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

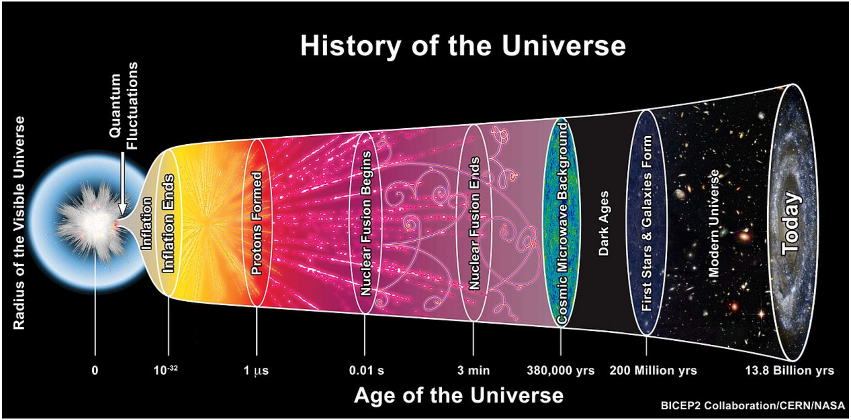
Plan for this seminar:

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:
   - $B^0 \to DK^*$, $D \to K_S^0 h^+ h^-$
   - $B^\pm \to D^* h^\pm$, $D \to K_S^0 h^+ h^-$
   - $B^\pm \to Dh^\pm$, $D \to K^+ K^- \pi^+ \pi^-$
4. Future prospects (Run 3 and beyond)

Introduction to *CP* violation

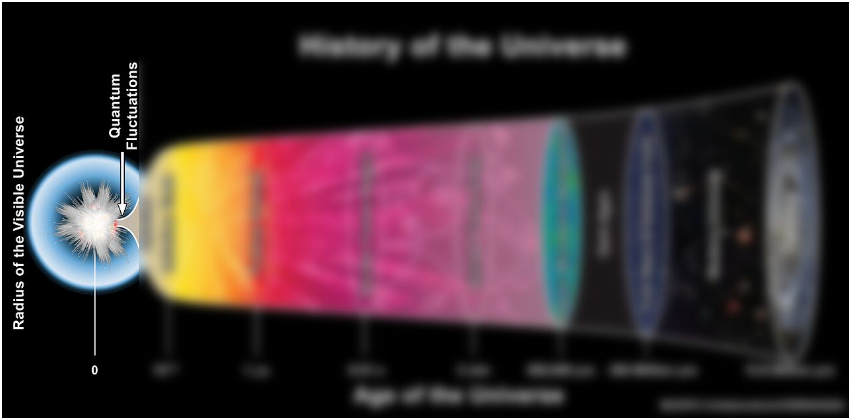
What is γ and why measure it?

Big Bang and matter-antimatter asymmetry



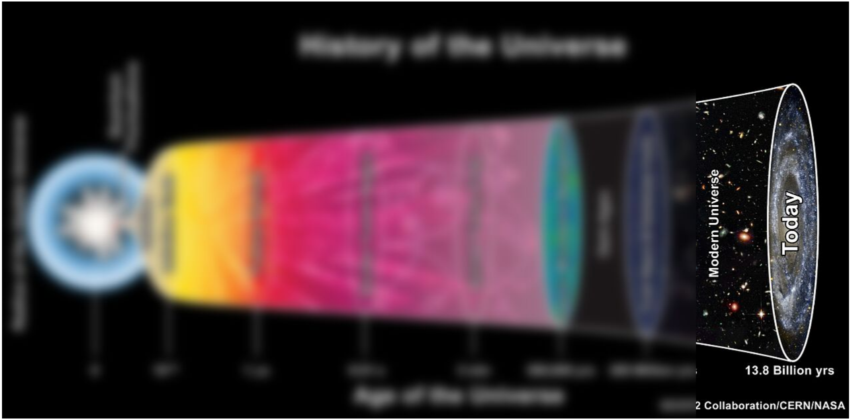
Where is the antimatter in the universe?

Big Bang and matter-antimatter asymmetry



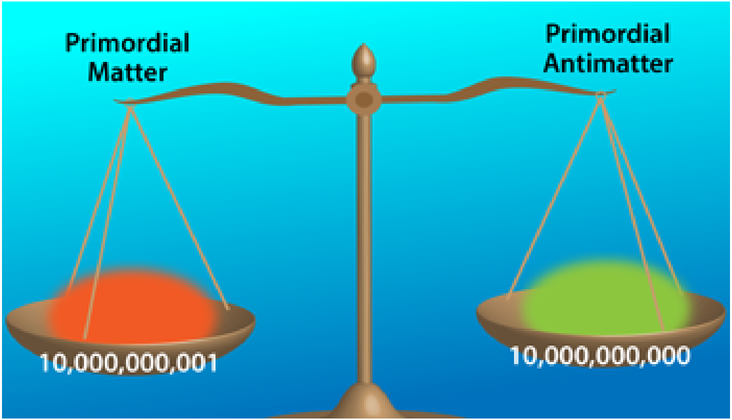
Initially equal amounts of matter and antimatter...

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

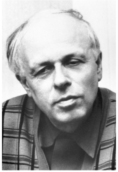


Photo from the Nobel Foundation archive.
Andrei Dmitrievich Sakharov
Prize share: 1/1

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

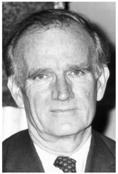


Photo from the Nobel Foundation archive.
Val Logsdon Fitch
Prize share: 1/2

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"

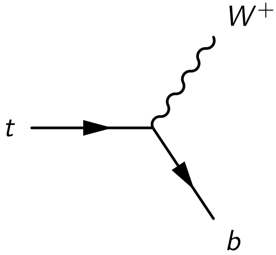
- CP violation discovery in 1964
- Phys. Rev. Lett. **13**, 138
- Observed $K_L^0 \to \pi^+\pi^-$
- Since, *CP* violation has also been observed in the B, B_s and D systems

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

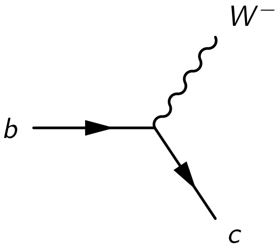
The CKM matrix and the Unitary Triangle

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

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

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:

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

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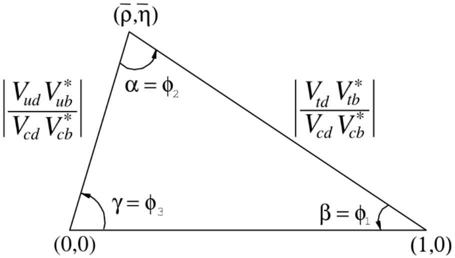

R. L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

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
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Prize share: 1/2

© The Nobel Foundation Photo: U. Montan
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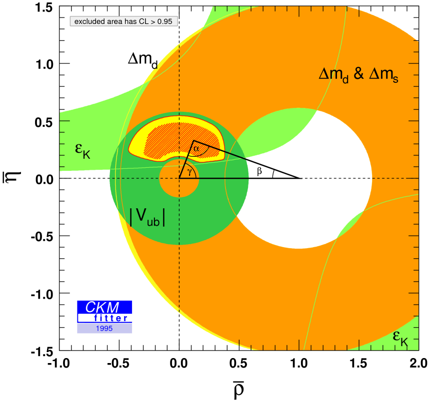
Precise knowledge of quark interactions will help us search for new physics with CPV, which may not have the same CKM structure

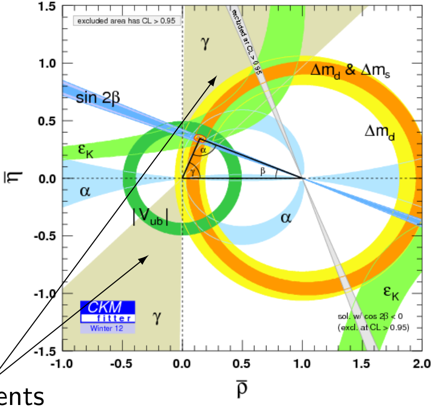
The CKM matrix and the Unitary Triangle

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

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

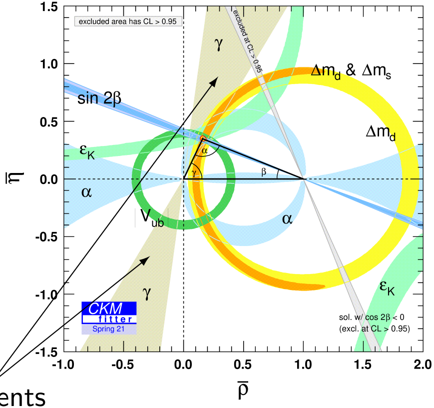


Direct γ measurements

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

The CKM matrix and the Unitary Triangle

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



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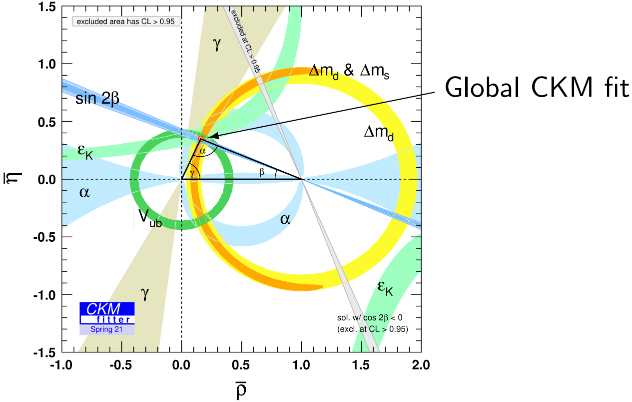

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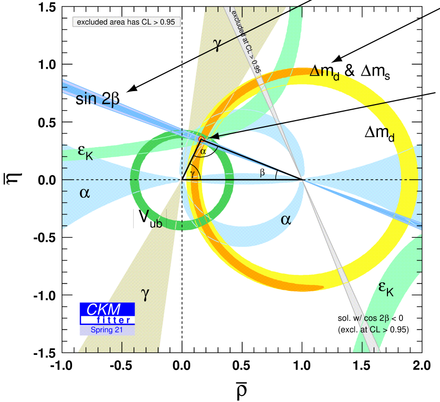
The CKM matrix and the Unitary Triangle

