Measurements of CKM angle γ at LHCb

T. Evans, on behalf of the LHCb collaboration, ICHEP 2022

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The CKM matrix

$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

$$\gamma \sim \delta_{13} = -\arg\left(V_{ub}\right)$$

δ_{13} responsible for all known CPV in the Standard Model!

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$$V_{\mathrm{CKM}}^{\dagger} V_{\mathrm{CKM}} = I$$
$$\implies V_{ub}^{*} V_{ud} + V_{cb}^{*} V_{cd} + V_{tb}^{*} V_{td} = 0$$

$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

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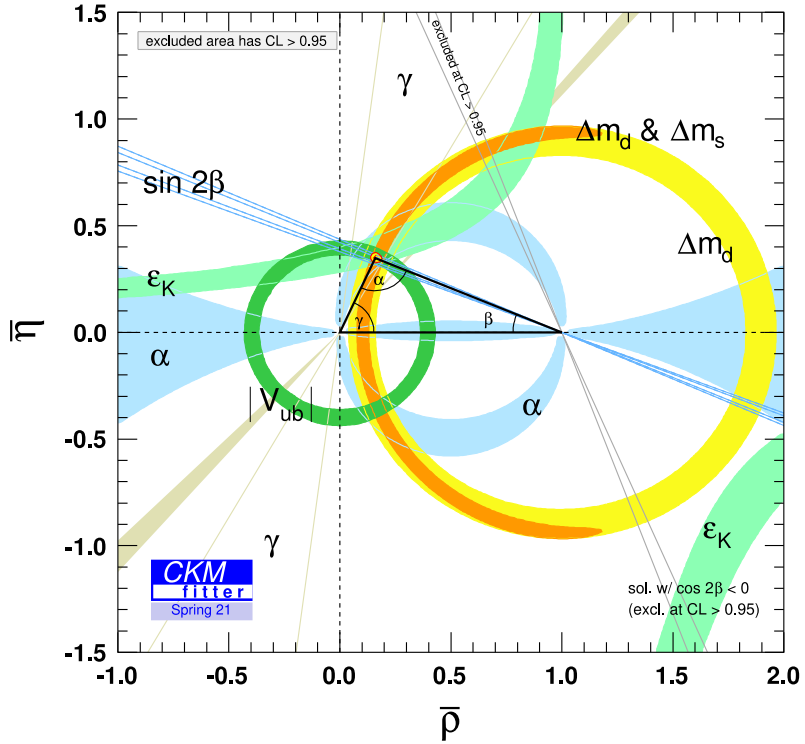
$$V_{\mathrm{CKM}}^{\dagger} V_{\mathrm{CKM}} = I$$
$$\Longrightarrow \; V_{ub}^{*} V_{ud} + V_{cb}^{*} V_{cd} + V_{tb}^{*} V_{td} = 0$$

or

$$1 + \frac{V_{ub}^{*} V_{ud}}{V_{cb}^{*} V_{cd}} + \frac{V_{tb}^{*} V_{td}}{V_{cb}^{*} V_{cd}} = 0$$

$$\gamma \equiv \arg\left(-\frac{V_{ud} V_{ub}^{*}}{V_{cd} V_{cb}^{*}}\right)$$



$$V_{\rm CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

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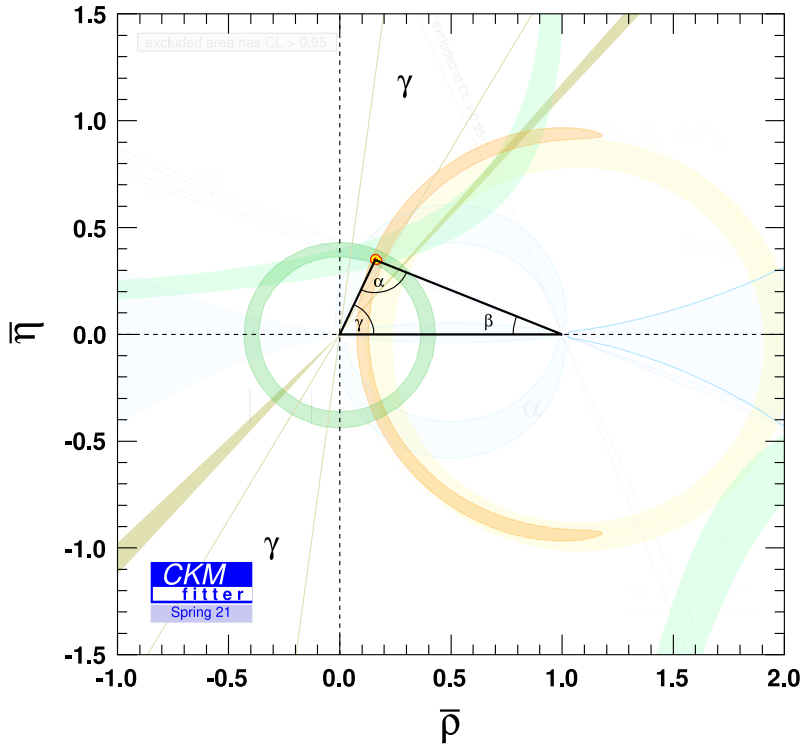

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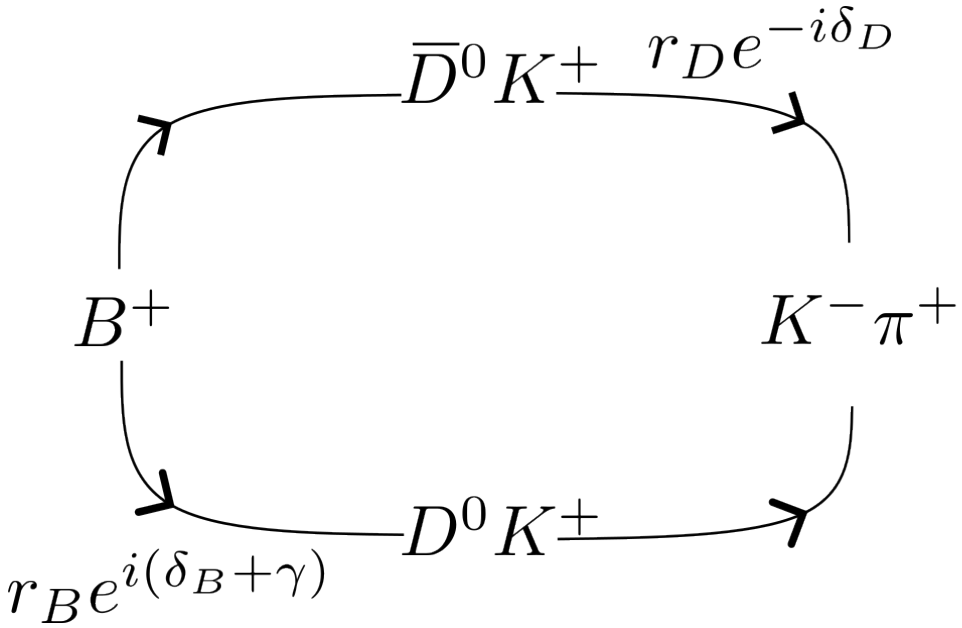
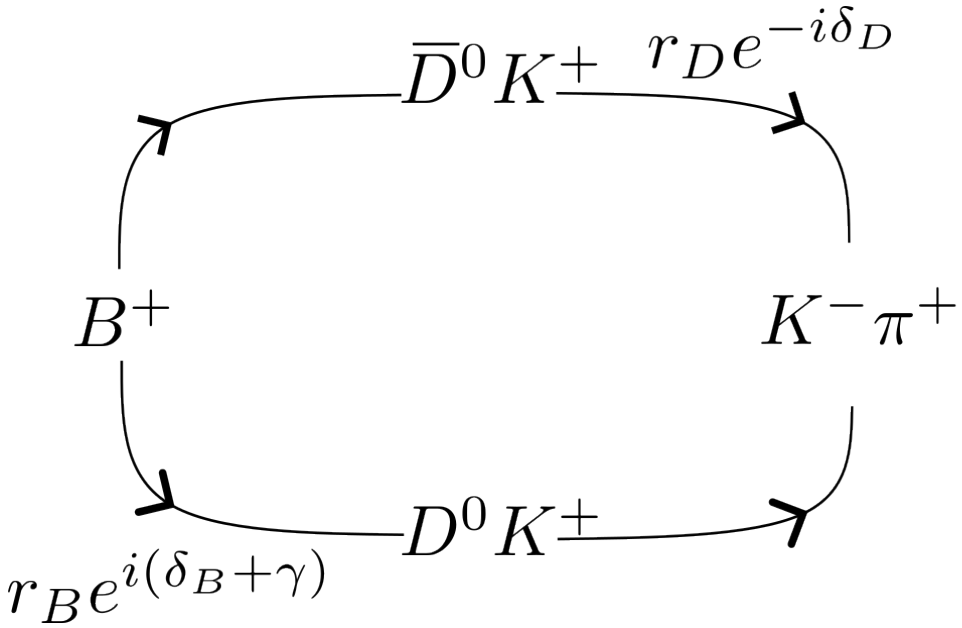


