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

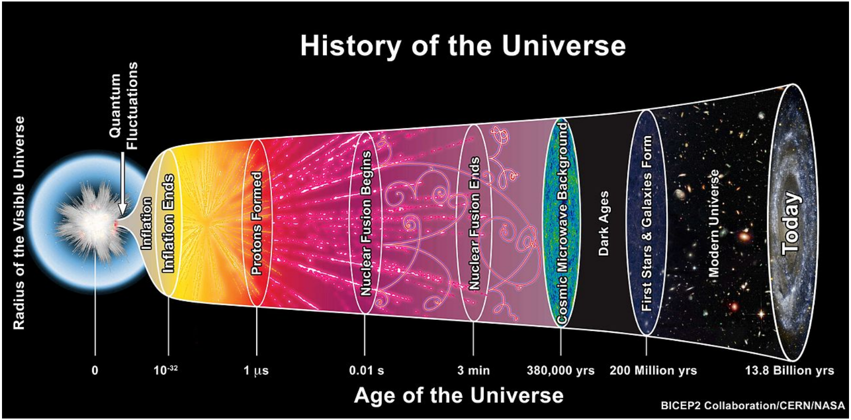
CERN LHC seminar

25th July 2023

Introduction to CP violation

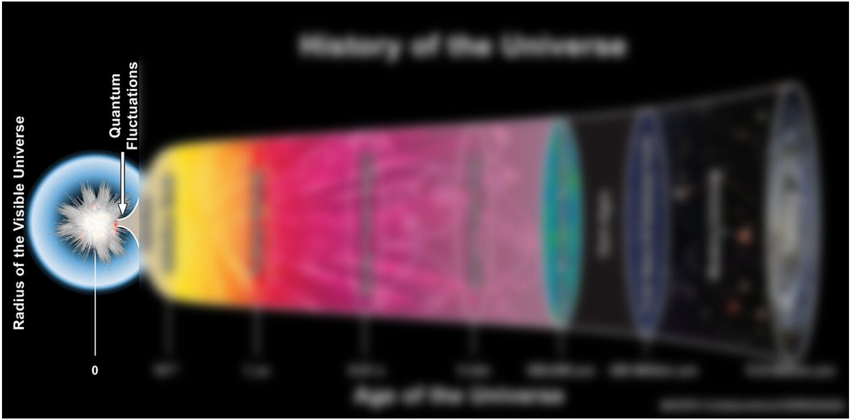
What is γ and why measure it?

Big Bang and matter-antimatter asymmetry



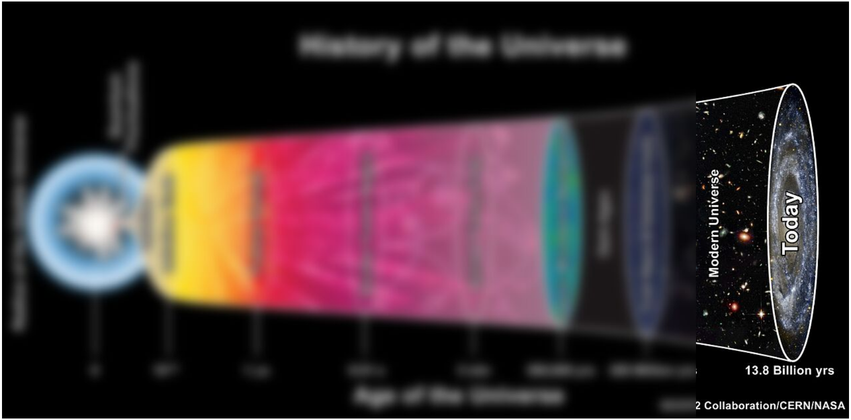
Where is the antimatter in the universe?

Big Bang and matter-antimatter asymmetry



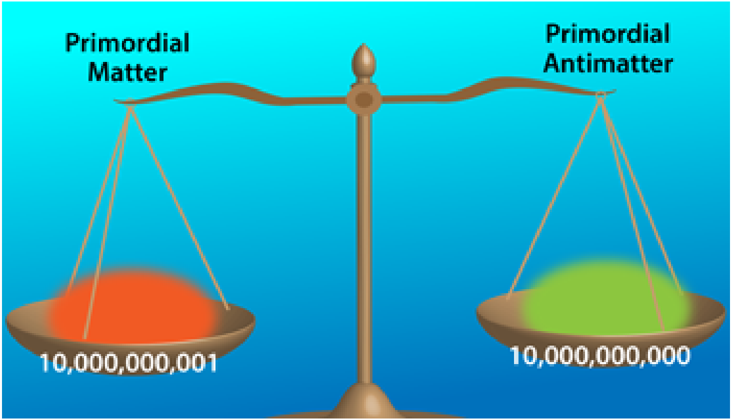
Initially equal amounts of matter and antimatter...

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?

CP violation

The Nobel Prize in Physics 1980

Photo from the Nobel Foundation archive.
James Watson Cronin
Prize share: 1/2

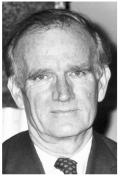


Photo from the Nobel Foundation archive.
Val Logsdon Fitch
Prize share: 1/2

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"

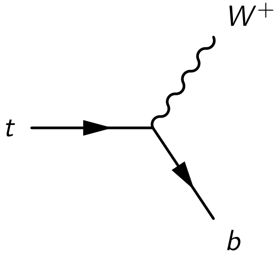
- CP violation discovery in 1964
- Phys. Rev. Lett. **13**, 138
- Observed $K_L^0 \to \pi^+\pi^-$
- Since, CP violation has also been observed in the B, B_s and D systems

Can Standard Model CPV explain the matter-antimatter asymmetry?
Or, could it be physics beyond the SM?