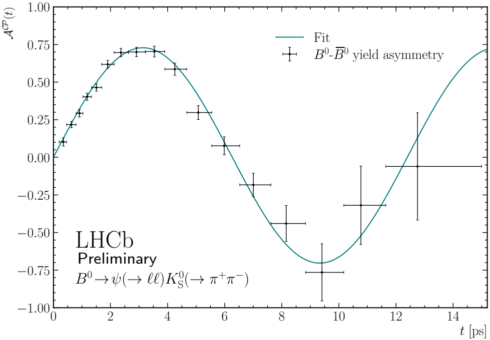
Loop level measurements of γ are dominated by $\sin(2\beta)$ and B^0/B_s^0 mixing

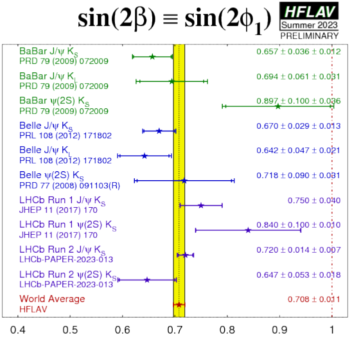


Global CKM fit

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(2β)





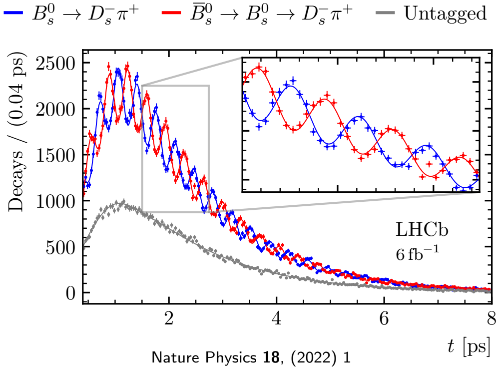
$$\text{World average: } \sin(2\beta) = 0.708 \pm 0.011$$

$$\beta = (22.5 \pm 0.4)^\circ$$

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



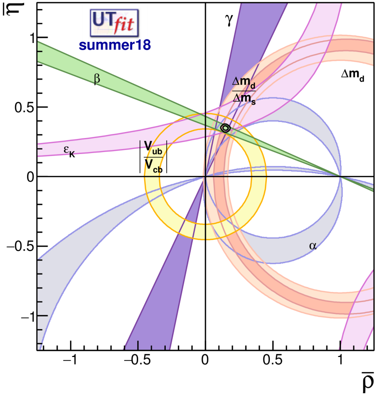
Nature Physics **18**, (2022) 1

HFLAV averages:

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

The CKM matrix and the Unitary Triangle

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

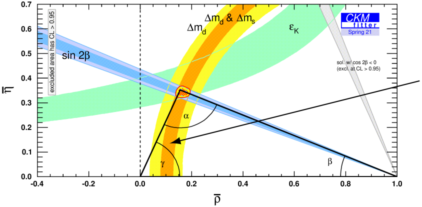


http://www.utfit.org/UTfit/

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

Why is the CKM angle γ of interest?



Dominated by lattice QCD

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

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

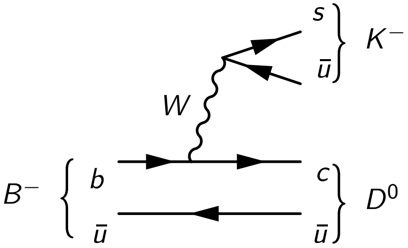
With precise γ measurements, we can compare with the indirect loop level measurements, which assume unitarity ("SM prediction")

How to measure γ?

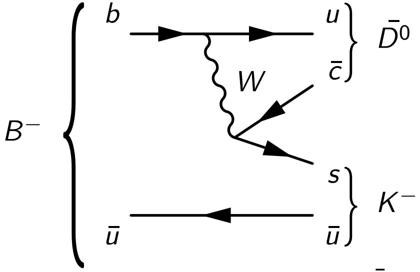
It's all about interference!

Sensitivity through interference

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

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

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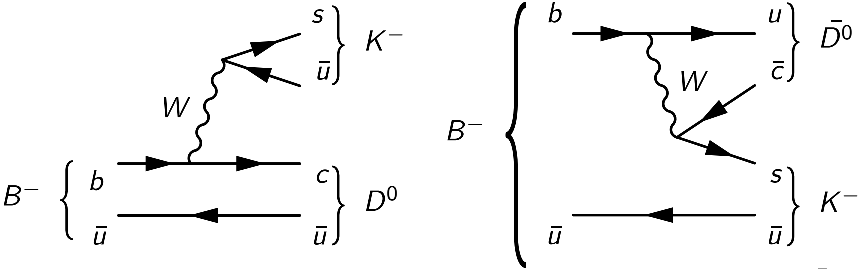
Measure γ through interference effects in $B^\pm \to DK^\pm$



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

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

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

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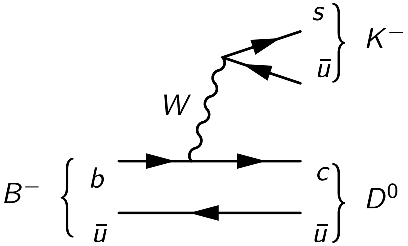

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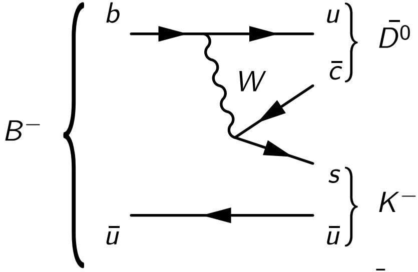

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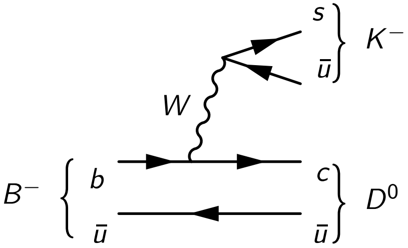
$$\mathcal{A}(B^+) = \mathcal{A}_B\left(\mathcal{A}_{\bar{D}^0} + \boxed{r_B}\, e^{i(\delta_B + \gamma)}\mathcal{A}_{D^0}\right)$$

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

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



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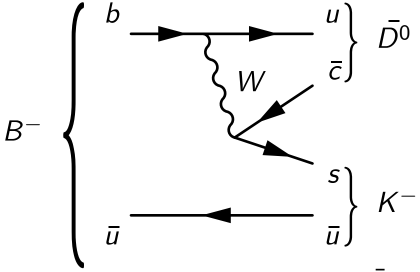

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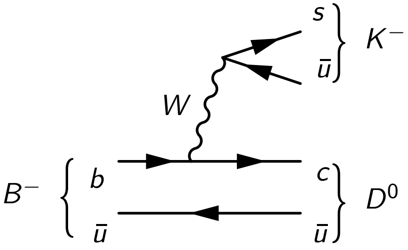
$$\mathcal{A}(B^+) = \mathcal{A}_B\big(\mathcal{A}_{\bar{D}^0} + r_B\, e^{i(\delta_B + \gamma)}\mathcal{A}_{D^0}\big)$$

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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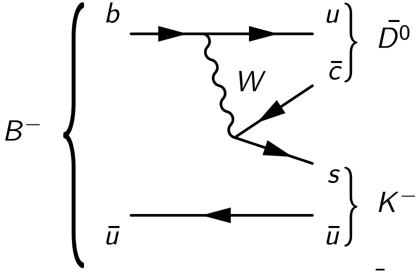

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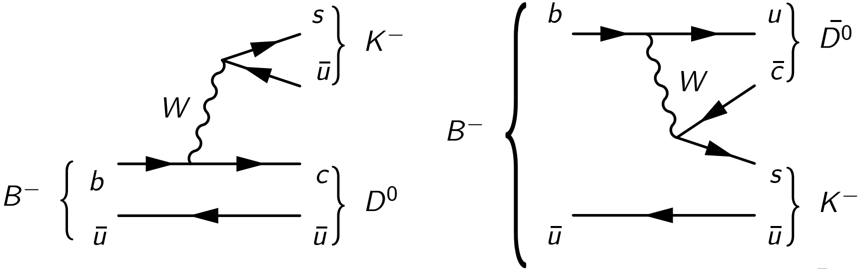
The weak phase γ swaps sign under CP

Sensitivity through interference

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



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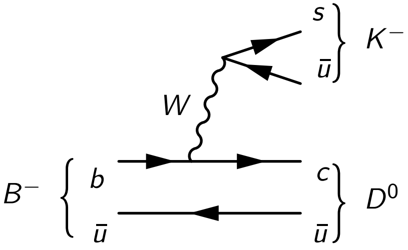
$$\mathcal{A}(B^+) = \mathcal{A}_B\left(\mathcal{A}_{\bar{D}^0} + r_B e^{i(\delta_B + \gamma)} \mathcal{A}_{D^0}\right)$$

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

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



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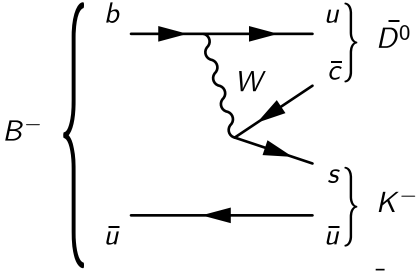

CKM+colour suppressed $B^- \to \bar{D}^0 K^-$

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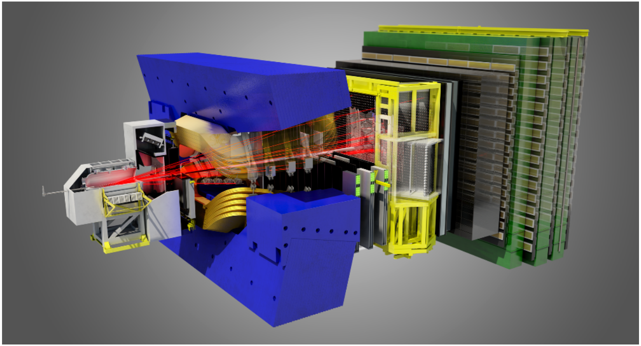
$$\mathcal{A}(B^+) = \mathcal{A}_B\left(\mathcal{A}_{\bar{D}^0} + r_B e^{i(\delta_B + \gamma)}\mathcal{A}_{D^0}\right)$$

