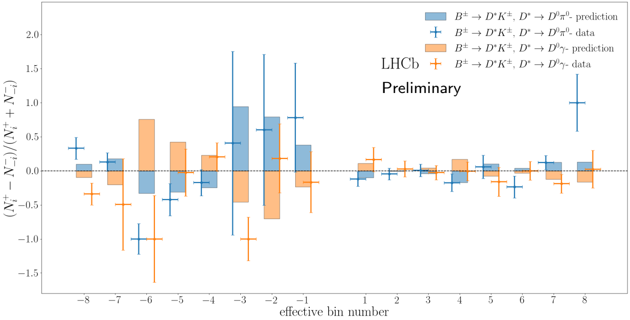


$D^* \to D\pi^0$ **(a)** $D^* \to D\gamma$

LHCb-PAPER-2023-012

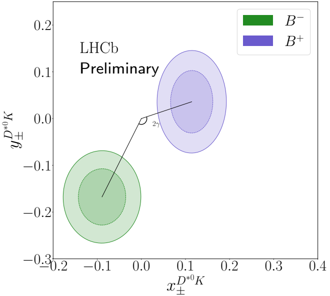
A 2D fit is necessary to separate signal from background

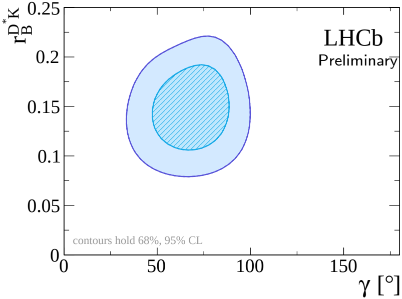
B decays to excited D^* final states



LHCb-PAPER-2023-012

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





LHCb-PAPER-2023-012

These results provide strong constraints on γ:

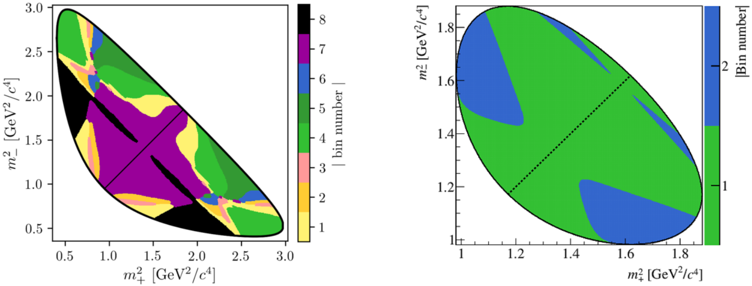
- $\gamma = (69 \pm 14)^\circ$
- $\delta_B^{D^*K} = (311 \pm 15)^\circ$
- $r_B^{D^*K} = 0.15 \pm 0.03$

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

A journey through five dimensions

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

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

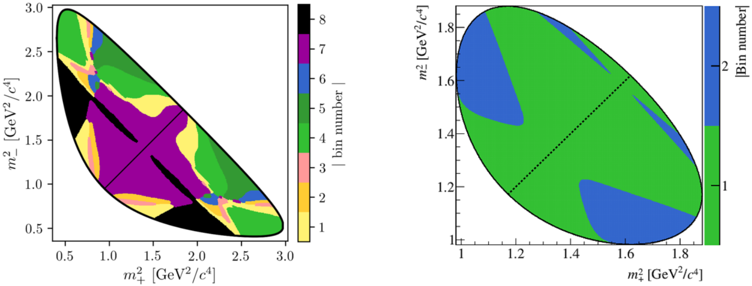


$K_S^0\pi^+\pi^-$ $\quad$ $K_S^0K^+K^-$

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

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

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



$K^0_S\pi^+\pi^-$ $K^0_S K^+ K^-$

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

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

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 γ measurement will be <u>model independent</u>

A binning scheme must satisfy the following:

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

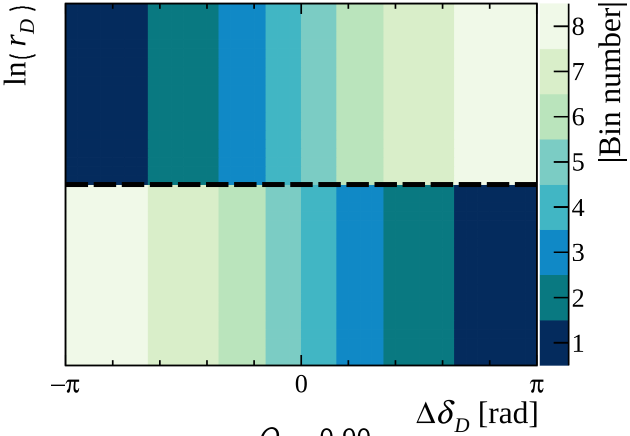
How to bin a 5-dimensional phase space?