$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$\Gamma \propto r_B^2 + r_D^2 + 2r_B r_D \cos\left(\delta_B + \delta_D \pm \gamma\right)$$



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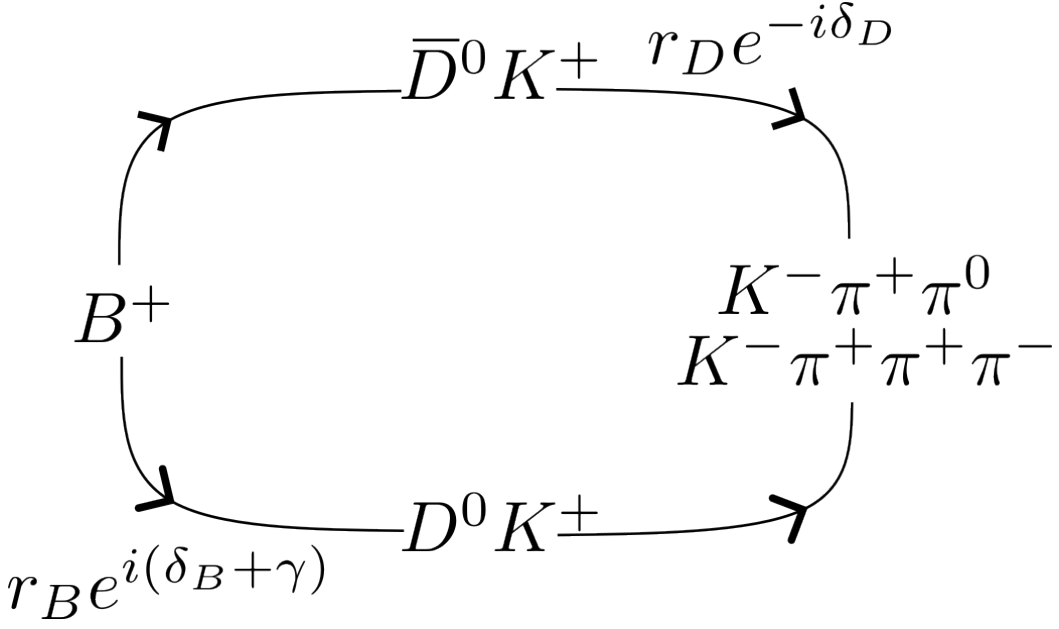
$R_D \to$ suppresses inteference, diluting sensitivity



$$R_D e^{i\delta_D} \propto \int d\psi \mathcal{A}_{\overline{D}}(\psi)\mathcal{A}_D(\psi)^*$$

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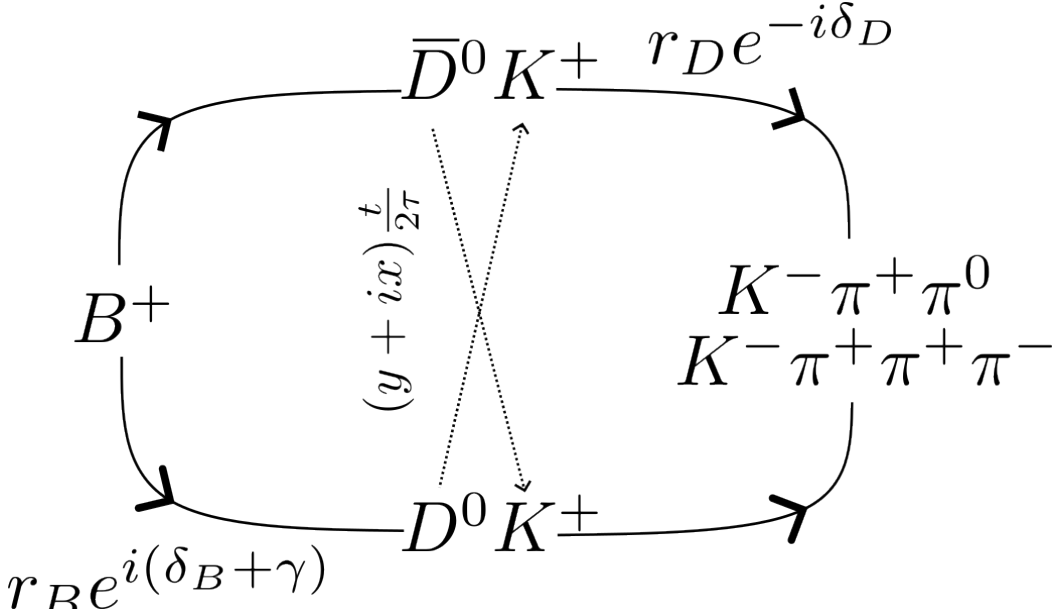


$$\begin{aligned}\Gamma \quad \propto \quad & r_D^2 + r_B^2 + 2r_D r_B R_D \cos(\delta_B + \delta_D \pm \gamma) \\ & - r_D R_D \left(y\cos\delta_D - x\sin\delta_D\right) + \frac{1}{2}\left(x^2 + y^2\right) \\ & - r_B \left(y\cos(\delta_B \pm \gamma) + x\sin(\delta_B \pm \gamma)\right)\end{aligned}$$

$$R_D e^{i\delta_D} \propto \int d\psi \mathcal{A}_{\overline{D}}(\psi)\mathcal{A}_D(\psi)^*$$