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

The LHCb detector

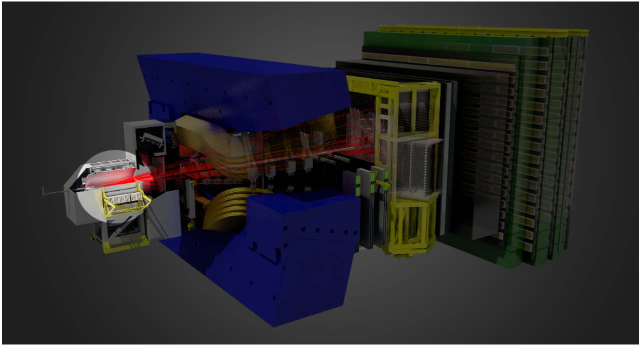
(Original Run 1 and 2 detector)

The LHCb detector



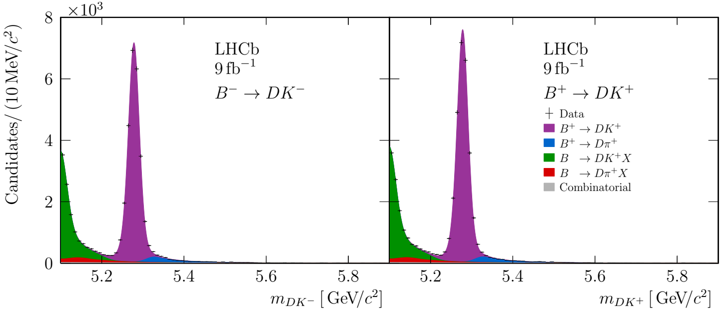
LHCb: A beauty experiment with a lot of charm

The LHCb detector



VELO: Vertex locator to reconstruct B and D vertices

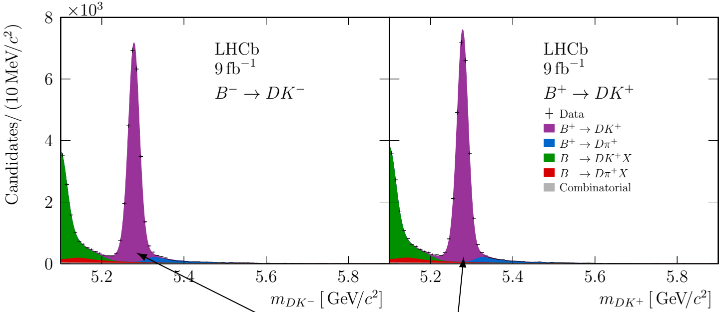
The LHCb detector



LHCb-PAPER-2022-017

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

The LHCb detector

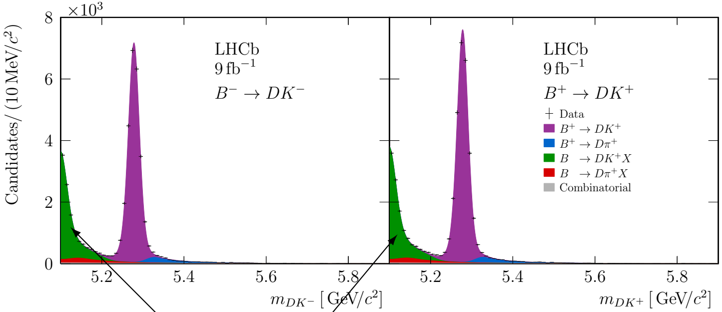


LHCb-PAPER-2022-017

Correctly reconstructed $B^{\pm}$ candidates

High signal efficiency

The LHCb detector

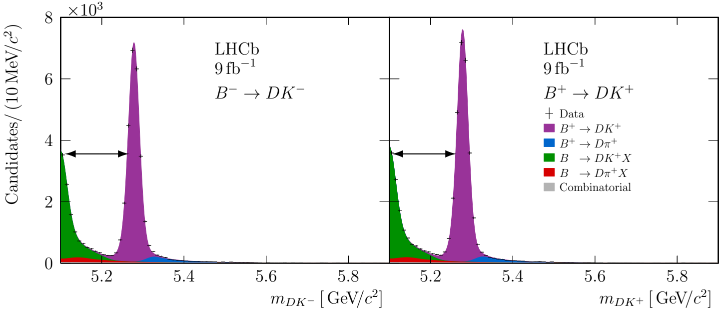


LHCb-PAPER-2022-017

Partially reconstructed background

B decays with missing pion or photon

The LHCb detector

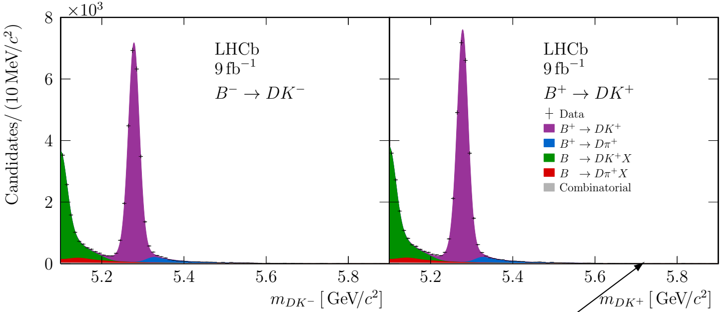


LHCb-PAPER-2022-017

Excellent mass resolution

Signal is well separated from partially reconstructed background

The LHCb detector

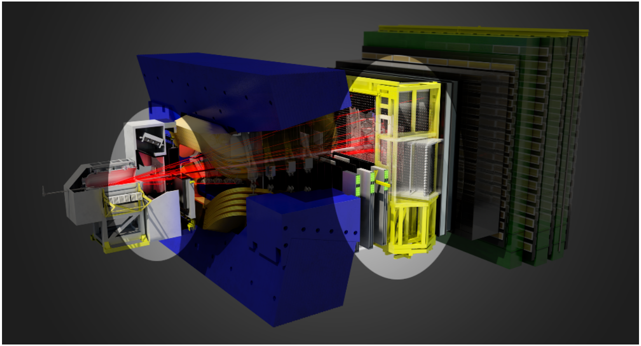


LHCb-PAPER-2022-017

Extremely low combinatorial background

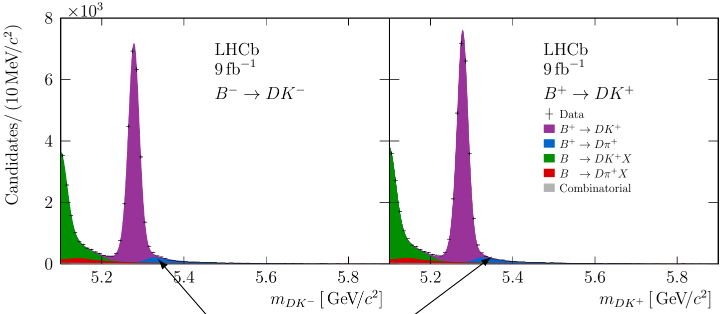
Clean environment at a hadron collider

The LHCb detector



RICH: Identify particles from B and D

The LHCb detector



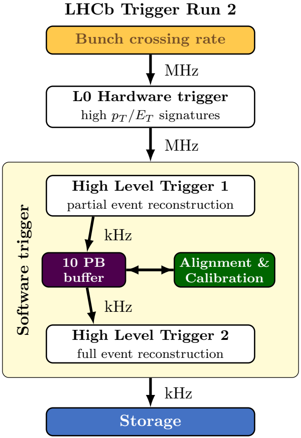
LHCb-PAPER-2022-017

Mis-ID from $D\pi^{\pm} \to DK^{\pm}$ is almost negligible

Without PID, this background would be 13 times larger than signal!

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



JINST **14** (2019) 04, P04013

Methods for measuring γ

How to interpret asymmetries?

What D final states?

Several methods are used to measure γ precisely

What D final states?

Several methods are used to measure γ precisely

1. CP eigenstates ("GLW method")
   - $D \to K^+K^-$, $\pi^+\pi^-$, ...
   - Phys. Lett. B **253** (1991) 483, Phys. Lett. B **265** (1991) 172

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

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

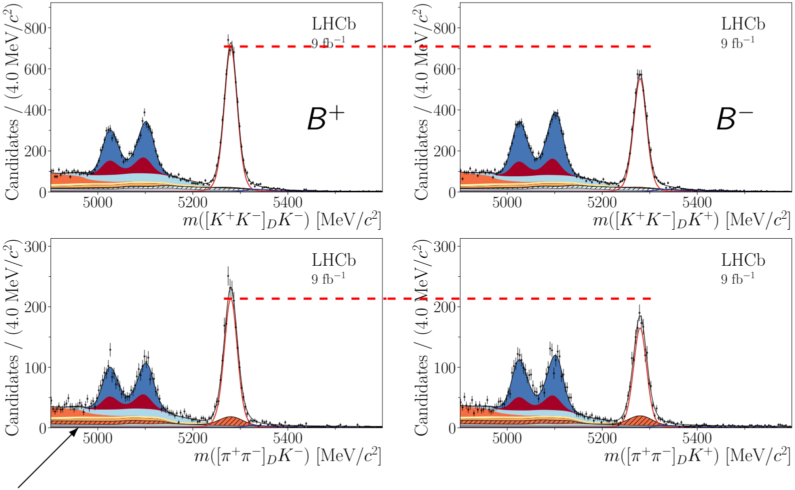
For CP eigenstates, $\mathcal{A}_{D^0} = \mathcal{A}_{\bar{D}^0}$

$$
\begin{tikzcd}
 & D^0K^- \arrow[dr, bend left, "\mathcal{A}_{D0}"] & \\
B^- \arrow[ur, bend left, "\mathcal{A}_B"] \arrow[dr, bend right, "\mathcal{A}_B r_B e^{i(\delta_B-\gamma)}"'] & & DK^- \\
 & \bar{D}^0K^- \arrow[ur, bend right, "\mathcal{A}_{D0}"'] &
\end{tikzcd}
$$

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

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

D decays to a CP eigenstate



Partially reconstructed background

JHEP **04** (2021) 081

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

What D final states?

