New precise measurements of CP violation and mixing in beauty and charm decays at LHCb

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on behalf of the LHCb collaboration

CERN seminar – 08/02/2022

Contents

- Two part seminar on CP violation and charm mixing
- Simultaneous determination of CKM angle γ and charm mixing parameters
    - JHEP 12 (2021) 141

Recently published in JHEP!

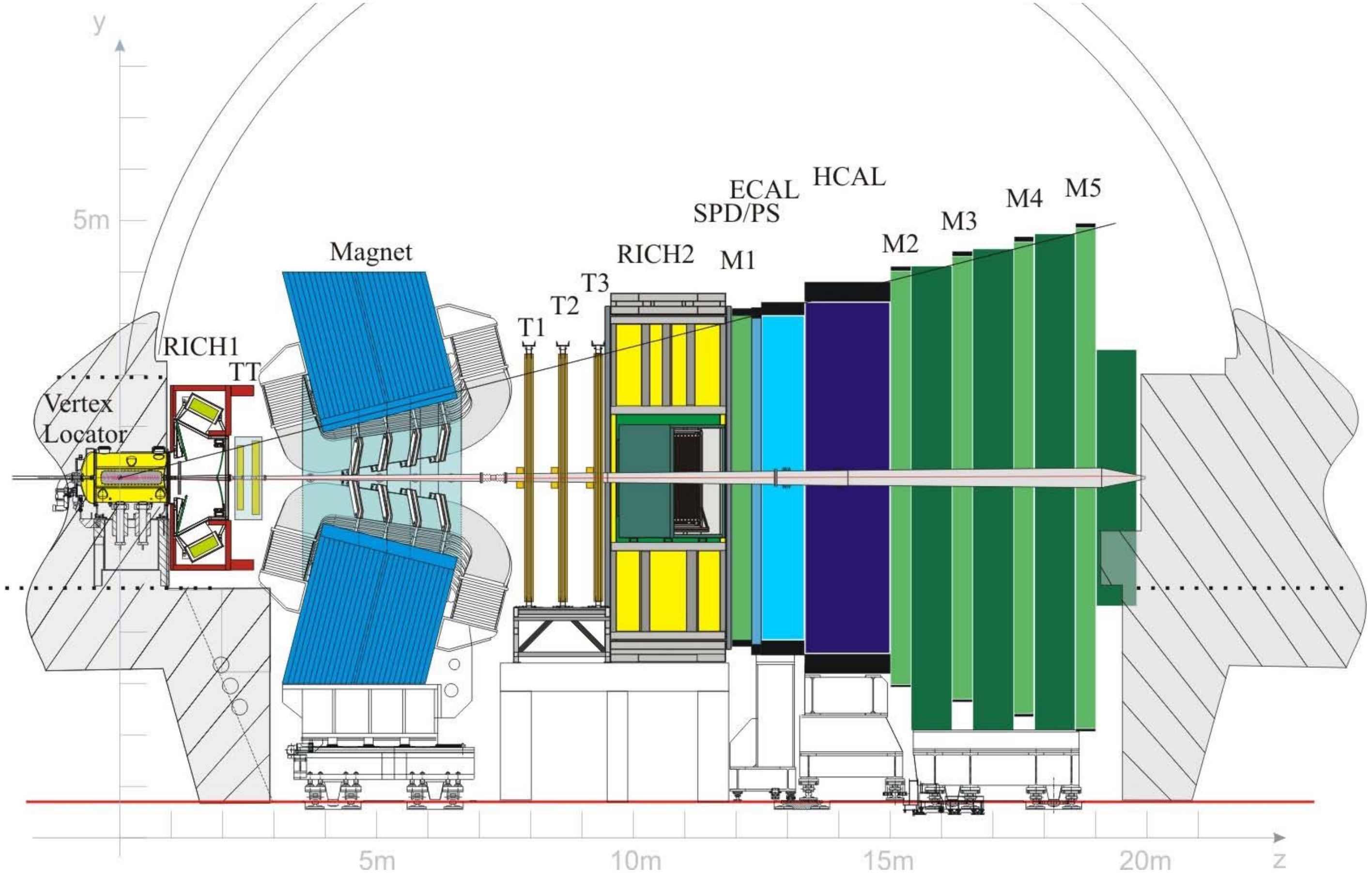
- Measurement of the charm mixing parameter $y_{CP} - y_{CP}^{K\pi}$ using two body D^0 decays
    - LHCb-PAPER-2021-041

Shown for the first time today!