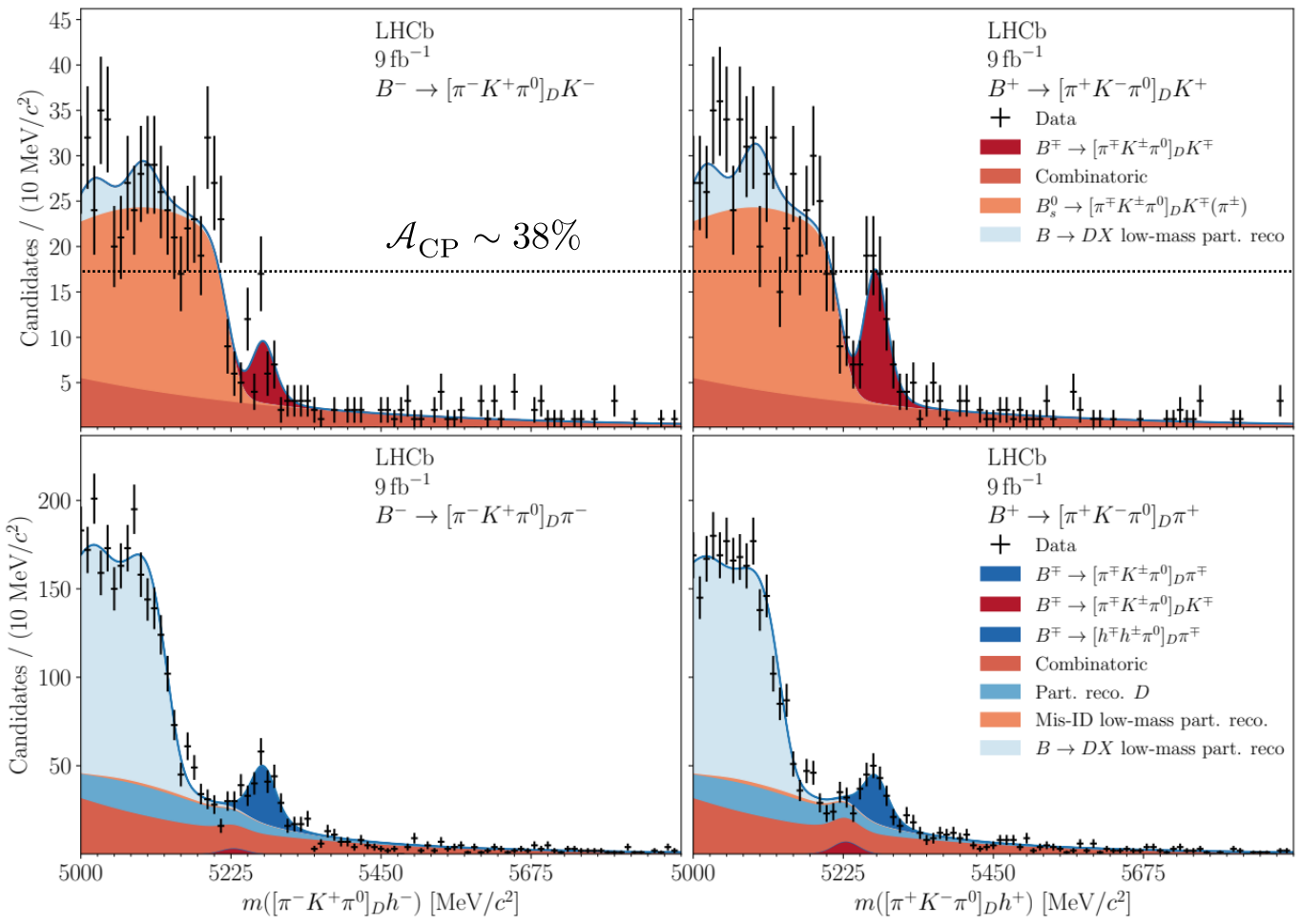
JHEP (submitted): arXiv:2112.10617

γ from $B^{\pm} \to D\,[h^{\pm}h'^{\mp}\pi^0]\,h^{\pm}$ decays

- π^0 reconstruction is a challenge..
- Use three different D decays:
  - $D \to K^{\pm}\pi^{\mp}\pi^0$ [pictured]
  - $D \to \pi^+\pi^-\pi^0$
  - $D \to K^+K^-\pi^0$
- + two B decays
  ($B^+ \to DK^+$ and $B^+ \to D\pi^+$)

  $\therefore$ total of 11 CP violating
  + related observables

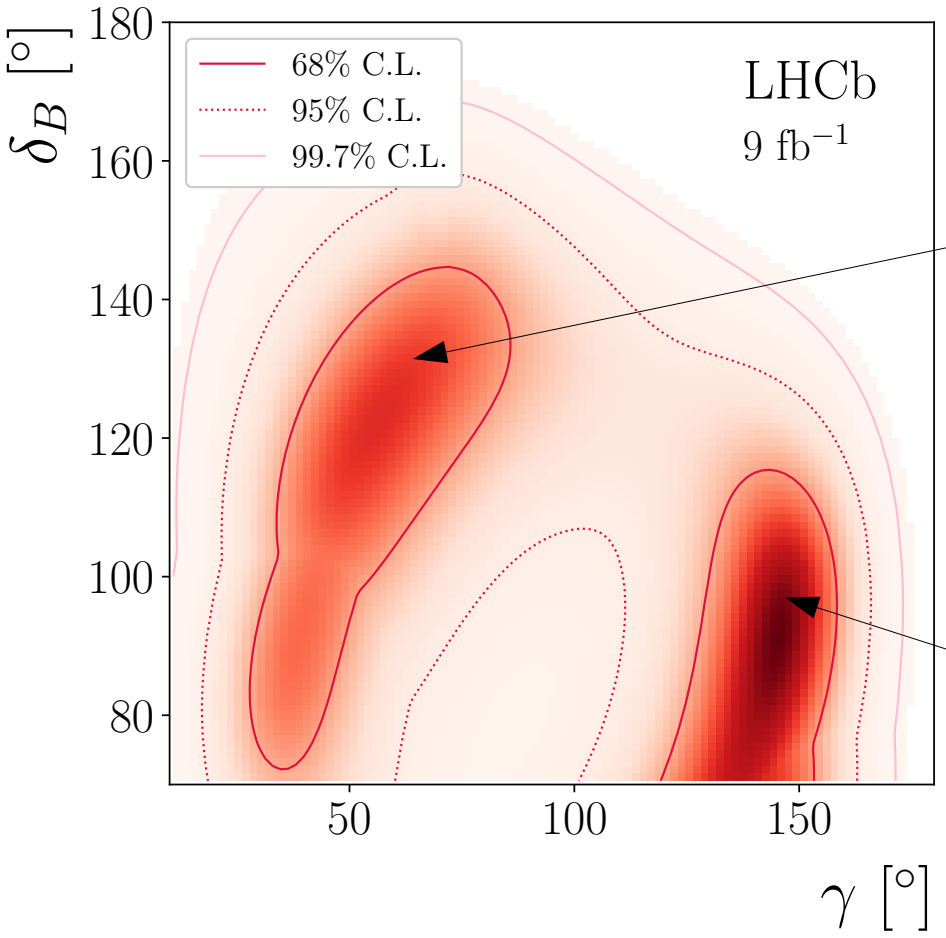
Full Run 1&2 Data set



JHEP (submitted): arXiv:2112.10617

γ from $B^{\pm} \to D\left[h^{\pm}h'^{\mp}\pi^{0}\right]h^{\pm}$ decays

Combine observables (using external inputs on D parameters) to constrain γ:



Local minima compatible with averages:

$$\gamma = (56\,^{+\,24}_{-\,19})^{\circ}$$

$$\delta_B = (122\,^{+\,19}_{-\,23})^{\circ}$$

$$r_B = (93\,^{+\,10}_{-\,9}) \times 10^{-3}$$

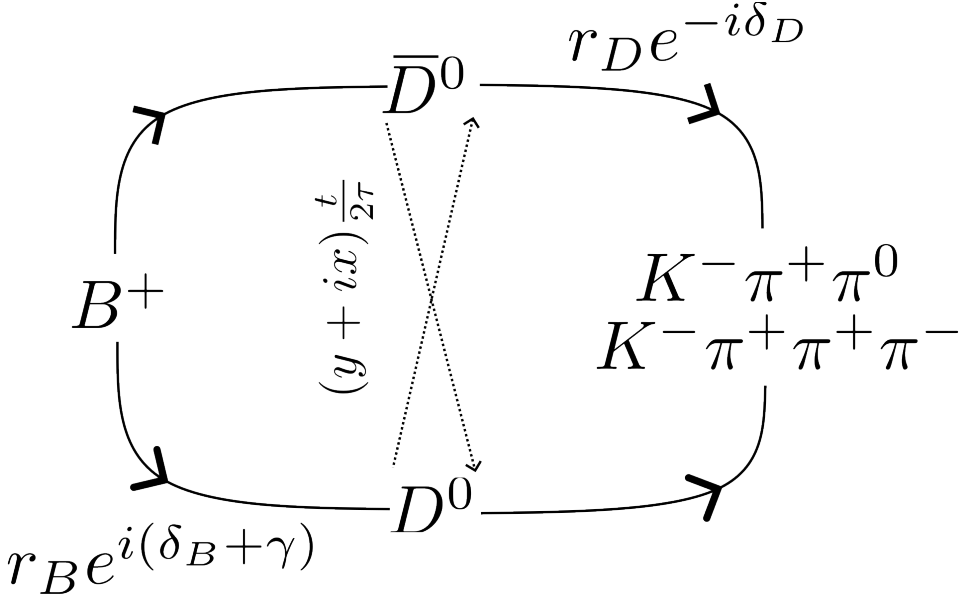
Global minima:

$$\gamma = (145\,^{+\,\,9}_{-\,39})^{\circ}$$

$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$\Gamma \propto r_B^2 + r_D^2 + 2 r_B r_D R_D \cos(\delta_B + \delta_D \pm \gamma)$$

$R_D \to$ suppresses inteference, diluting sensitivity



$$\begin{aligned}\Gamma \quad \propto \quad & r_D^2 + r_B^2 + 2 r_D r_B R_D \cos(\delta_B + \delta_D \pm \gamma) \\ & - r_D R_D \left(y \cos\delta_D - x \sin\delta_D\right) + \frac{1}{2}\left(x^2 + y^2\right) \\ & - r_B \left(y \cos(\delta_B \pm \gamma) + x \sin(\delta_B \pm \gamma)\right)\end{aligned}$$

Local or phase-space dependent

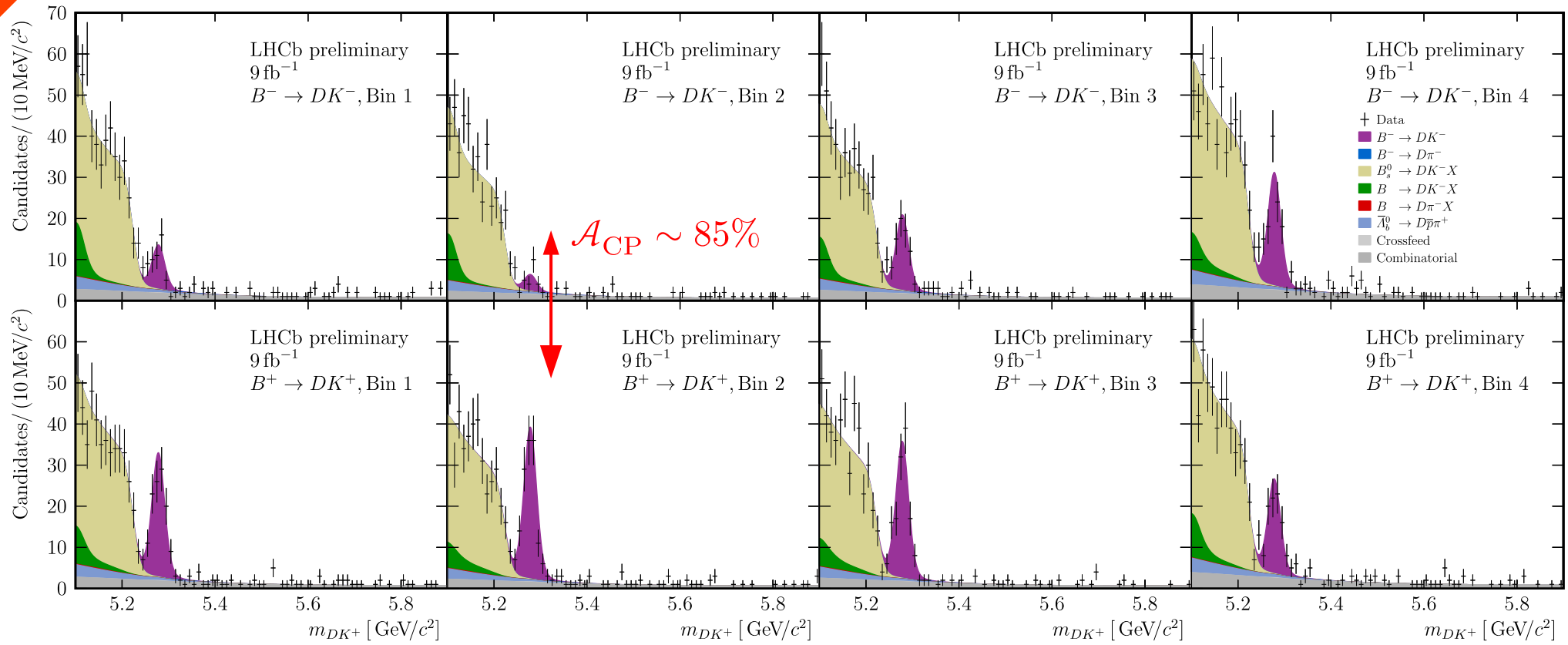
$$R_D e^{i\delta_D} \propto \int d\psi \mathcal{A}_{\overline{D}}(\psi) \mathcal{A}_D(\psi)^*$$

LHCb
In preparation

γ from $B^{\pm} \to D\,[K^-\pi^+\pi^+\pi^-]\,h^{\pm}$ decays

$R_{K3\pi} \sim 0.4 \implies$ potentially large benefits from binned analysis

$\therefore$ Measure observables in 4 bins of D-decay phase-space [arXiv:1909.10196]