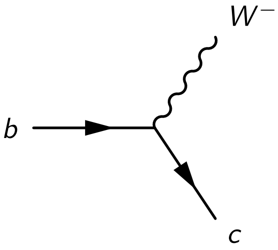
The CKM matrix and the Unitary Triangle

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 Cabbibo-Kobayashi-Maskawa matrix V_{CKM} has a single complex phase that is responsible for all CPV in SM

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

V_{CKM} must be unitary, which gives us 9 constraints, such as:

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

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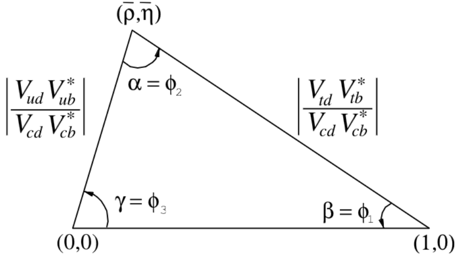
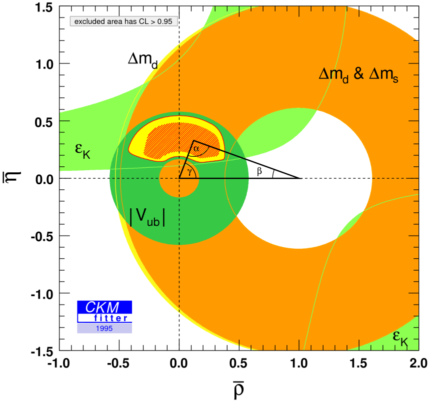


R. L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

The CKM matrix and the Unitary Triangle

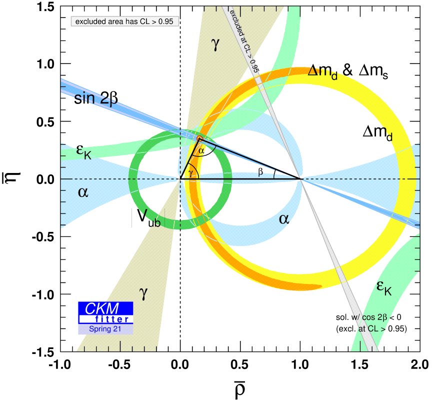
Initially, the Unitary Triangle was poorly constrained...



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

... but a tremendous effort has been made the last 30 years!



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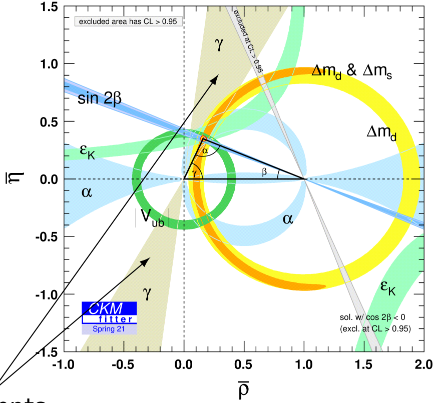

Direct γ measurements

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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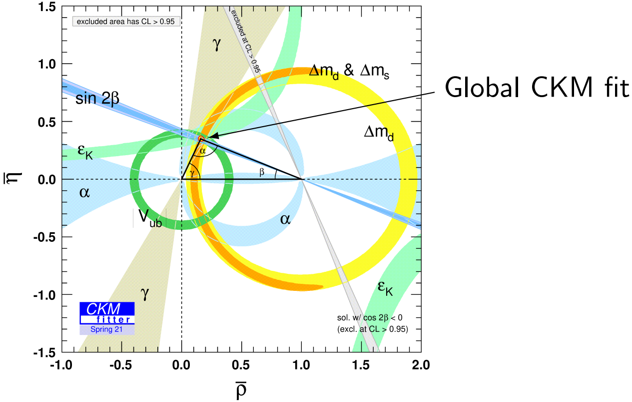
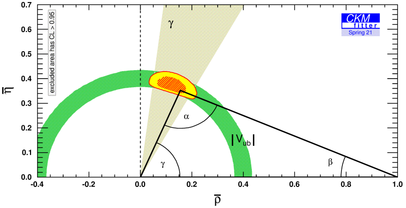


CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005), updated results and plots available at: http://ckmfitter.in2p3.fr

The CKM matrix and the Unitary Triangle

- Why is $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ important?
  1. Negligible theoretical uncertainties: Ideal SM benchmark
  2. Only CKM angle accessible in tree level decays
  3. Compare with global CKM fit: Is the Unitary Triangle a triangle?