Several methods are used to measure γ precisely

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

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

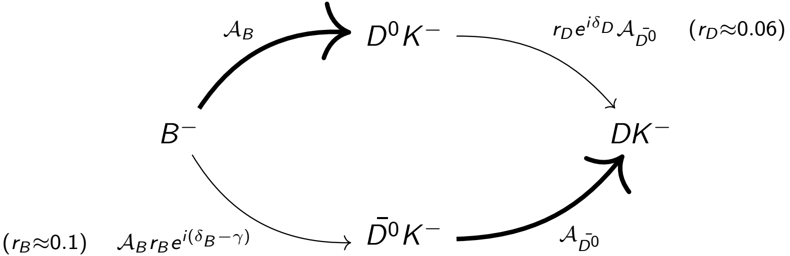
$$\begin{tikzcd}
& D^0 K^- \arrow[dr, "r_D e^{i\delta_D}\mathcal{A}_{\bar{D}^0} \quad (r_D \approx 0.06)"] & \\
B^- \arrow[ur, "\mathcal{A}_B"] \arrow[dr, "(r_B \approx 0.1) \quad \mathcal{A}_B r_B e^{i(\delta_B - \gamma)}"'] & & DK^- \\
& \bar{D}^0 K^- \arrow[ur, "\mathcal{A}_{\bar{D}^0}"'] &
\end{tikzcd}$$

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

Doubly Suppressed Cabibbo D decays

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



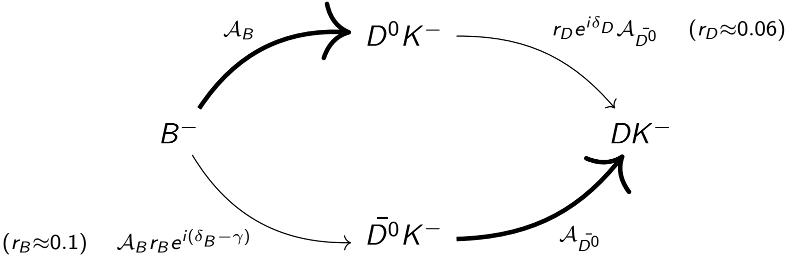
$$|\mathcal{A}(B^-)|^2 \propto r_D^2 + r_B^2 + 2 r_B r_D \cos(\delta_B - \gamma + \delta_D)$$

$r_D \approx \tan^2(\theta_c)$ 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



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

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

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

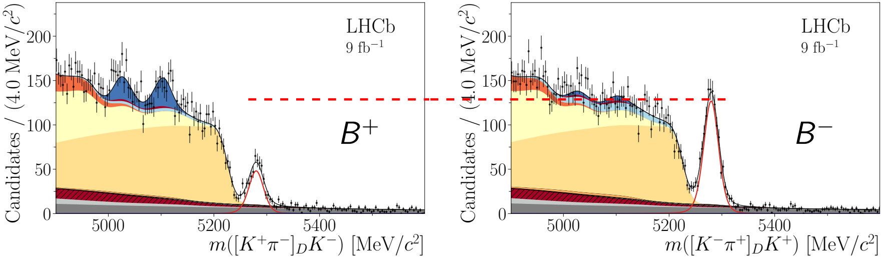
$(r_D \approx 0.06)$

$(r_B \approx 0.1)$

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

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

Doubly Suppressed Cabibbo D decays

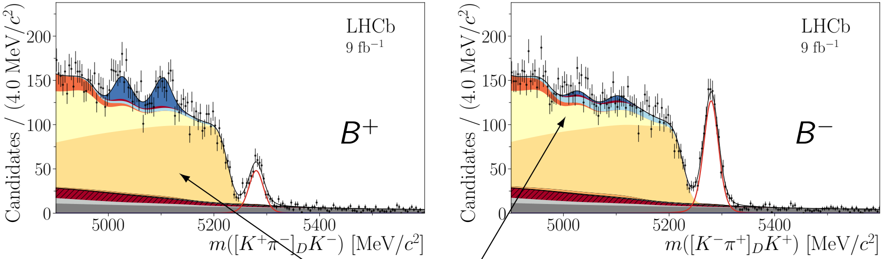


JHEP **04** (2021) 081

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

Note: Total branching fraction is 5.5×10^{-8}!

Doubly Suppressed Cabibbo D decays

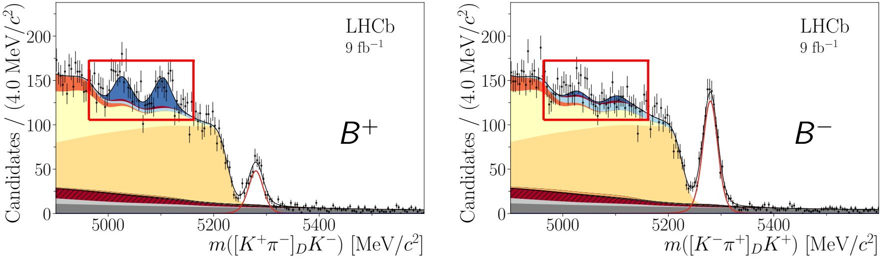


JHEP **04** (2021) 081

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

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

Doubly Suppressed Cabibbo D decays

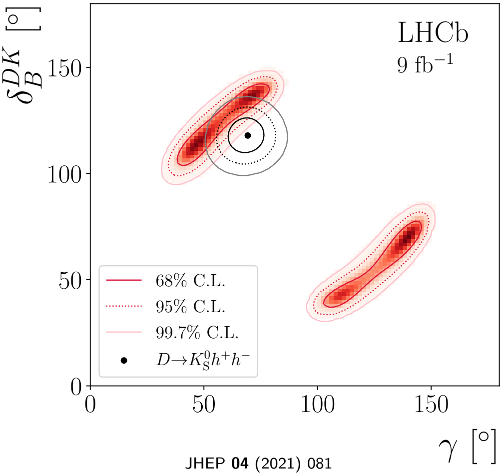


JHEP **04** (2021) 081

Asymmetry is also seen in the double-peaked background

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

Combined CP eigenstate and DCS decays



JHEP **04** (2021) 081

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

Multi-body D decays

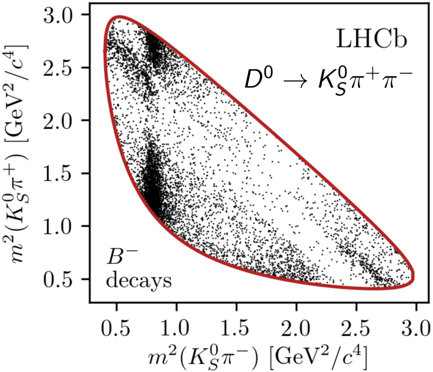
- Multi-body decays can have many intermediate resonances
- Decay amplitudes therefore vary across "phase space"

Degrees of freedom for an N-body decay

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

Multi-body D decays

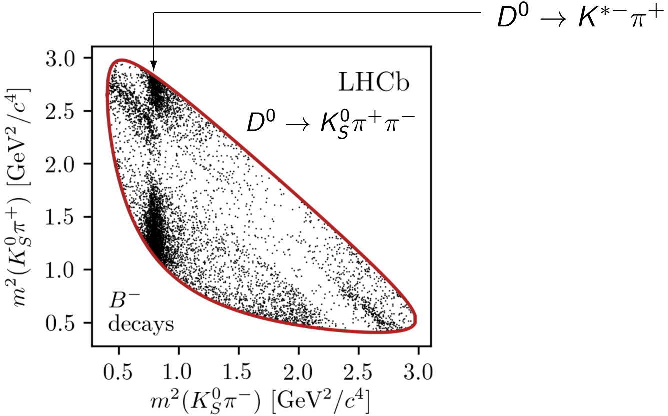
For 3-body decays, phase space is two-dimensional: Dalitz plots



JHEP **02** (2021) 169

Multi-body D decays

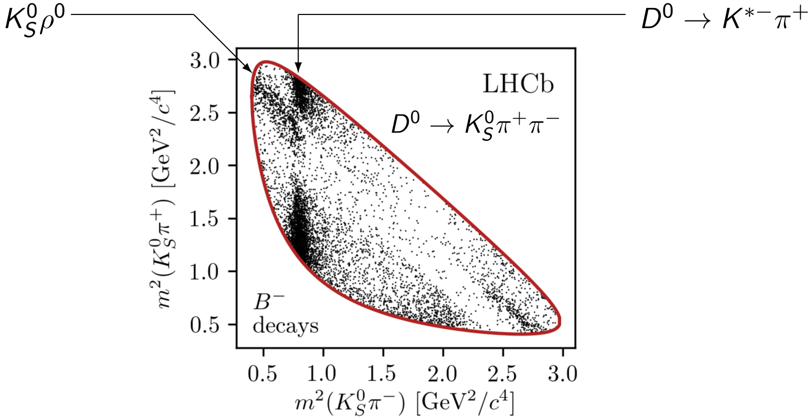
For 3-body decays, phase space is two-dimensional: Dalitz plots



JHEP **02** (2021) 169

Multi-body D decays

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



JHEP **02** (2021) 169

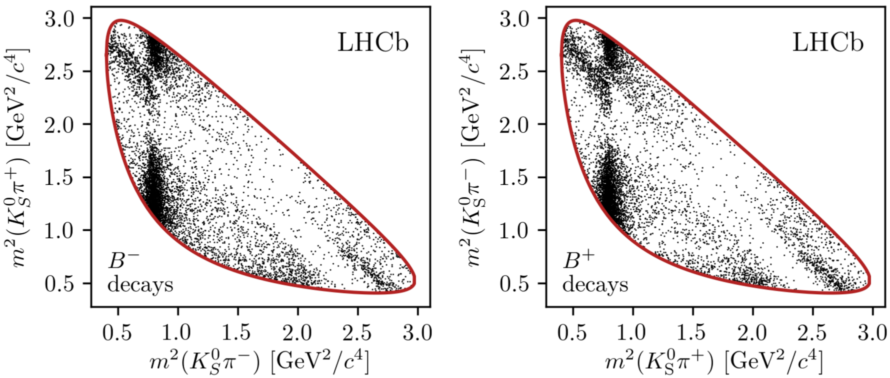
Multi-body D decays

$B^{\pm}$ 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

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

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



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

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

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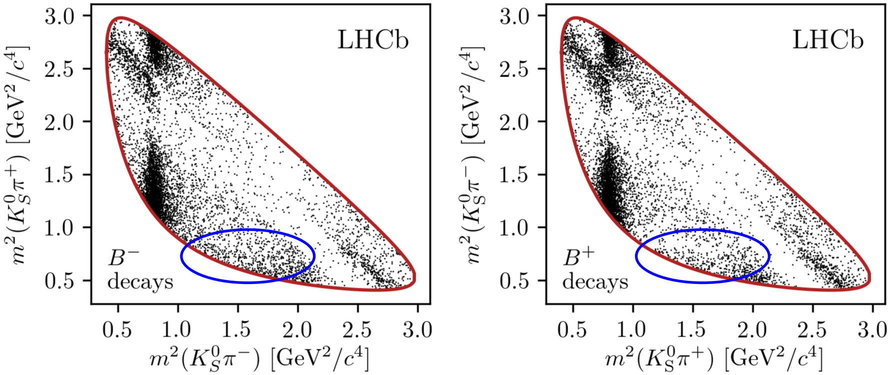
Can you find the asymmetries?