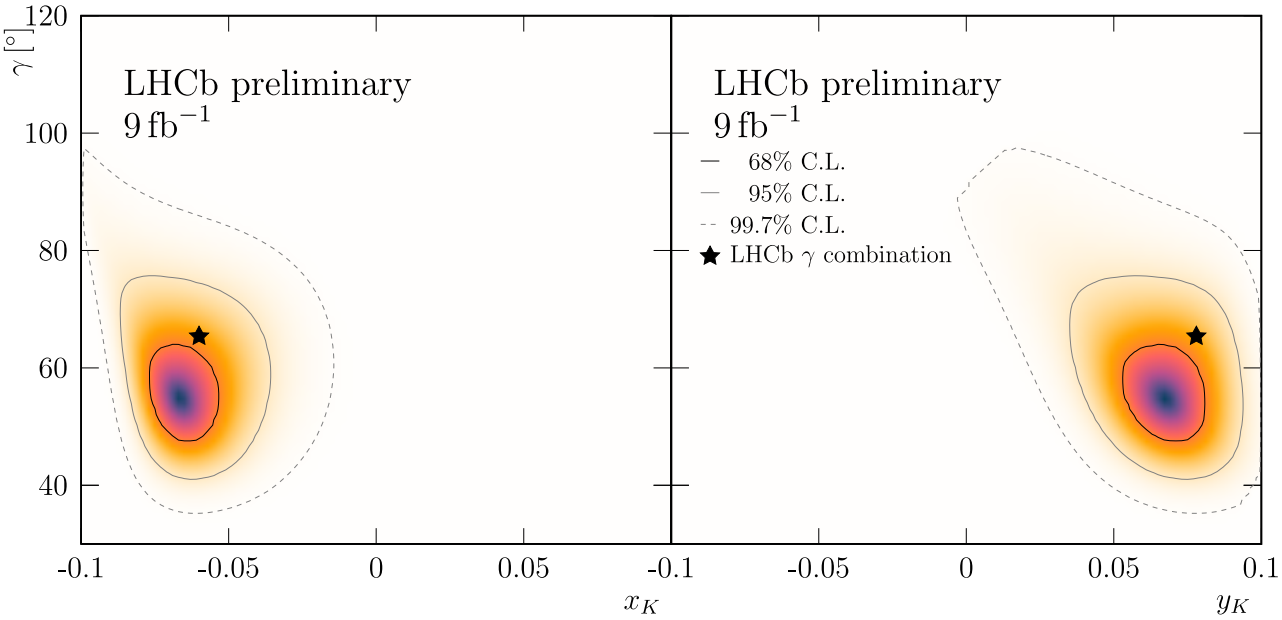


Full Run 1&2 Data set

LHCb
In preparation

γ from $B^{\pm} \to D\,[K^-\pi^+\pi^+\pi^-]\,h^{\pm}$ decays

Combine with inputs for D decay parameters to determine γ:



$$\gamma = \left(54.8\,^{+\,6.0\,+\,0.6\,+\,6.7}_{-\,5.8\,-\,0.6\,-\,4.3}\right)^{\circ}$$

$$\delta_B^K = \left(134.6\,^{+\;\;6.0\,+0.7\,+\;\;8.6}_{-\;\;6.0\,-0.7\,-\;\;8.7}\right)^{\circ}$$

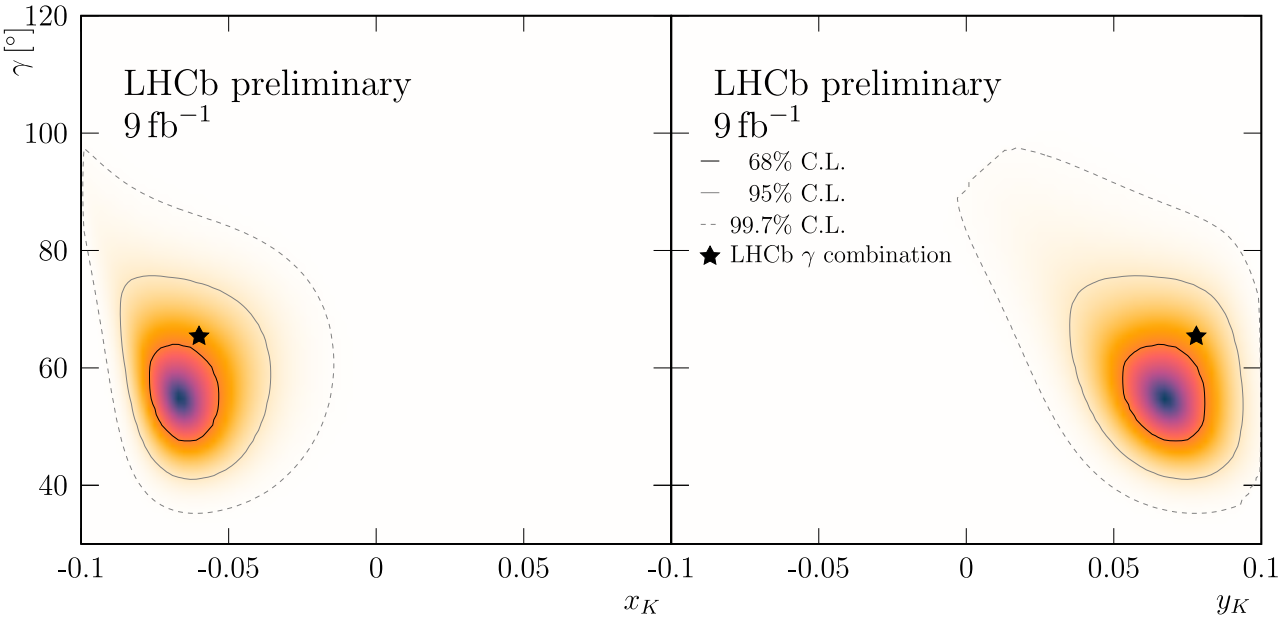
$$r_B^K = \left(\;\;94.6\,^{+\;\;3.1\,+0.5\,+\;\;3.0}_{-\;\;3.1\,-0.5\,-\;\;2.3}\right) \times 10^{-3}$$

Parameterise as: $x_k + iy_k = r_B^K e^{i\delta_B^K}$

LHCb
In preparation

γ from $B^{\pm} \to D\,[K^-\pi^+\pi^+\pi^-]\,h^{\pm}$ decays

Combine with inputs for D decay parameters to determine γ:



Large expected improvement from incoming $20\,\text{fb}^{-1}$ of BES-III $\psi(3770)$ data

$$\gamma = \left(54.8\,^{+\,6.0\,+\,0.6\,+\,6.7}_{-\,5.8\,-\,0.6\,-\,4.3}\right)^{\circ}$$

$$\delta_B^K = \left(134.6\,^{+\,\,6.0\,+0.7\,+\,\,8.6}_{-\,\,6.0\,-0.7\,-\,\,8.7}\right)^{\circ}$$

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Parameterise as: $x_k + iy_k = r_B^K e^{i\delta_B^K}$

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γ / charm combination

B decay	D decay	Data set
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	Run 1&2
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^-\pi^+$	Run 1
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	Run 1
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	Run 1&2
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	Run 1&2
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	Run 1&15/16
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^-\pi^+$	Run 1&15/16
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+\pi^-\pi^-\pi^+$	Run 1
$B^0 \to DK^{*0}$	$D \to h^+h^-$	Run 1&15/16
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^-\pi^+$	Run 1&15/16
$B^0 \to DK^{*0}$	$D \to K^0_S h^+h^-$	Run 1
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	Run 1
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	Run 1
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	Run 1&2

D decay	Observable(s)	Data set
$D^0 \to h^+h^-$	ΔA_{CP}	Run 1&2
$D^0 \to h^+h^-$	y_{CP}	Run 1
$D^0 \to h^+h^-$	ΔY	Run 1&2
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm, (x'^\pm)^2, y'^\pm$	Run 1
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm, (x'^\pm)^2, y'^\pm$	Run 1&15/16
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	Run 1
$D^0 \to K^0_S\pi^+\pi^-$	x, y	Run 1
$D^0 \to K^0_S\pi^+\pi^-$	$x_{CP}, y_{CP}, \Delta x, \Delta y$	Run 1&2