LHCb experiment

JINST 3 S08005

- General purpose detector in the forward region
  - Excellent particle identification (K-π separation)
  - Very good momentum resolution (0.5 – 1.0%)
  - Excellent impact parameter resolution
  - Very good decay time resolution
  - Real-time analysis, calibration and alignment



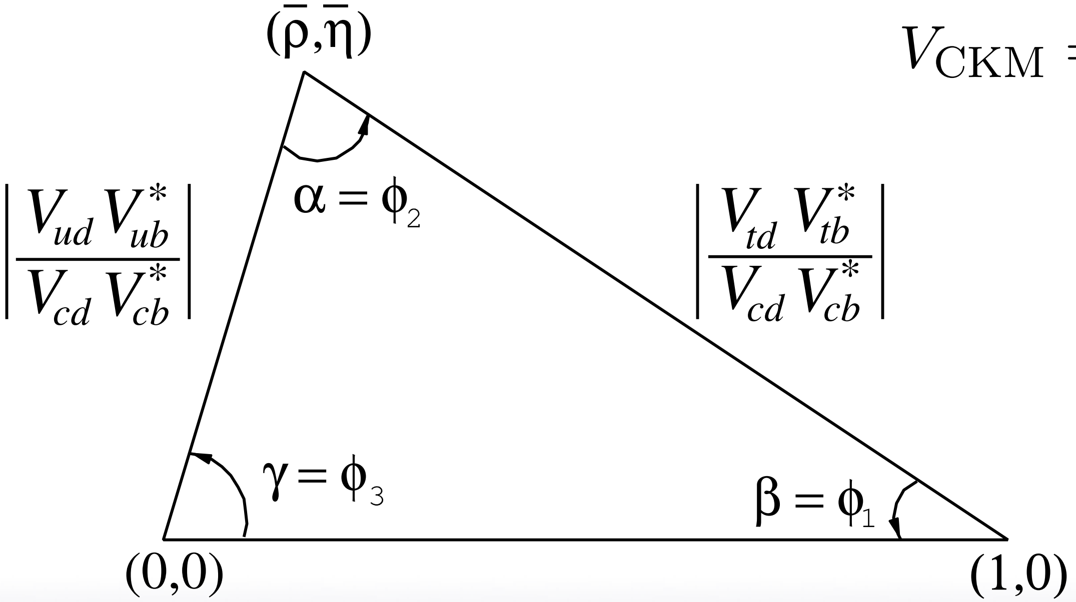
Introduction to the CKM angle γ

- CKM quark mixing matrix
  - Describes transitions between quarks

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

- Wolfenstein parameterisation
  - Unitary condition defines triangles

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



The area of this triangle (and all of the others) is related to the total amount of CP violation in the quark sector

Introduction to the CKM angle γ (II)

- CKM parameters are free parameters of SM
  - Must be measured by experiments

- The angle γ is a standard candle
  - Measure with tree-level decays, theoretically simple (negligible uncertainties)

- Direct measurements (from B decays)