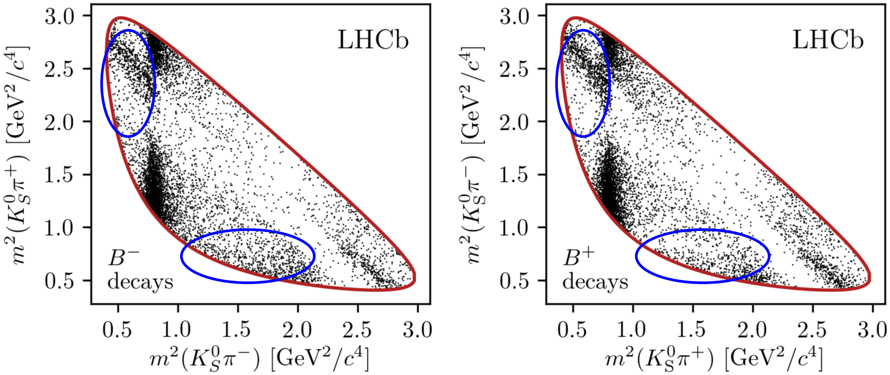
Multi-body D decays



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

JHEP **02** (2021) 169

Can you find the asymmetries?



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

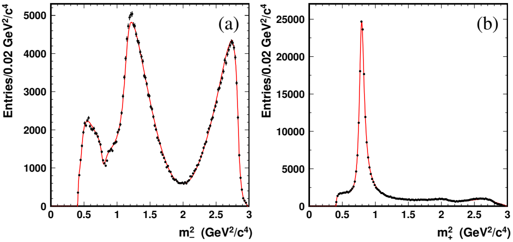
$B^+ \to [K_S^0\pi^+\pi^-]_D K^+$

JHEP **02** (2021) 169

Can you find the asymmetries?

Multi-body D decays

- Interpretation of γ from the multi-body charm decays 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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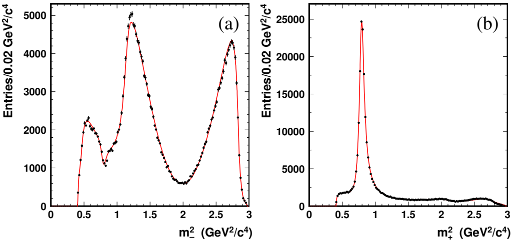
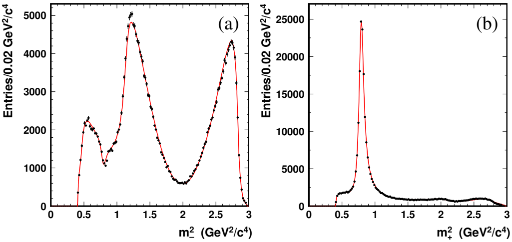


Phys. Rev. D **73** (2006) 112009

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 $\mathcal{A}(\Phi) = \sum_i a_i \mathcal{F}_i$
  2. Lineshapes $\mathcal{F}_i$ can be Breit-Wigner, etc.
  3. Fit $|\mathcal{A}|^2$ to <u>data</u> to determine the complex coefficients a_i

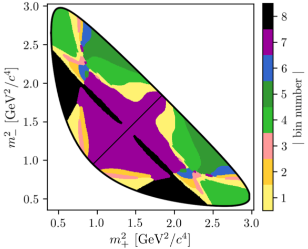


Phys. Rev. D **73** (2006) 112009

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

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

1. Divide phase space into "bins" using the amplitude model
2. Bins should encompass regions with similar $\delta_D(\Phi)$
   - Avoid diluting the sensitivity to γ
3. Measure the average $\delta_D(\Phi)$ in each bin



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

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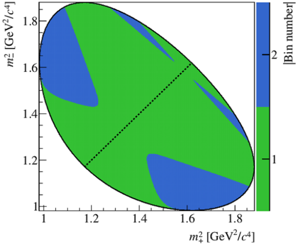
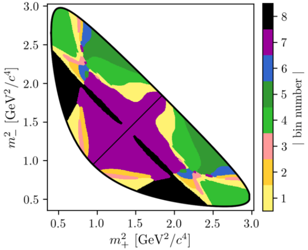


$K_S^0K^+K^-$

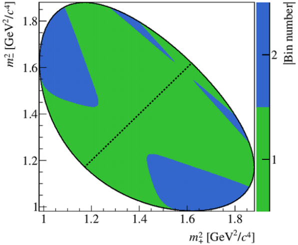
Solution: Measure $\delta_D(\Phi)$ directly at charm factories

- 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!



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

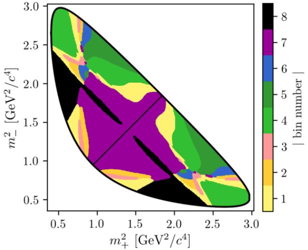
JHEP **02** (2021) 169



$K_S^0 K^+K^-$

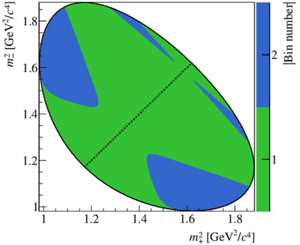
Solution: Measure $\delta_D(\Phi)$ directly at charm factories

- 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



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

JHEP **02** (2021) 169

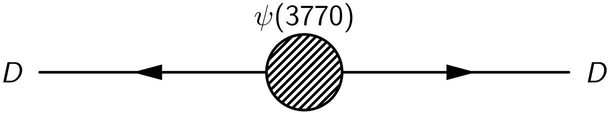


$K_S^0K^+K^-$

Quick digression: Charm factories 101

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

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

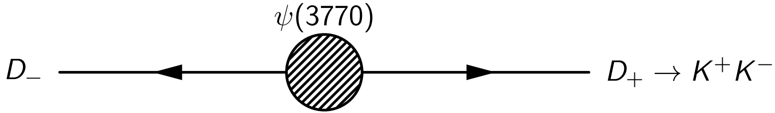


- $D\bar{D}$ pair are entangled, or quantum correlated
- Decay properties, such as branching fractions, are correlated

Quick digression: Charm factories 101

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

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



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

Quick digression: Charm factories 101

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

- CP-odd wave function and decay rate:

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

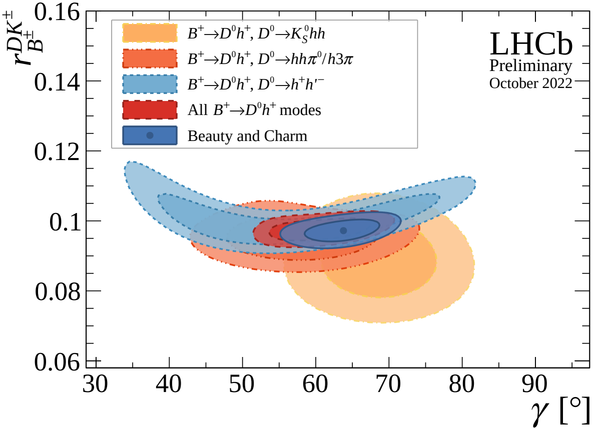
$$|\mathcal{A}(D_-)|^2 = |\mathcal{A}(D^0)|^2 + |\mathcal{A}(\bar{D}^0)|^2 - \boxed{2|\mathcal{A}(D^0)||\mathcal{A}(\bar{D}^0)|\cos(\delta_D)}$$

Charm factories have direct access to δ_D

The LHCb γ combination

How to combine a decade of γ measurements

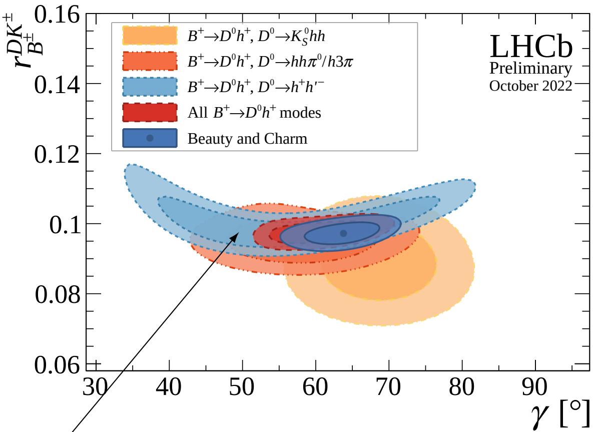
The LHCb γ combination



JHEP **12** (2021) 141

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

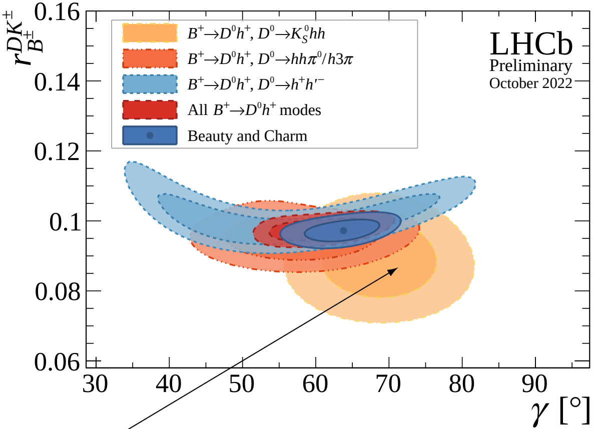
The LHCb γ combination



JHEP **12** (2021) 141

CP eigenstates and DCS decays: Narrow bands of degenerate solutions

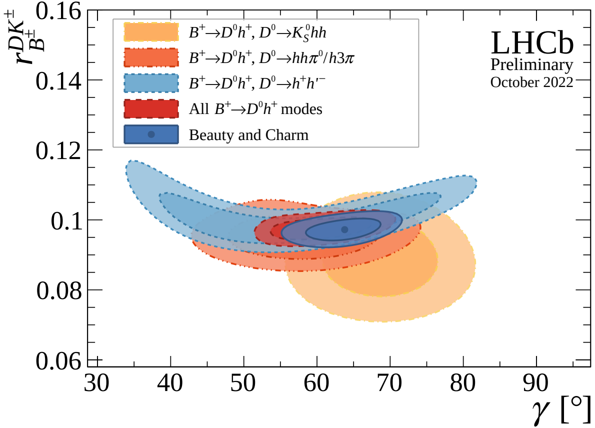
The LHCb γ combination



JHEP **12** (2021) 141

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

The LHCb γ combination



JHEP **12** (2021) 141

A combination of direct γ measurements is necessary!