+ Critical input from BES-III (/CLEO-c) for D decay parameters

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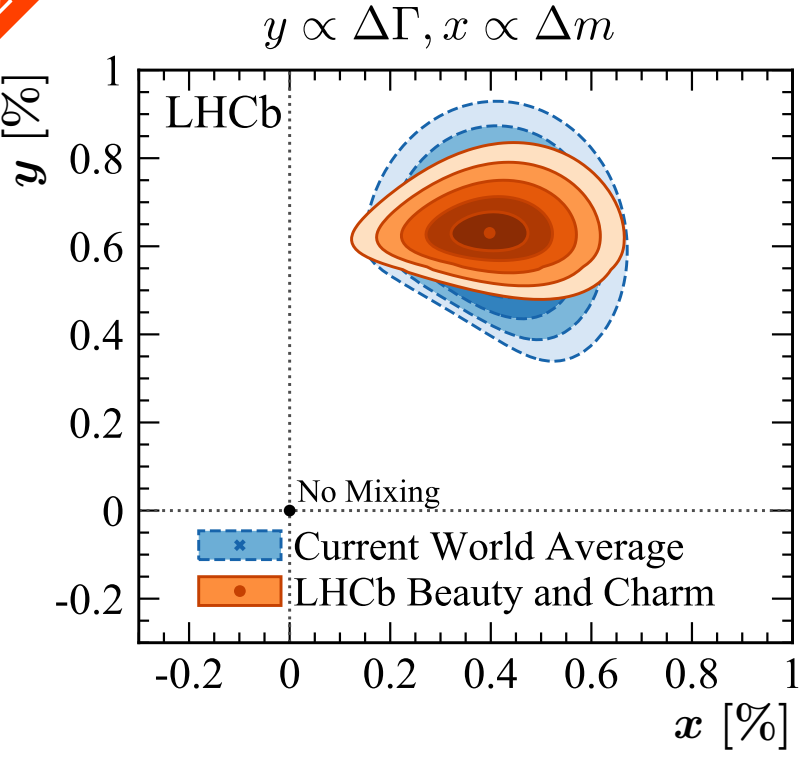
γ / charm combination



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$B^0 \to DK^{*0}$	$D \to K^0_S h^+h^-$	Run 1
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	Run 1
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	Run 1
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	Run 1&2

NEW!

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$D^0 \to h^+h^-$	ΔA_{CP}	Run 1&2
$D^0 \to h^+h^-$	y_{CP}	Run 1
$D^0 \to h^+h^-$	ΔY	Run 1&2
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm, (x'^\pm)^2, y'^\pm$	Run 1
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm, (x'^\pm)^2, y'^\pm$	Run 1&15/16
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	Run 1
$D^0 \to K^0_S\pi^+\pi^-$	x, y	Run 1
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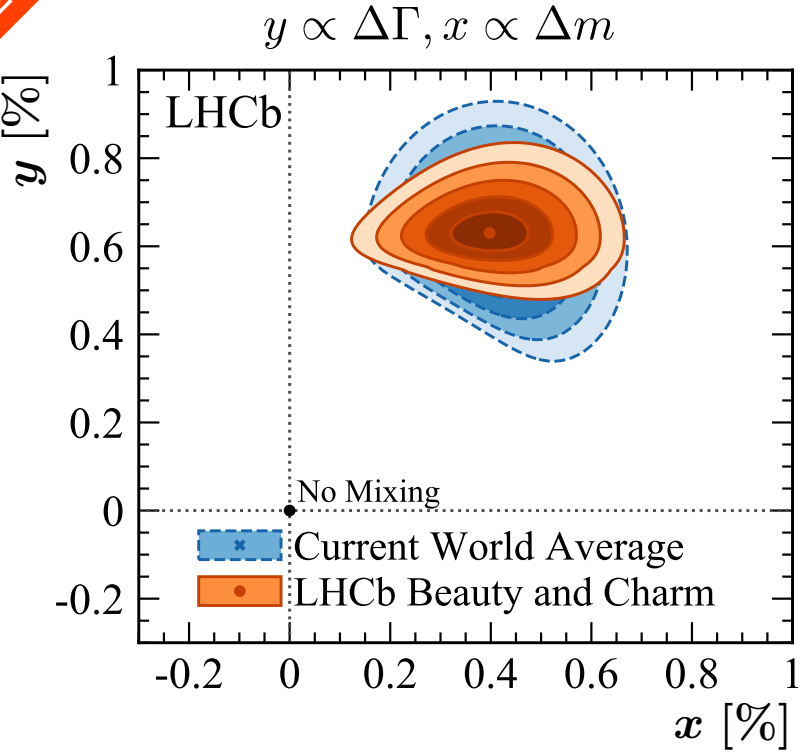
γ / charm combination



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See Surapat's talk
This afternoon @ 2:30

+ Critical input from BES-III (/CLEO-c) for D decay parameters

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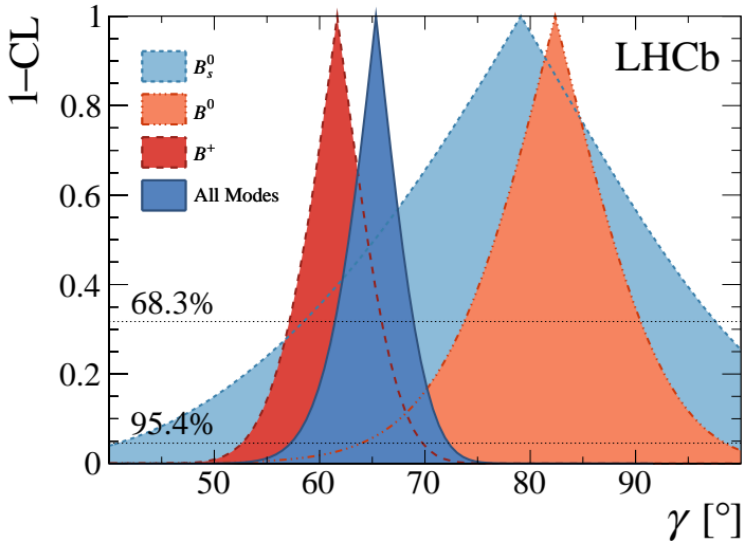
γ / charm combination



$$\gamma = (65.4\,^{+\,3.8}_{-\,4.2})^\circ$$

(indirect $\gamma \sim (65.5\,^{+\,1}_{-\,2})^\circ$)