Tree level: $\gamma = \left(72.1^{+5.4}_{-5.7}\right)^\circ$

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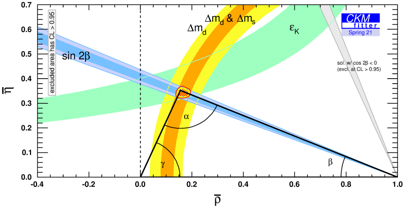

Loop level: $\gamma = \left(65.5^{+1.1}_{-2.7}\right)^\circ$

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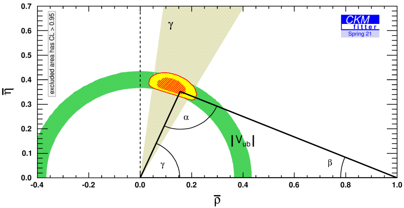

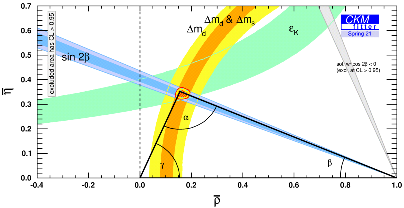

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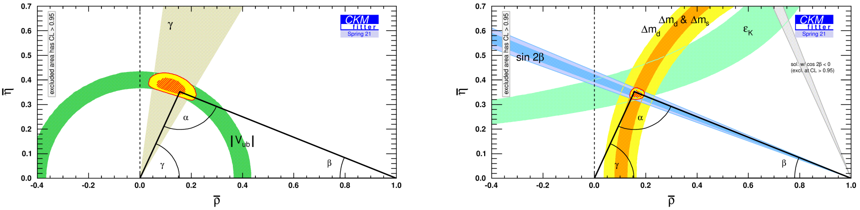

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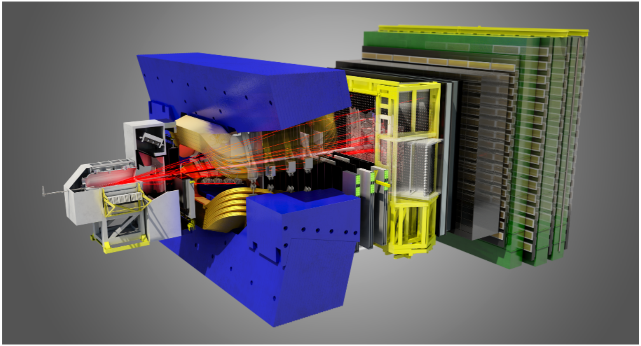
Need to reduce uncertainties significantly in direct measurements!

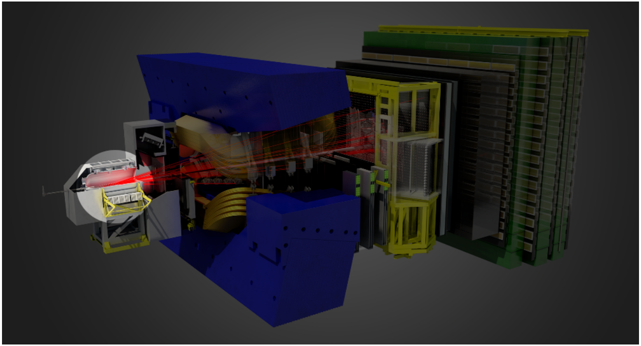
The LHCb detector

The LHCb detector



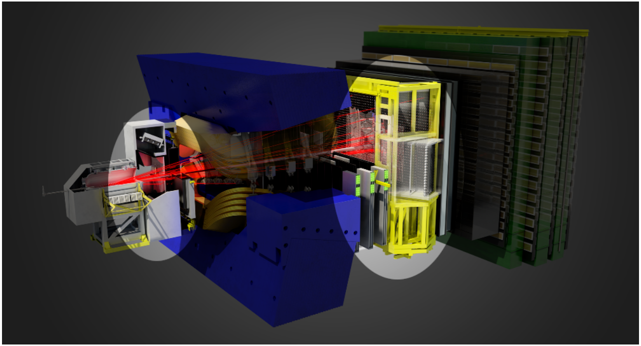
LHCb: A beauty experiment with a lot of charm

The LHCb detector



VELO: Vertex locator to reconstruct B and D vertices

The LHCb detector



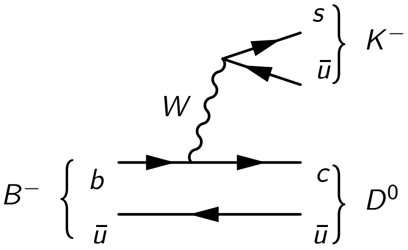
RICH: Identify B and D daughter particles

How to measure γ?

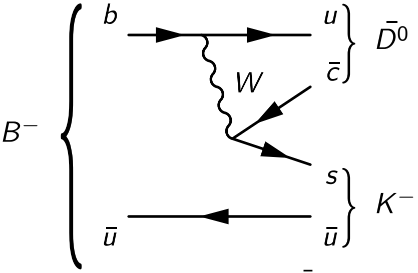
It's all about interferences!

Sensitivity through interference

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



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



Suppressed $B^- \to \bar{D}^0 K^-$

- Superposition of D^0 and $\bar{D}^0$
- $b \to u\bar{c}s$ and $b \to c\bar{u}s$ interference $\to$ Sensitivity to γ

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

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

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

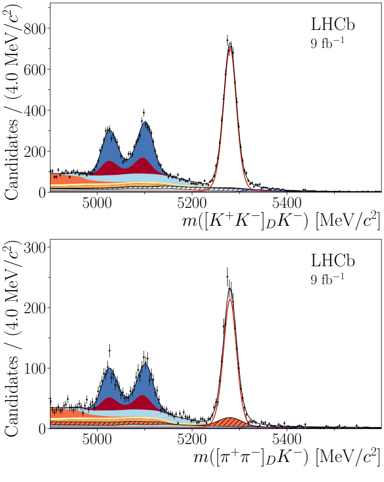
Naively, we expect the size of CPV effects to be around $r_B \approx 10\%$

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

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

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

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 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-Cabbibo Suppressed decays
   - $D \to K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, ...
3.