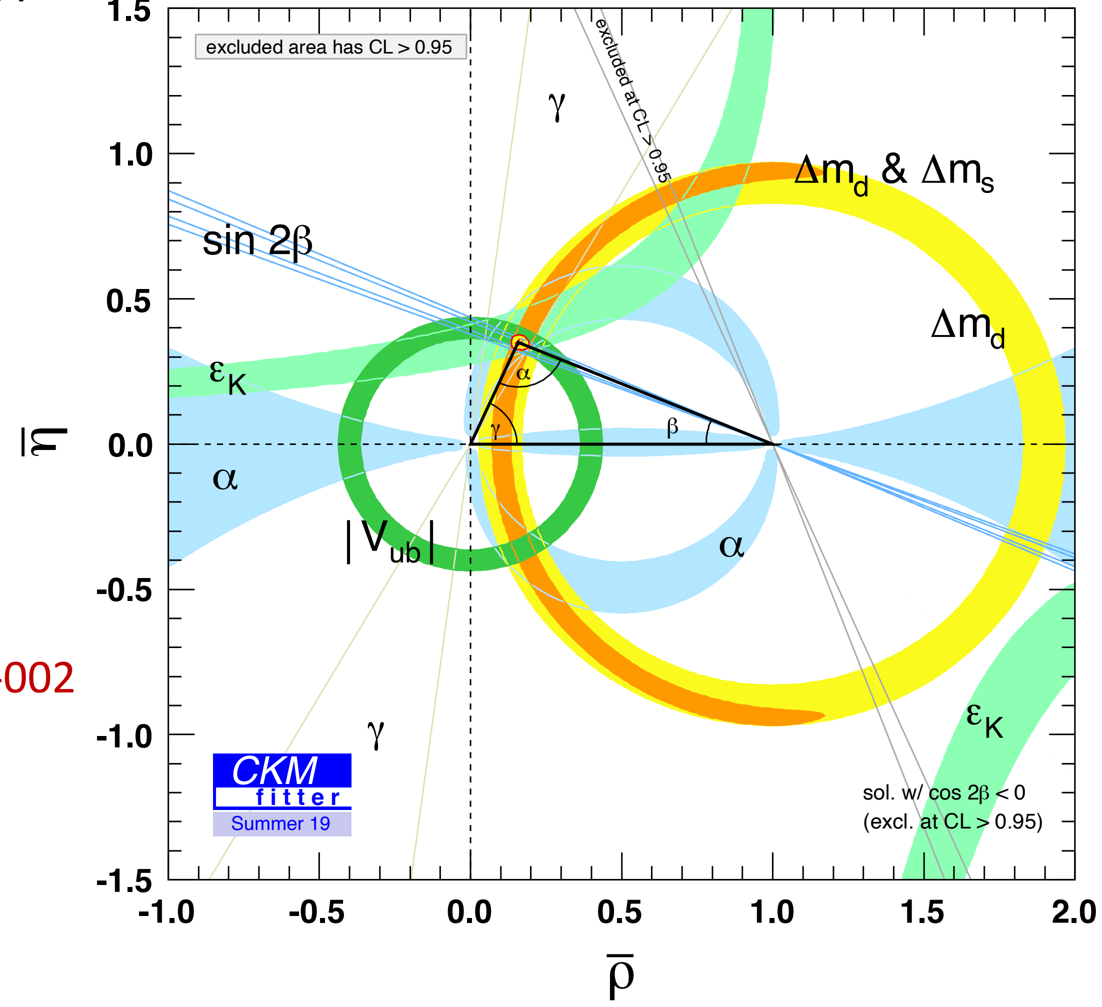
$$\gamma = (74.0^{+5.0}_{-5.8})^\circ$$ LHCb-CONF-2018-002

- Indirectly inferred from other constraints

$$\gamma = (65.8 \pm 2.2)^\circ \quad , \quad \gamma = (65.55^{+0.90}_{-2.65})^\circ$$