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$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+\pi^-\pi^-\pi^+$	Run 1
$B^0 \to DK^{*0}$	$D \to h^+h^-$	Run 1&15/16
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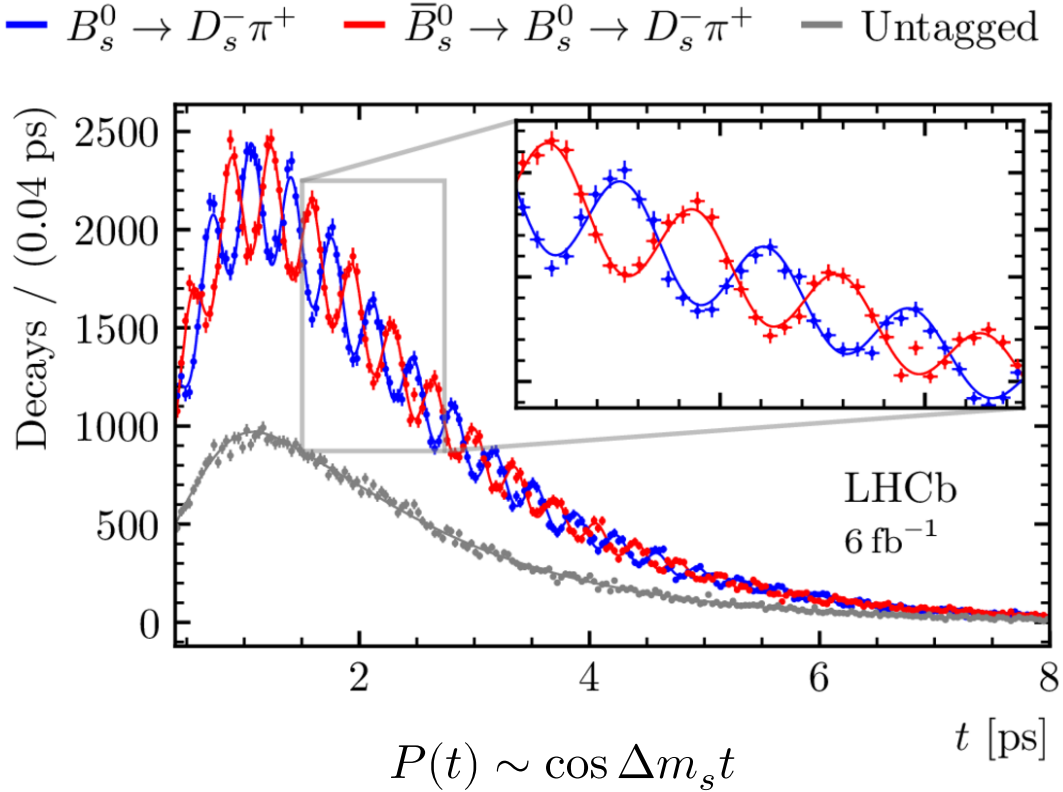
+ Critical input from BES-III (/CLEO-c) for D decay parameters

Nature 18, (2022) 1-5

Δm_s from $B_s^0 \to D_s^- \pi^+$



$$P(t) \sim \cos \Delta m_s t$$

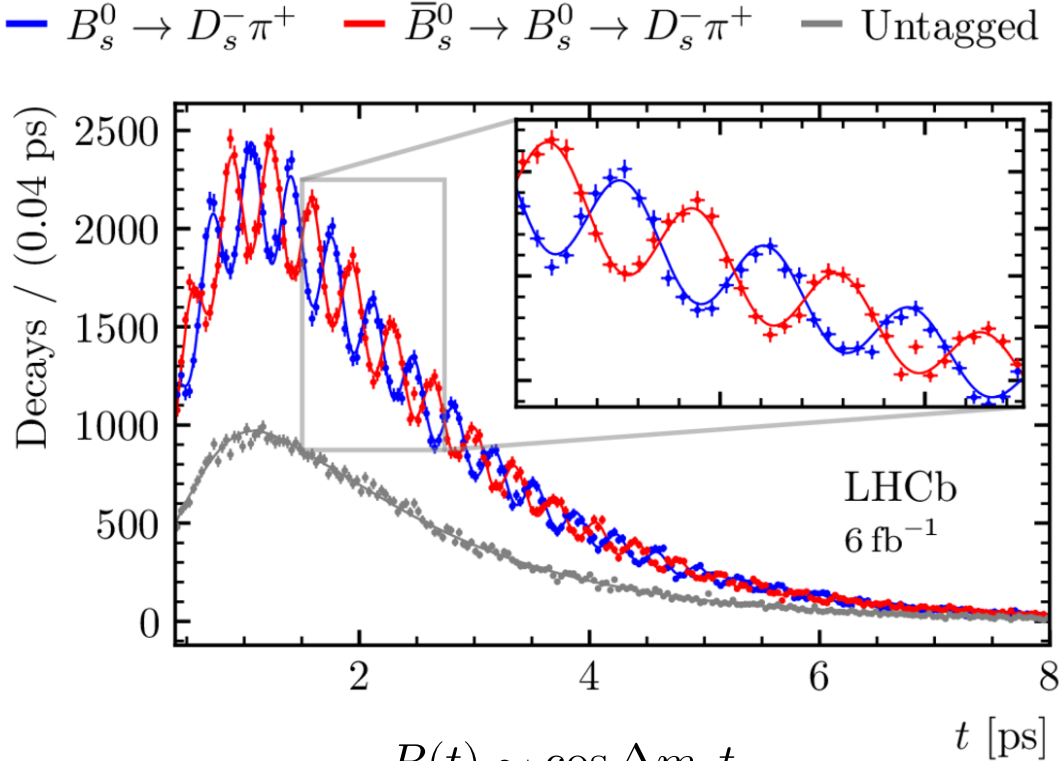
Finds:

$$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\,\text{ps}^{-1}$$

Important input for γ from $B_s^0 \to D_s^- K^+$

Nature 18, (2022) 1-5

Δm_s from $B_s^0 \to D_s^- \pi^+$

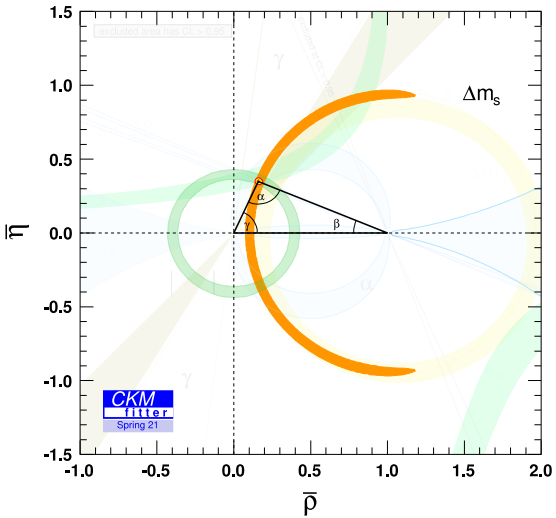


$$P(t) \sim \cos \Delta m_s t$$

Finds:

$$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\,\text{ps}^{-1}$$

Important input for γ from $B_s^0 \to D_s^- K^+$



And an important CKM measurement!