Doubly Suppressed Cabbibo D decays

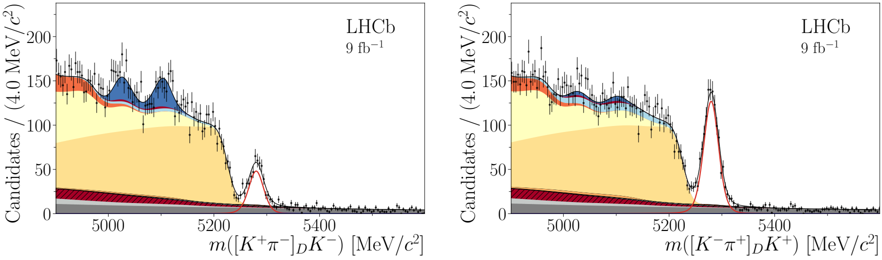
Interference effects can be greatly enhanced

Use a Doubly Suppressed Cabbibo 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 Cabbibo 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?

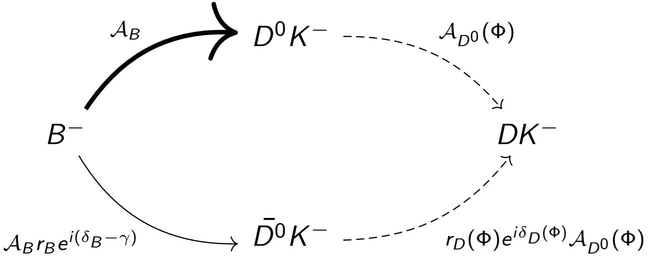
No single method is sufficient to determine γ precisely!

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

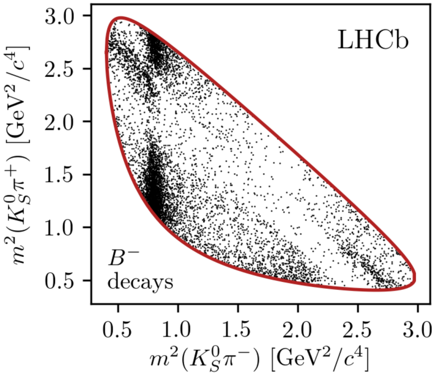
The three-body D-decay phase space is two-dimensional $\implies$ Dalitz plot

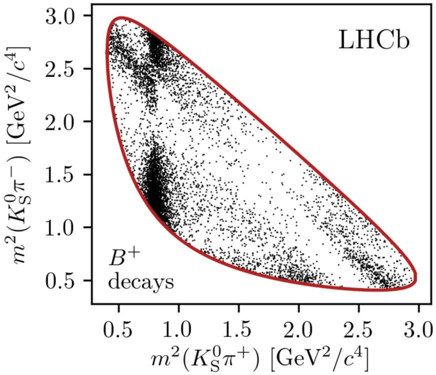
$B^{\pm}$ decay rate depends on the D^0 and $\bar{D}^0$ strong-phase difference



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

Multi-body D decays





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

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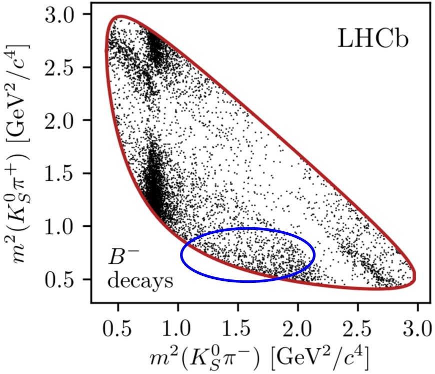
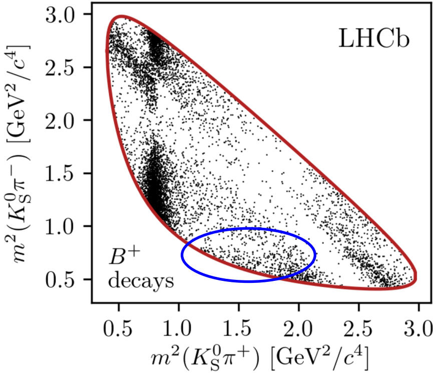
Can you find the asymmetries?

Multi-body D decays





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

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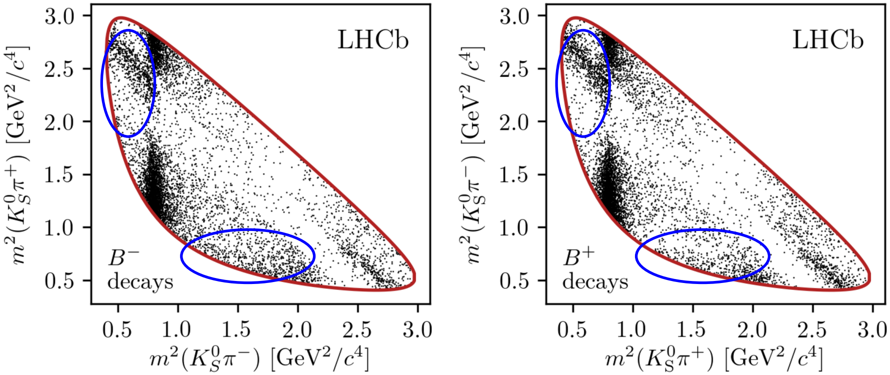
Can you find the asymmetries?