UT Fit CKM fitter

$$\gamma \equiv \arg[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}]$$



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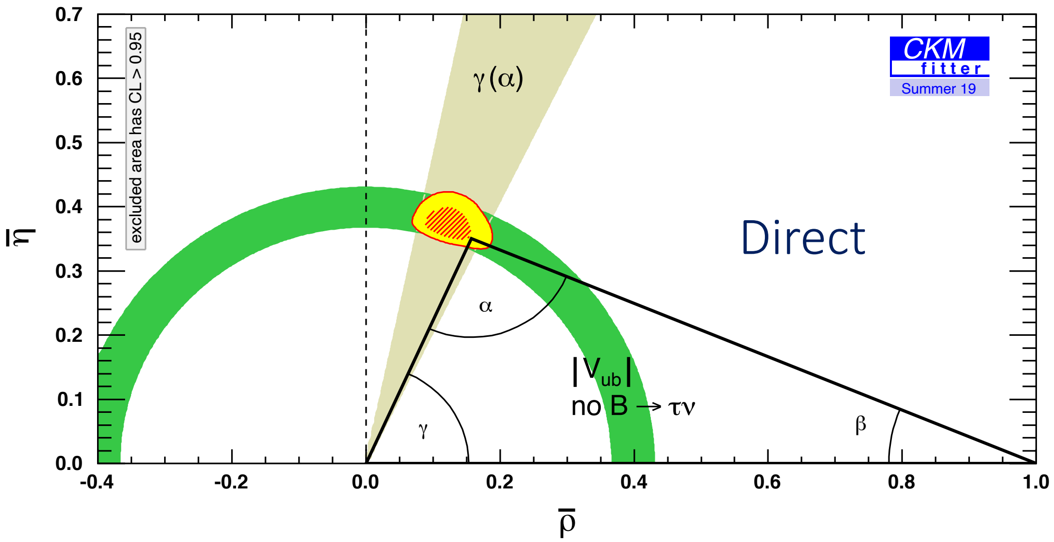
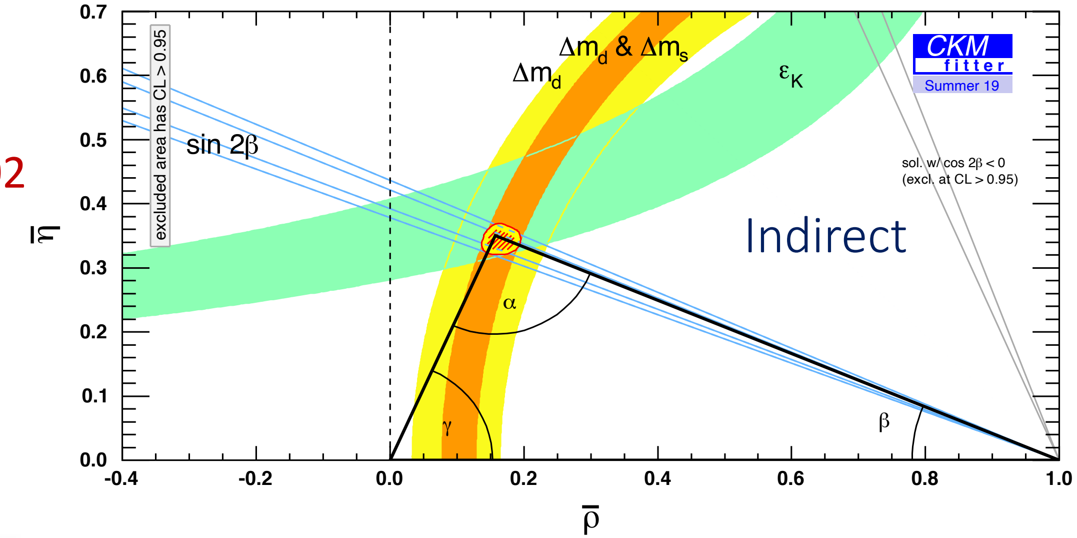
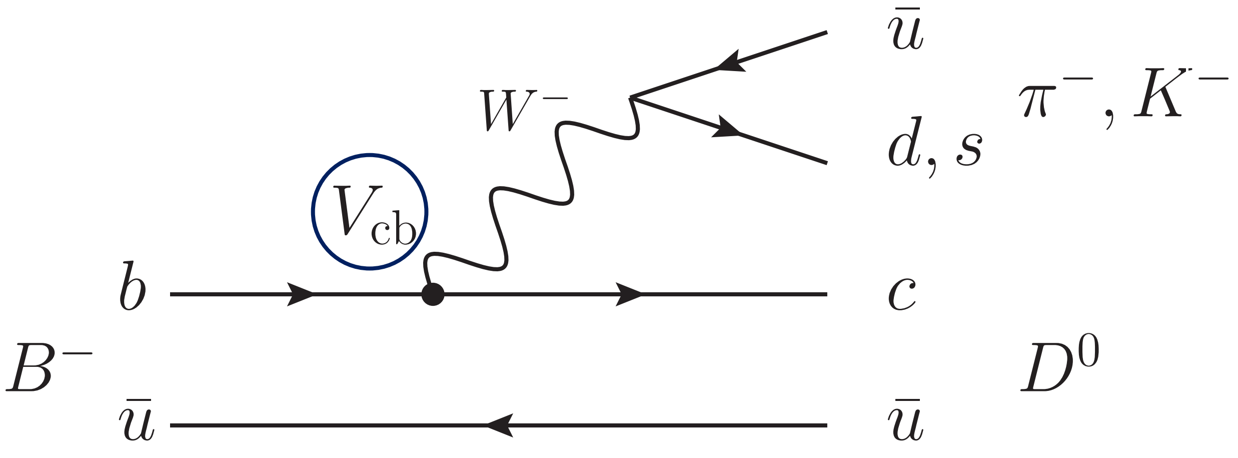