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

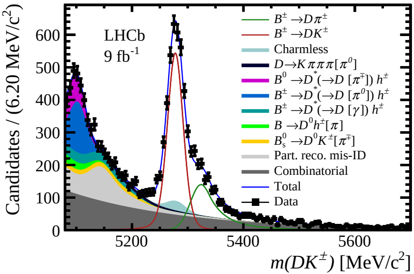


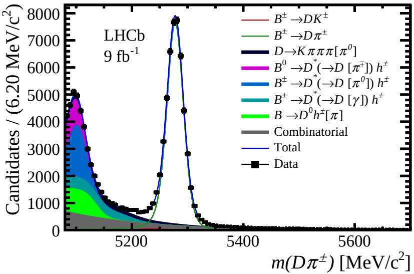
$Q = 0.90$

Bins $i < 0$ on top, $i > 0$ below

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

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

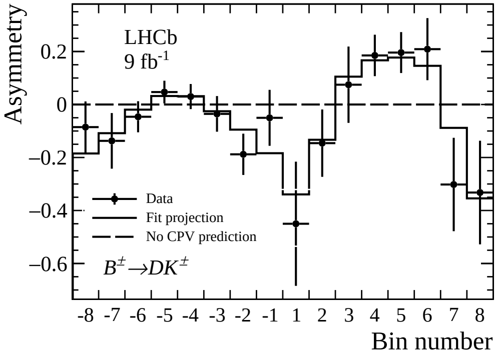




Eur. Phys. J. C **83**, 547 (2023)

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

Phase-space binned $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$



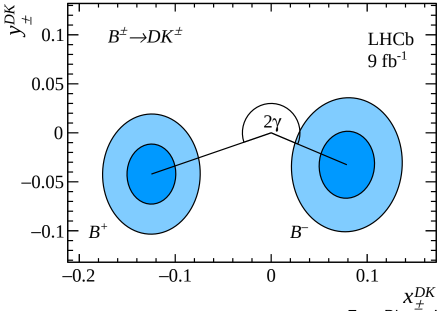
Eur. Phys. J. C **83**, 547 (2023)

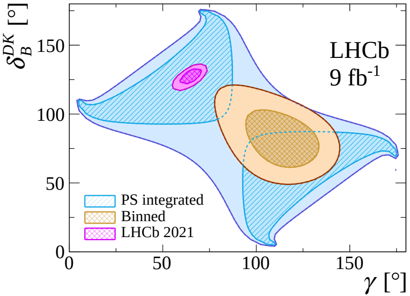
- Clear bin asymmetries are seen, and the non-trivial distribution is driven by the change in strong-phase differences across phase space
- While the interpretation of γ require charm inputs, the observed bin asymmetries are model independent

Phase-space binned $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$

From the phase-space binned asymmetries, we obtain:

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





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

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:

- The measurements presented today will make valuable improvements to future γ combinations
- Several interesting Run 1+2 results are in the pipeline:
  1. Update of $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ with charm inputs from BESIII
  2. GLW and ADS results from $B^0 \to DK^{*0}$ could shed light on the (slight) tension between B^0 and $B^{\pm}$
  3. Time-dependent measurements, such as $B_s^0 \to D_s^- K^+$ 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
  - γ is still dominated by statistical uncertainties!

Summary and future prospects

In summary:

1. Long journey towards a precise determination of γ
2. Two recent results of $B^{\pm} \to D^{*} h^{\pm}$ and $B^{0} \to DK^{*0}$ with $D \to K_{S}^{0} h^{+} h^{-}$, using external inputs from BESIII
   - Unique synergy between beauty and charm factories
3. A binned measurement with the channel $B^{\pm} \to [K^{+} K^{-} \pi^{+} \pi^{-}]_{D} K^{\pm}$ 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 after Run 3 and 4!

In summary:

1. Long journey towards a precise determination of γ
2. Two recent results of $B^{\pm} \to D^{*} h^{\pm}$ and $B^{0} \to DK^{*0}$ with $D \to K_{S}^{0} h^{+} h^{-}$, using external inputs from BESIII
   - Unique synergy between beauty and charm factories
3. A binned measurement with the channel $B^{\pm} \to [K^{+}K^{-}\pi^{+}\pi^{-}]_{D}K^{\pm}$ 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!

Thanks for your attention!