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

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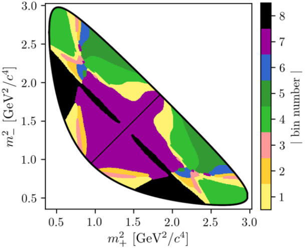
Can you find the asymmetries?

Multi-body D decays

- 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



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

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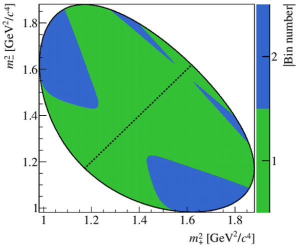
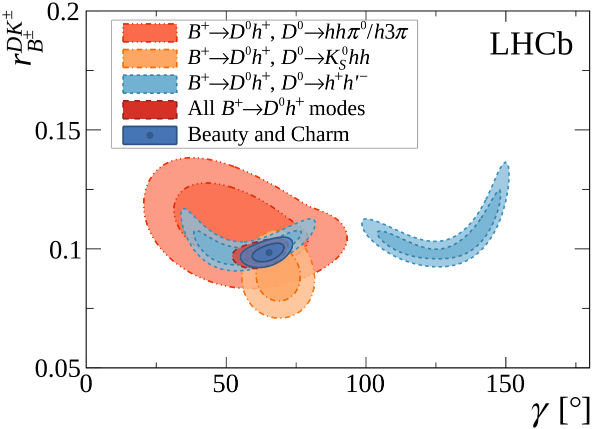


$K_S^0K^+K^-$

The LHCb γ and charm combination

Lots of beauty in charm!

The LHCb γ and charm combination



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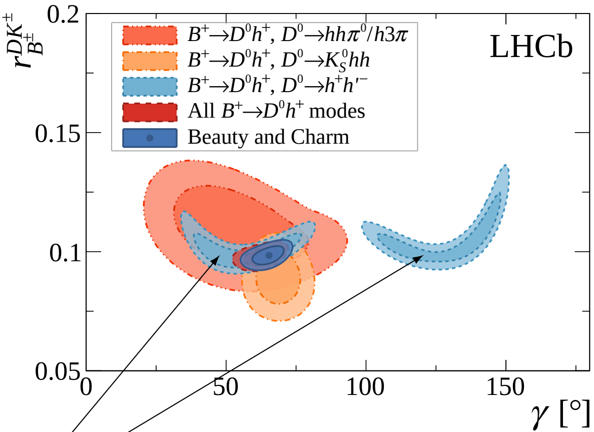
Currently, γ measurements are dominated by $B^\pm \to Dh^\pm$

The LHCb γ and charm combination



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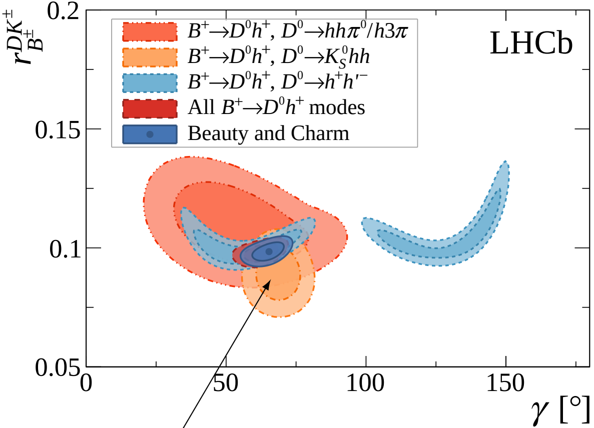
GLW+ADS: Narrow bands, but many degenerate solutions



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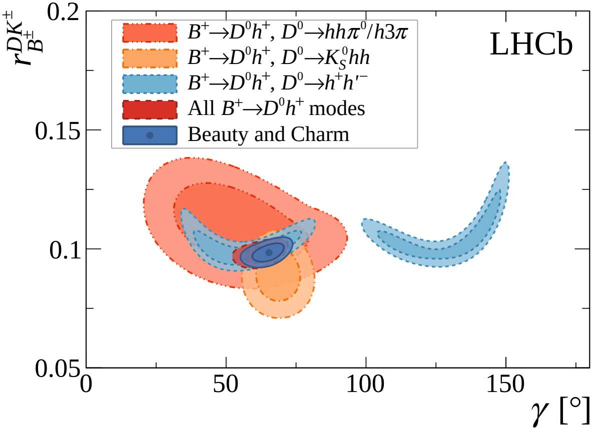
BPGGSZ: Wider, but unqiue solution

The LHCb γ and charm combination



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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...

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

- And many more...