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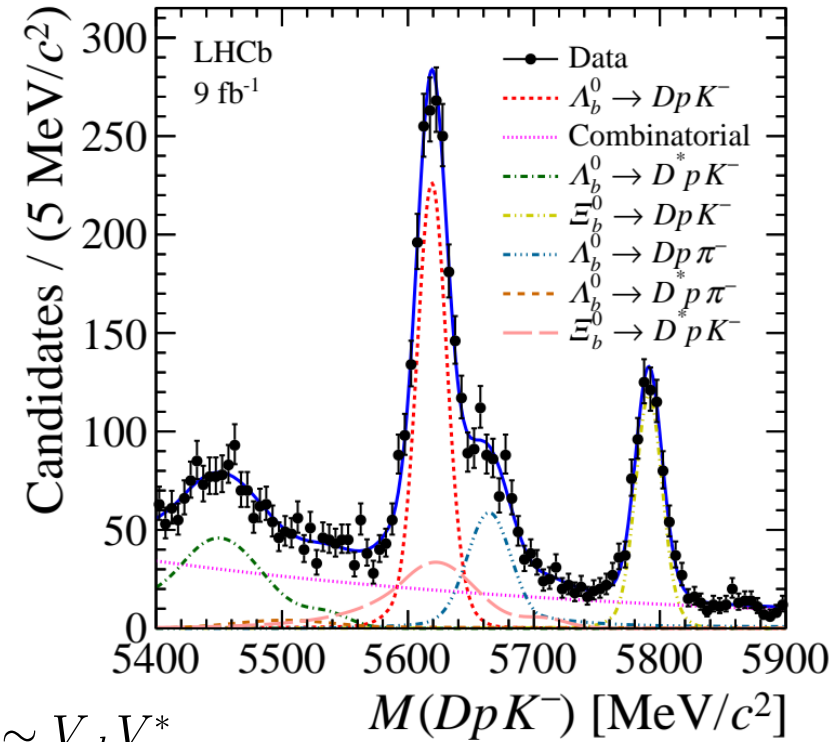
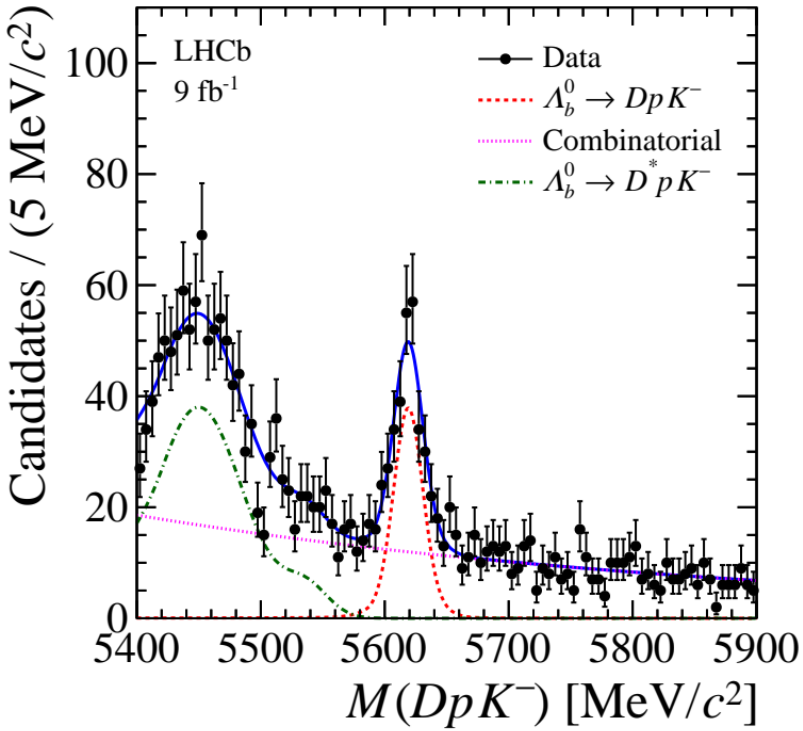
Search for CPV in $\Lambda_b^0 \to DpK^-$ decays

Initial state (currently) unique to LHC



$\sim V_{cb}V_{us}^*$

$\Lambda_b^0 \to D[K^-\pi^+]K^-p$



$\sim V_{ub}V_{cs}^*$

$\Lambda_b^0 \to D[K^+\pi^-]K^-p$

$\to$ First observation of suppressed mode

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Search for CPV in $\Lambda_b^0 \to DpK^-$ decays

Measure:

$$R = \frac{\Gamma(\Lambda_b^0 \to D\,[K^-\pi^+]\,pK^-)}{\Gamma(\Lambda_b^0 \to D\,[K^+\pi^-]\,pK^-)} = 7.1 \pm 0.8^{+0.4}_{-0.3}$$

$$A = \frac{\Gamma(\Lambda_b^0 \to D\,[K^+\pi^-]\,pK^-) - \Gamma(\overline{\Lambda}_b^0 \to D\,[K^-\pi^+]\,\overline{p}K^+)}{\Gamma(\Lambda_b^0 \to D\,[K^+\pi^-]\,pK^-) + \Gamma(\overline{\Lambda}_b^0 \to D\,[K^-\pi^+]\,\overline{p}K^+)} = 0.12 \pm 0.09^{+0.02}_{-0.03}$$

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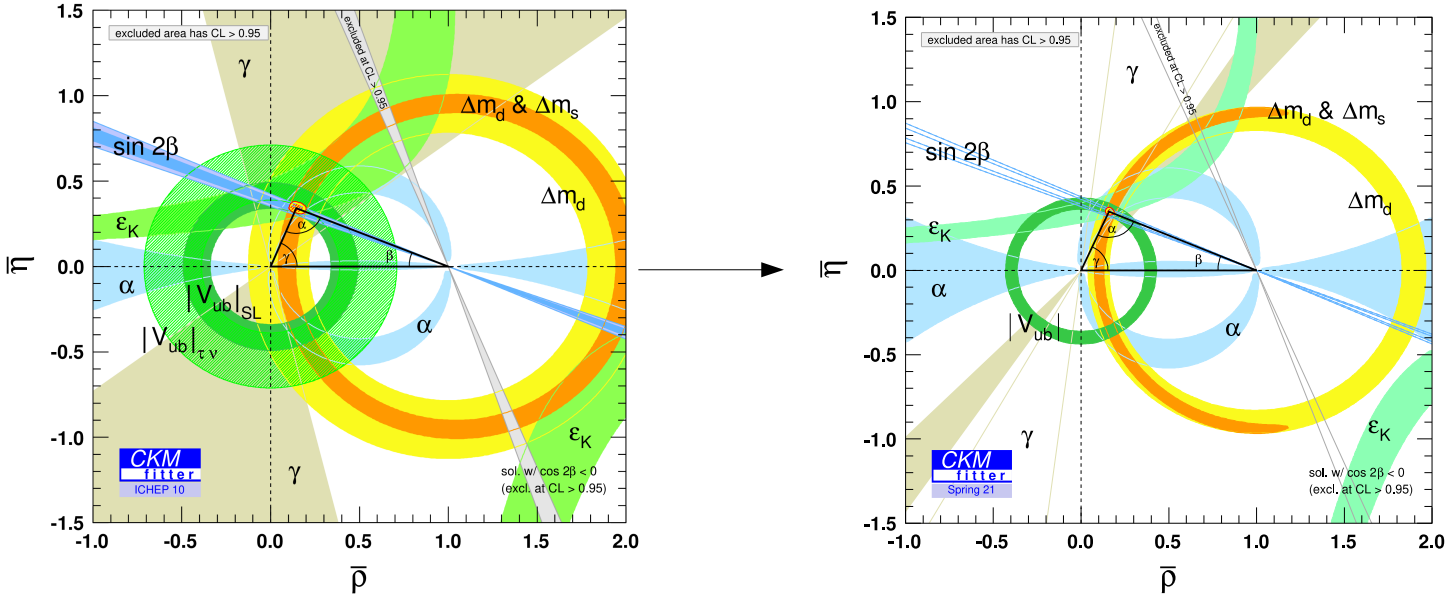
No evidence of CPV in baryons yet ...

R ratio looks very favourable for future studies with more D decays ...



- 10 years of measurements have been game changing for flavour physics.
- γ no longer the least precisely known of the weak phases!
- LHCb already achieved target precision of $< 4^\circ$ for first generation experiment - with many more modes still to add!
- Aiming for $< 1^\circ$ in the upgrade era ..