The LHCb γ combination

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 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...

The LHCb γ 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. $B_s^0 \to D_s^- K^+$

- And many more...

The LHCb γ 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. $B_s^{0} \to D_s^{-}K^{+} \leftarrow$ 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

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...

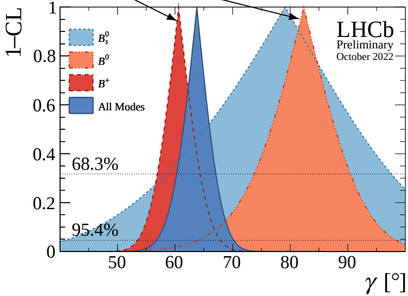
	Measurement	χ^2	No. of obs.
Beauty sector	$B^\pm \to Dh^\pm, D \to h^\pm h'^\mp$	2.37	8
	$B^\pm \to Dh^\pm, D \to K_S^0 h^+ h^-$	4.80	6
	$B^\pm \to Dh^\pm, D \to K_S^0 K^\pm \pi^\mp$	7.29	7
	$B^\pm \to D^* h^\pm, D \to h^\pm h'^\mp$	7.49	16
	$B^\pm \to DK^{*\pm}, D \to h^\pm h'^\mp(\pi^+\pi^-)$	3.44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

LHCb-CONF-2022-003

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

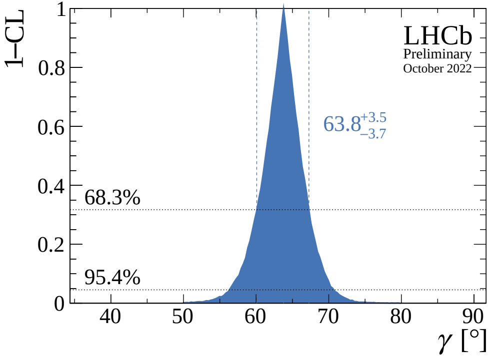
1. $B^{\pm} \to DK^{\pm}$
2. $B^{\pm} \to D^{*0}K^{\pm}$
3. $B^0 \to DK^{*0}$
4. $B_s^0 \to D_s^- K^+$
   - And many more...



LHCb-CONF-2022-003

The LHCb γ combination

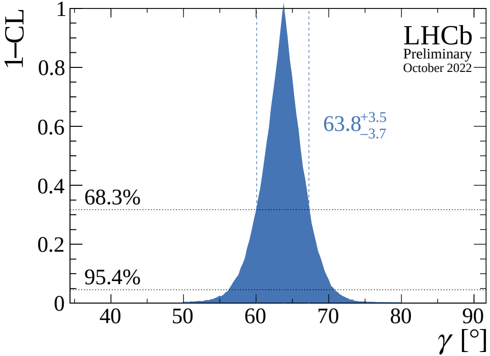
Our most precise knowledge of γ comes from the combination measurements



LHCb-CONF-2022-003

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

Our most precise knowledge of γ comes from the combination measurements

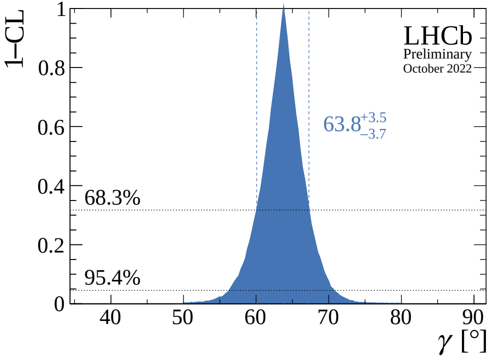


LHCb-CONF-2022-003

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

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

Our most precise knowledge of γ comes from the combination measurements



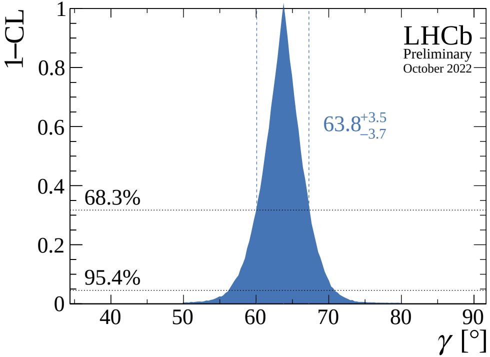
LHCb-CONF-2022-003

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

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



LHCb-CONF-2022-003

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

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

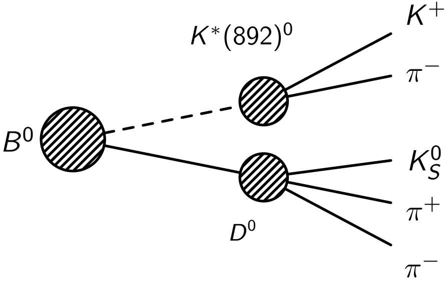
Neutral B decays

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!

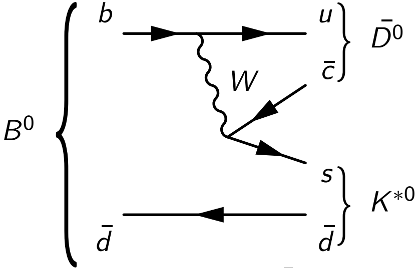


$$B^0 \to (K_S^0 h^+ h^-)_D (K^+ \pi^-)_{K^*}$$

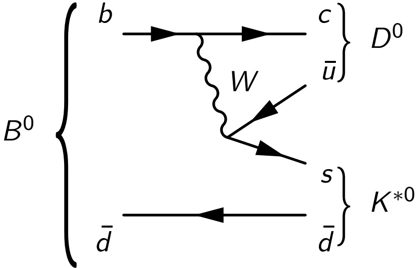
This results supersedes that of JHEP **08** (2016) 137

Neutral B decays

In $B^0 \to DK^{*0}$, there is no relative colour suppression



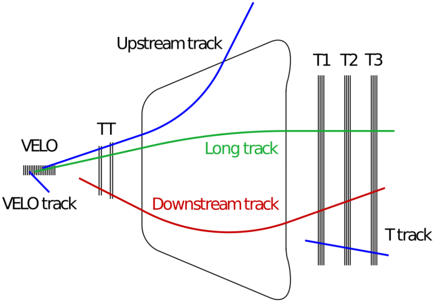
Favoured $B^0 \to \bar{D}^0 K^{*0}$



CKM suppressed $B^0 \to D^0 K^{*0}$

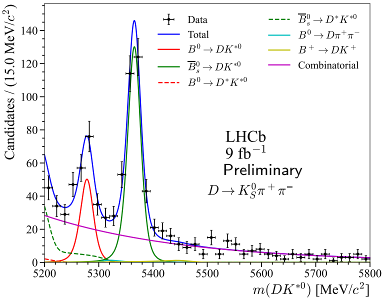
The interference is therefore expected to be ~ 3 times larger

Neutral B decays

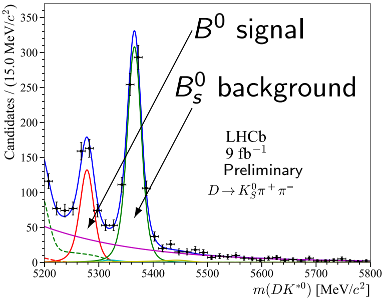


Tracking and vertexing in LHCb, PoS VERTEX2018 (2019) 039

- Two separate selections of K_S^0:
  1. LL (Long track): K_S^0 decays in the VELO
  2. DD (Downstream track): K_S^0 decays downstream of the VELO



LL

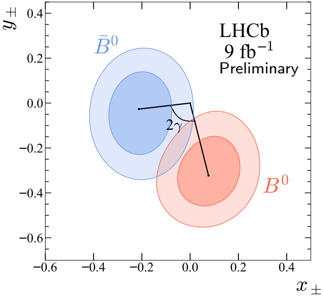


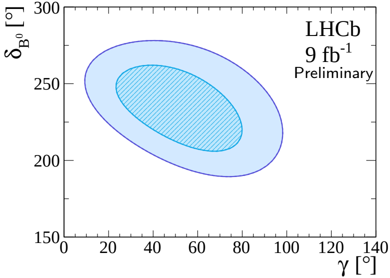
DD

LHCb-PAPER-2023-009

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

Neutral B decays





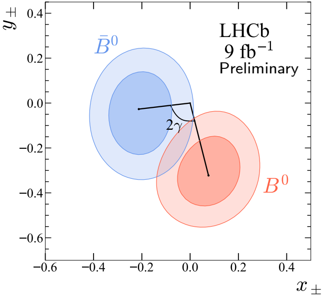
LHCb-PAPER-2023-009

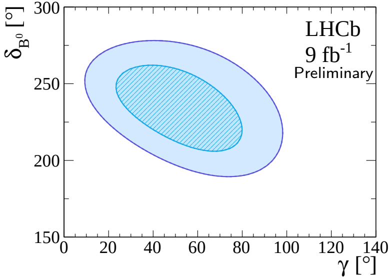
- Measured CP-violating observables:

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

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

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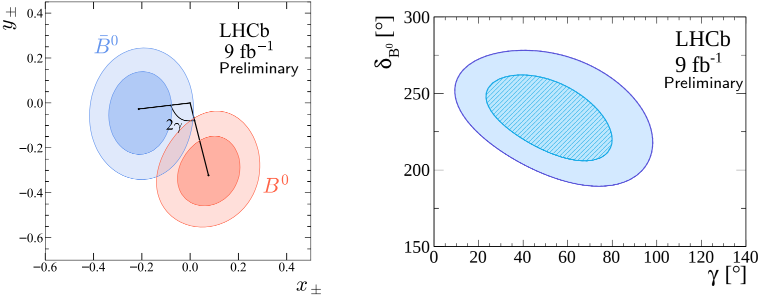
  - $\gamma = (49 \pm 20)^\circ \leftarrow$ This will reduce tension between B^0 and $B^\pm$
  - $\delta_{B^0} = (236 \pm 19)^\circ$
  - $r_{B^0} = 0.27 \pm 0.07$

Neutral B decays

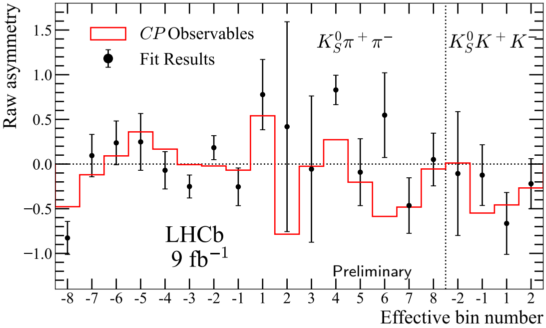


LHCb-PAPER-2023-009

- Measured CP-violating observables:

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

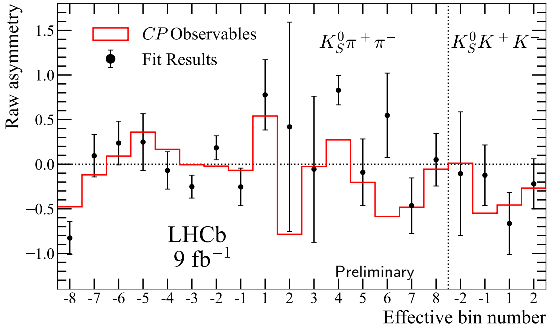
- Measured value of γ is consistent with world average:
  - $\gamma = (49 \pm 20)^\circ \leftarrow$ This will reduce tension between B^0 and $B^\pm$
  - $\delta_{B^0} = (236 \pm 19)^\circ$
  - $r_{B^0} = 0.27 \pm 0.07 \leftarrow$ Compatible with expectation: $r_{B^0} \approx 3 r_{B^\pm}$



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

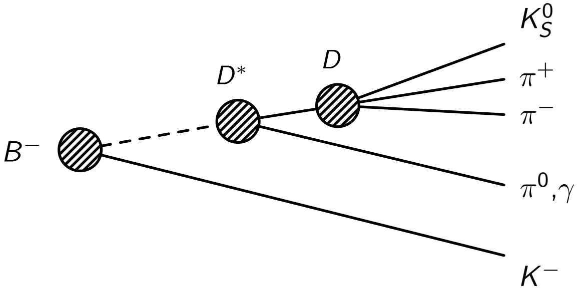
B decays to excited D^* final states

A measurement with neutral particles

B decays to excited D^* final states

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

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

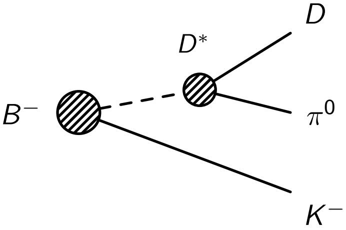


$B^- \to [D\gamma, \pi^0]_{D^*} K^-$, $D \to K_S^0 \pi^+ \pi^-$

Analysis is similar to $B^\pm \to DK^\pm$
Requires additional reconstruction of $D^* \to D\pi^0$ and $D^* \to D\gamma$

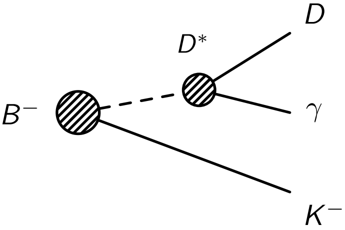
B decays to excited D^* final states

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



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

Angular momentum conservation

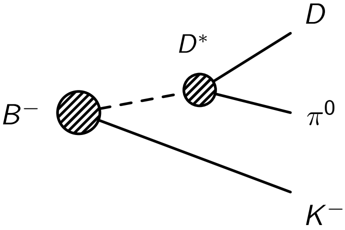


$B^- \to [D\gamma]_{D^*} K^-$

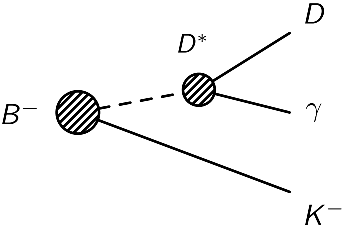
Parity conservation

Both decays must proceed with $\underline{L = 1}$ due to conservation laws

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



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



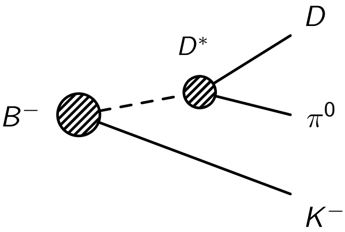
$B^- \to [D\gamma]_{D^*} K^-$

π^0: CP$= -1$

γ: CP$= +1$

However, π^0 and γ have opposite intrinsic CP

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



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

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

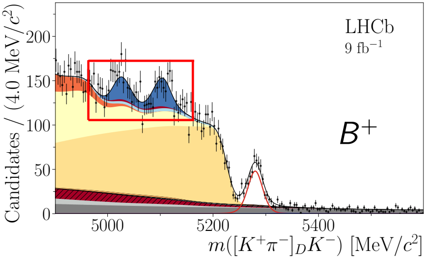
$\mathcal{A}(D^0) + r_B e^{i(\delta_B - \gamma)} \mathcal{A}(\bar{D}^0)$

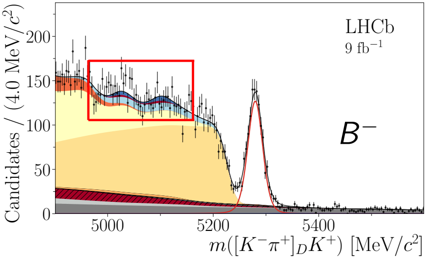
$\mathcal{A}(D^0) - r_B e^{i(\delta_B - \gamma)} \mathcal{A}(\bar{D}^0)$

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

Reminder: Partially reconstructed ~~background~~ decays

Asymmetries previously measured for CP eigenstates and DCS decays

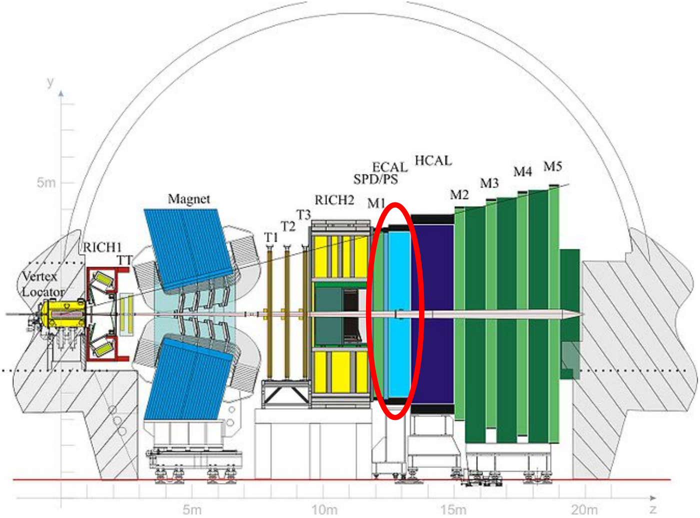


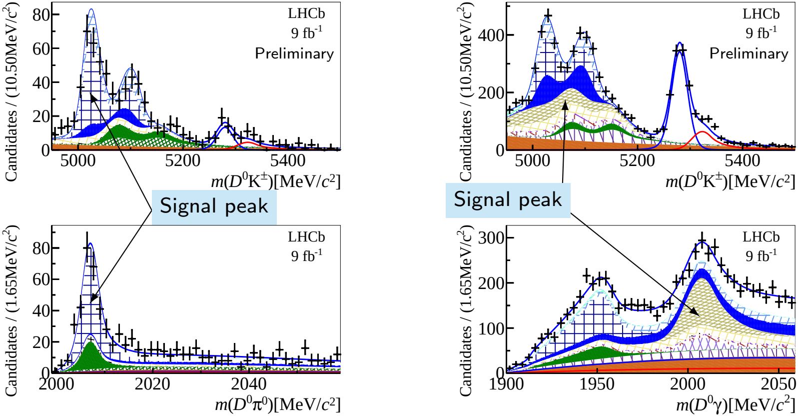


JHEP **04** (2021) 081

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

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



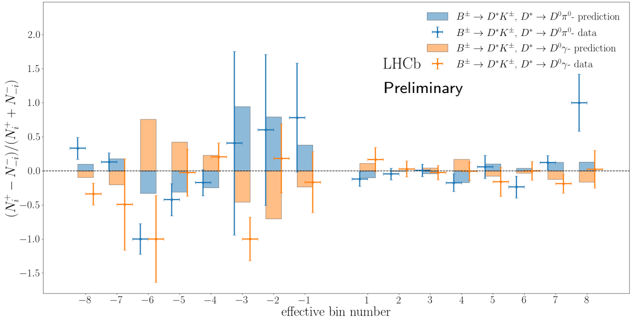


$D^* \to D\pi^0$ (a) $D^* \to D\gamma$

LHCb-PAPER-2023-012

A 2D fit is necessary to separate signal from background

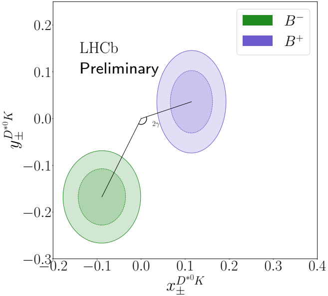
B decays to excited D^* final states

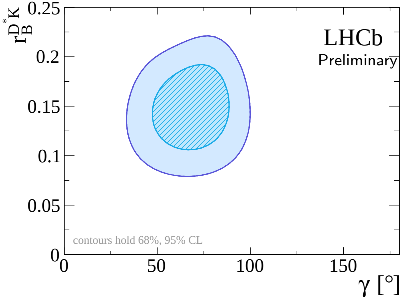


LHCb-PAPER-2023-012

- 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 opposite in sign

B decays to excited D^* final states





LHCb-PAPER-2023-012

These results provide strong constraints on γ:

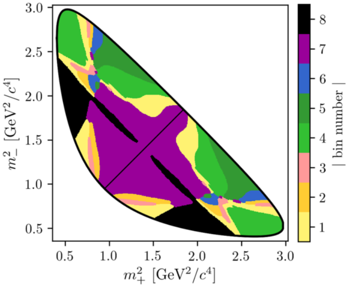
- $\gamma = (69 \pm 14)^\circ$
- $\delta_B^{D^*K} = (311 \pm 15)^\circ$
- $r_B^{D^*K} = 0.15 \pm 0.03$

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

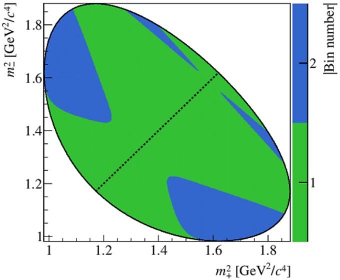
A journey through five dimensions

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:



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

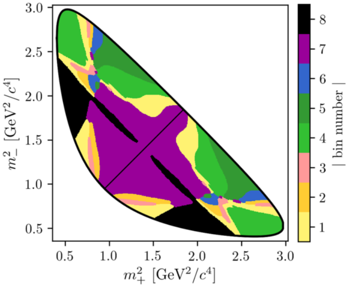


$K_S^0K^+K^-$

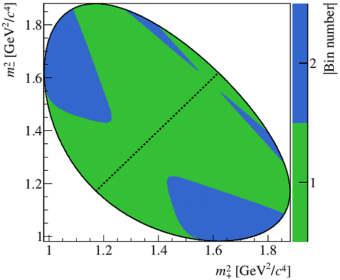
- Bin boundaries are optimised for sensitivity to γ by CLEO
- We would like to do this for $D^0 \to K^+K^-\pi^+\pi^-$...

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

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



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

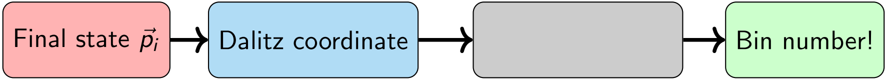


$K_S^0K^+K^-$

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

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

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



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

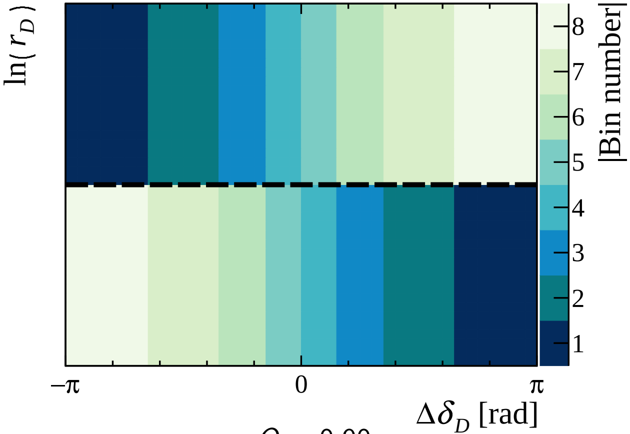
But how do we define a binning scheme (in 5D)?

Final state $\vec{p}_i$ → Dalitz coordinate → Amplitude model → Bin number!

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

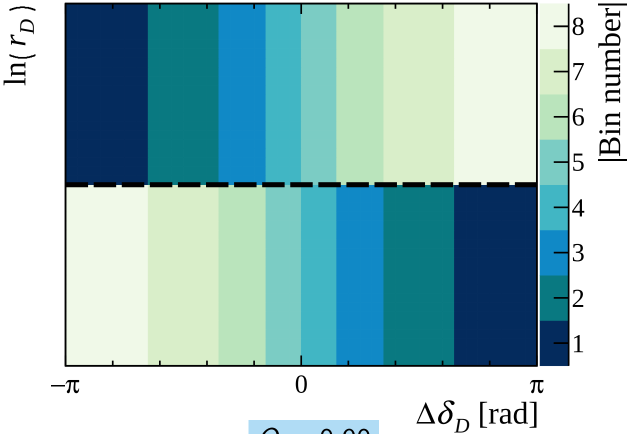
Binning scheme



$Q = 0.90$

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

Binning scheme

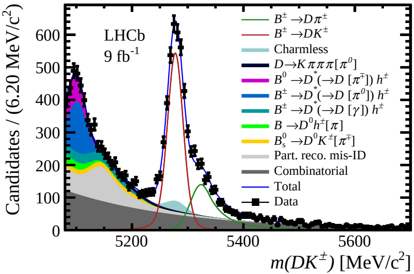


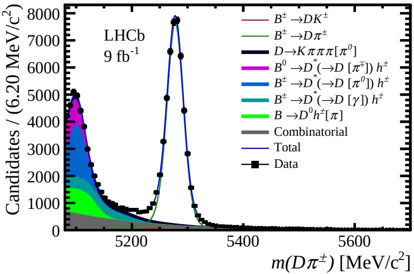
$Q = 0.90$

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

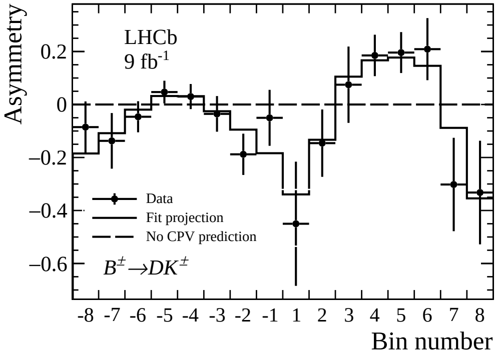




Eur. Phys. J. C **83**, 547 (2023)

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

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



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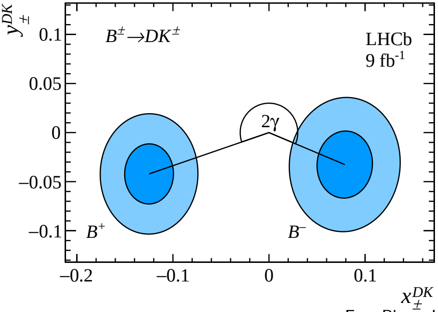
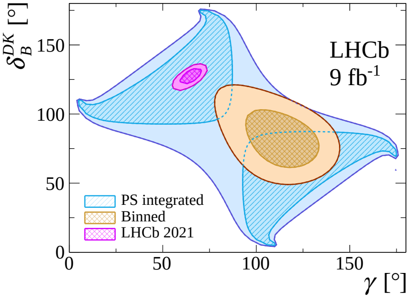
- Clear bin asymmetries are seen, and the non-trivial distribution is driven by the change in strong-phase differences across phase space
- While the interpretation of γ require inputs from charm threshold, the observed bin asymmetries are model independent

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

From the phase-space binned asymmetries, we obtain:

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





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

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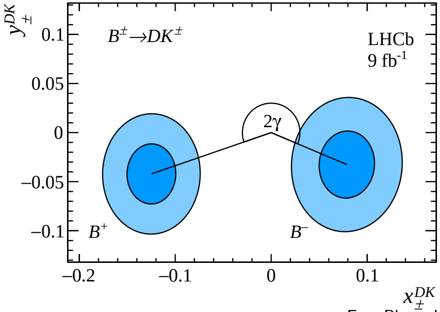

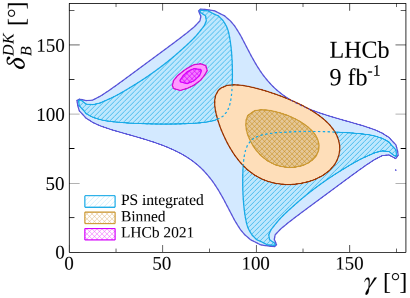

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Ultimately, the charm strong-phase differences will be measured directly at BESIII, and the γ measurement will be model independent

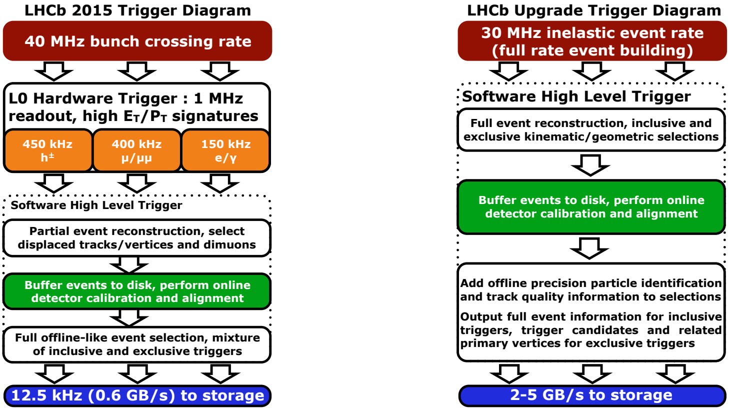
The angle γ of the Cabibbo-Kobayashi-Maskawa ansatz

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

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 $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ with charm inputs from BESIII
  2. Results with CP eigenstates and DCS decays from $B^0 \to DK^{*0}$ will bring the γ precision in B^0 closer to that in the $B^{\pm}$ system
  3. Partially reconstructed analysis of $B^{\pm} \to D^* h^{\pm}$, with $D \to K_S^0 h^+ h^-$, will be complementary to the analysis presented today
  4. Time-dependent measurements, such as $B_s^0 \to D_s^- K^+$ with Run 2, will be interesting to compare with results from $B^{\pm}/B^0$

Exciting times ahead with fully software-based trigger:



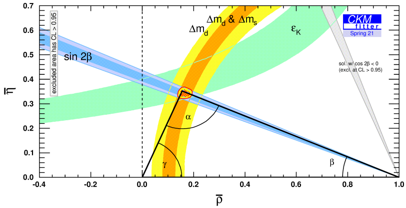
LHCb-FIGURE-2020-016

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

We expect to reach 1° precision after Run 4



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

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 $B^\pm \to D^* h^\pm$ and $B^0 \to DK^{*0}$ with $D \to K_S^0 h^+ h^-$, using external inputs from BESIII
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
   - With Upgrade II, we hope to bring this down further to 0.4°

Summary and future prospects

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Thanks for your attention!

Backup slides

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

A binning scheme must satisfy the following:

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