The LHCb γ and charm combination

Other B decays are also interesting for γ measurements:

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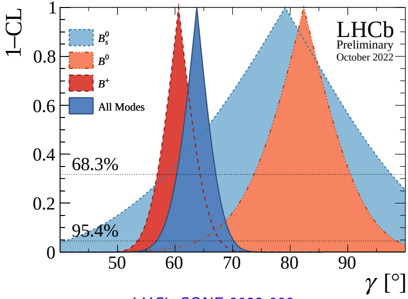
2. $B^{\pm} \to D^{*0}K^{\pm}$
3. $B^{0} \to DK^{*0}$
4. $B_s^{0} \to D_s^{-}K^{+}$

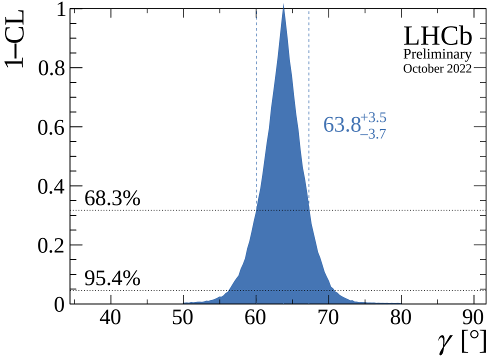
- And many more...



LHCb-CONF-2022-003

The LHCb γ and charm combination

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



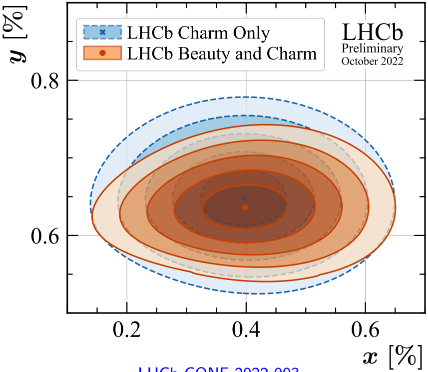
LHCb-CONF-2022-003

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 $\delta_D^{K\pi}$

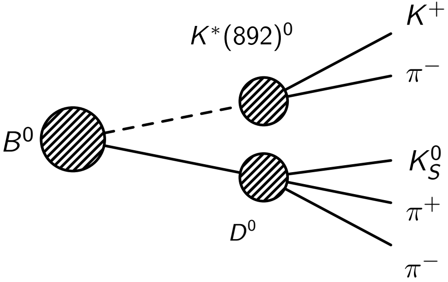
Neutral B decays

More interference with less statistics

Neutral B decays

Neutral B decays are analysed with an identical strategy:

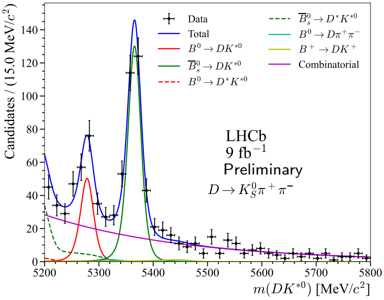
LHCb-PAPER-2023-009 (in preparation) New results!



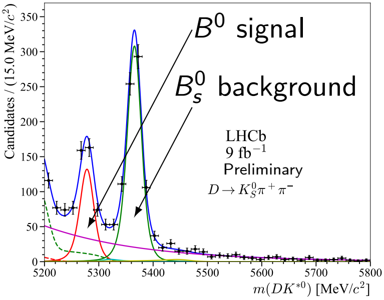
$$B^0 \to (K_S^0 h^+ h^-)_D (K^+\pi^-)_{K^*}$$

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

Neutral B decays



LL

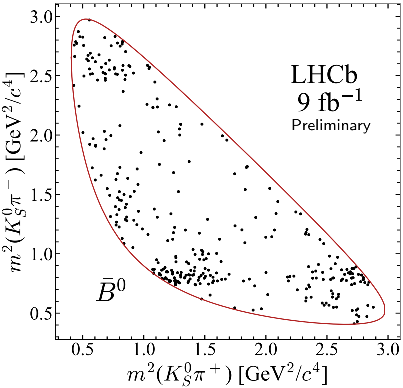


DD

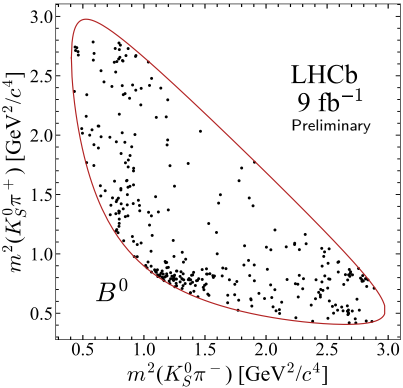
LHCb-PAPER-2023-009

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

Neutral B decays



$\bar{B}^0$

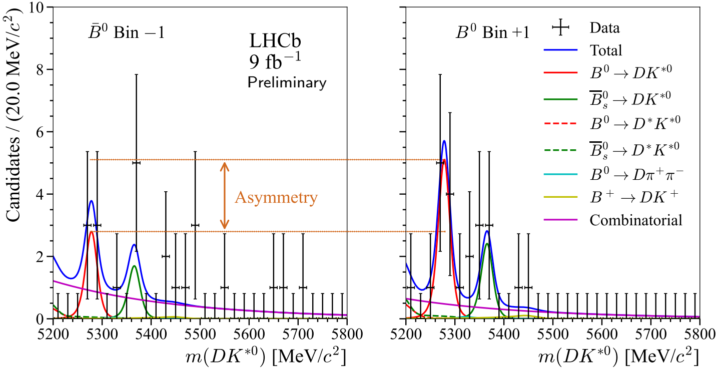


B^0

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

Can you find the asymmetries?

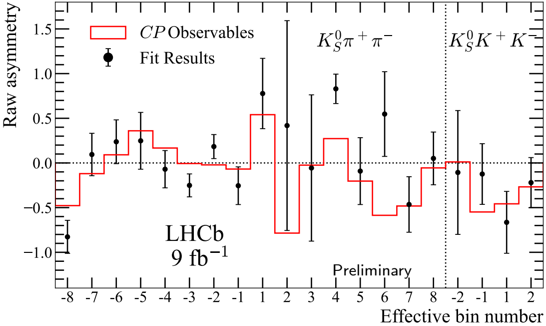
Neutral B decays



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_s^0 decays, and these are not looked for

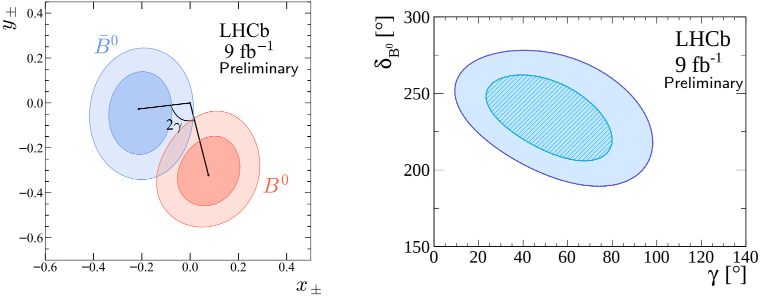
Neutral B decays



LHCb-PAPER-2023-009

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

Neutral B decays



LHCb-PAPER-2023-009

- Measured CP-violating observables:

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

- Measured value of 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!

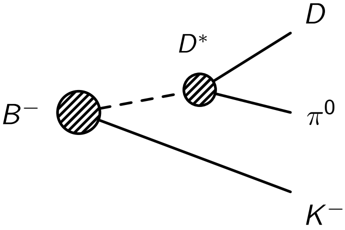
B decays to excited D^* final states

A measurement with neutral particles

B decays to excited D^* final states

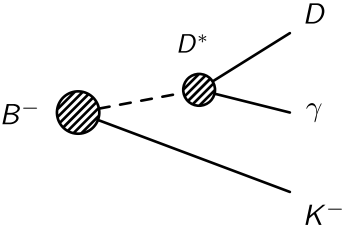
$B^- \to D^* K^-$ decays are also a powerful probe of CPV:

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



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

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

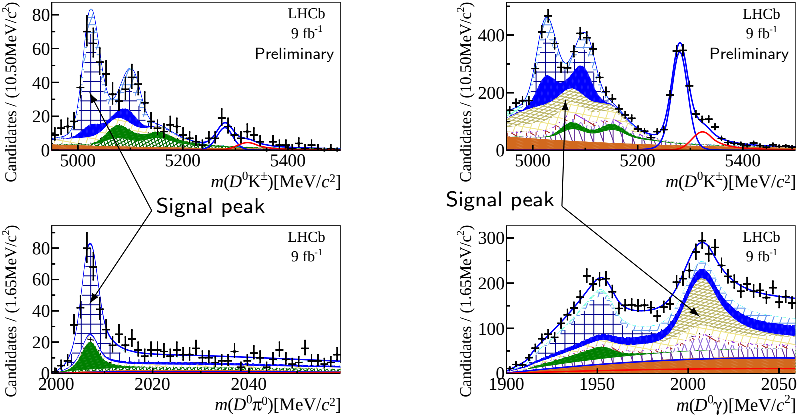


$B^- \to [D\gamma]_{D^*} K^-$

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

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

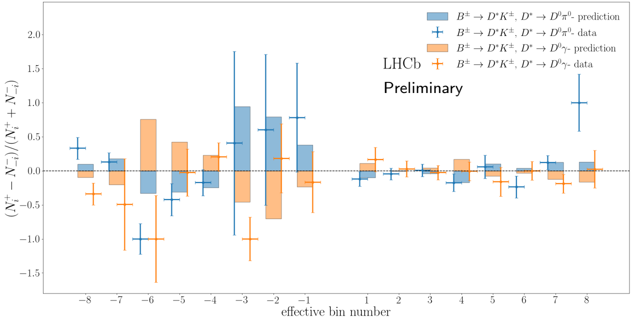


$D^* \to D\pi^0$ **(a)** $D^* \to D\gamma$

LHCb-PAPER-2023-012

A 2D fit is necessary to separate signal from background

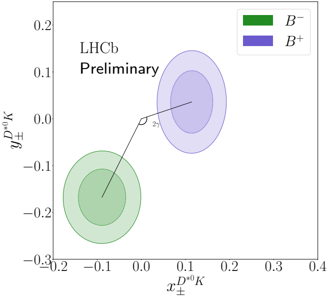
B decays to excited D^* final states

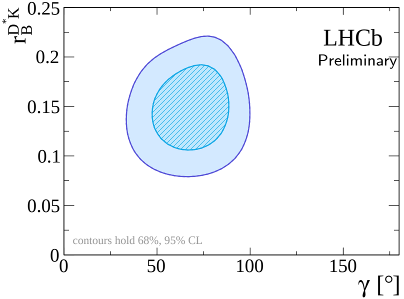


LHCb-PAPER-2023-012

- 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

B decays to excited D^* final states





LHCb-PAPER-2023-012

These results provide strong constraints on γ:

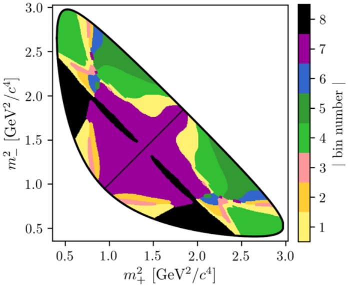
- $\gamma = (69 \pm 14)^\circ$
- $\delta_B^{D^*K} = (311 \pm 15)^\circ$
- $r_B^{D^*K} = 0.15 \pm 0.03$

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

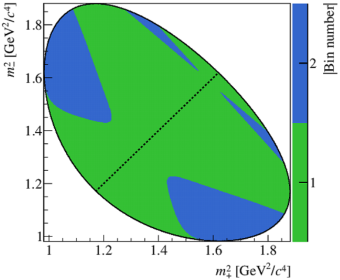
A journey through five dimensions

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:



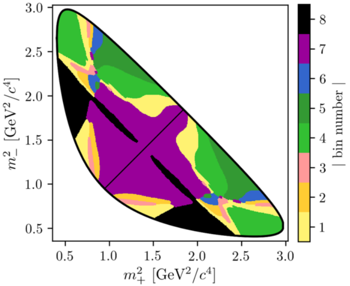
$K_S^0\pi^+\pi^-$



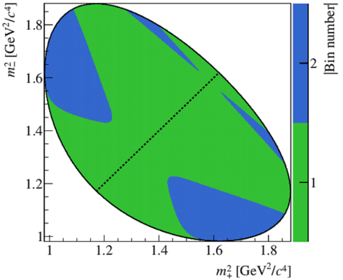
$K_S^0 K^+ K^-$

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

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



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



$K_S^0 K^+ K^-$

- 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 model independent

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

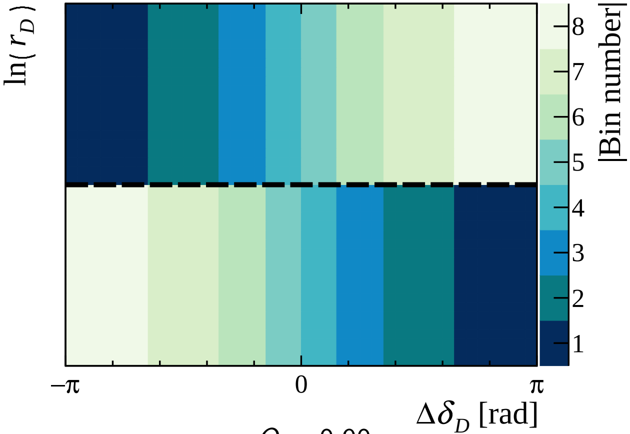
How to bin a 5-dimensional phase space?

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

Binning scheme

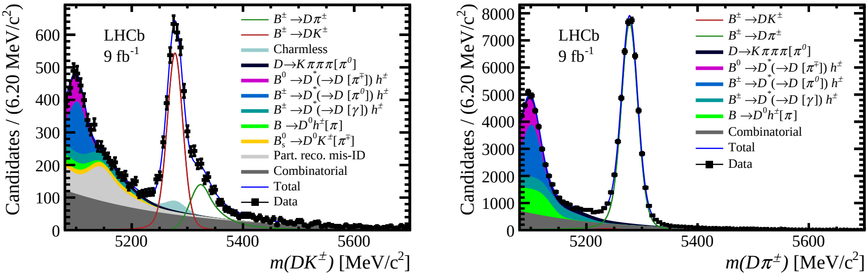


$Q = 0.90$

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



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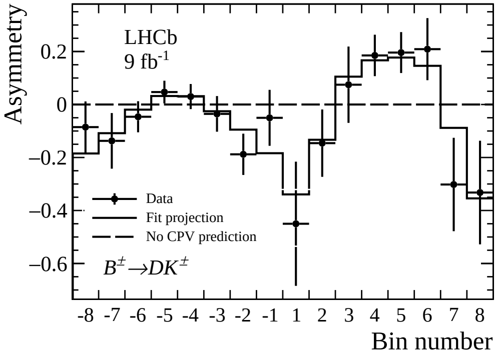
- $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm$ signal yield:
  - $B^\pm \to DK^\pm$: 3026 ± 38
  - $B^\pm \to D\pi^\pm$: 44349 ± 218

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



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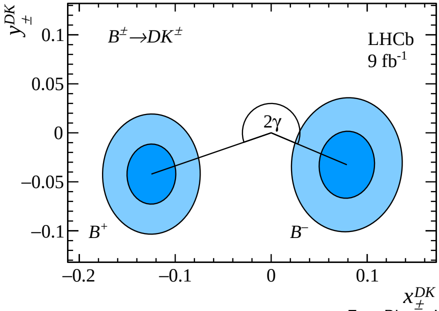
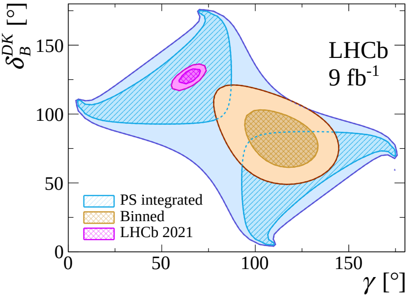
- Clear bin asymmetries are seen, and the non-trivial distribution is driven by the change in strong-phase differences across phase space
- While the interpretation of γ require charm inputs, the observed bin asymmetries are model independent

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!

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 $B^{0} \to D K^{*0}$ 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!