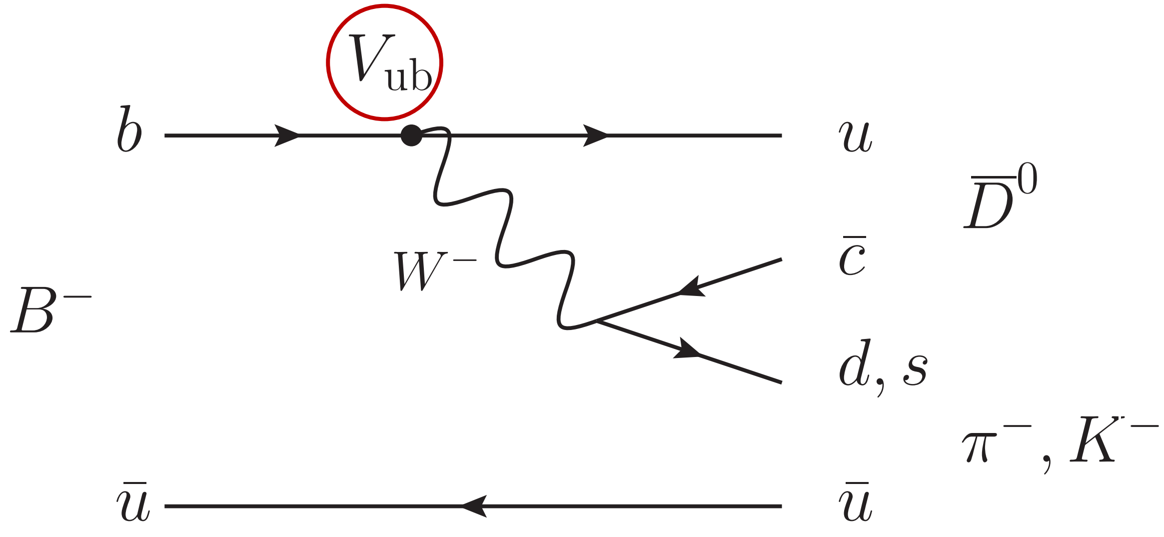


Measuring the CKM angle γ

$$\gamma \equiv \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$$

- Exploit the effects of interference
  - Need at least two paths to the same final state: $b \to cW$ (V_{cb}) and $b \to uW$ (V_{ub})
  - Consider the golden mode $B^\pm \to DK^\pm$





Same initial and final states when D^0 and $\overline{\text{D}}^0$ decay in the same way

Measuring the CKM angle γ (II)

$$\gamma \equiv \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$$

- Exploit the effects of interference
  - Need at least two paths to the same final state: $b \to cW\ (V_{cb})$ and $b \to uW\ (V_{ub})$
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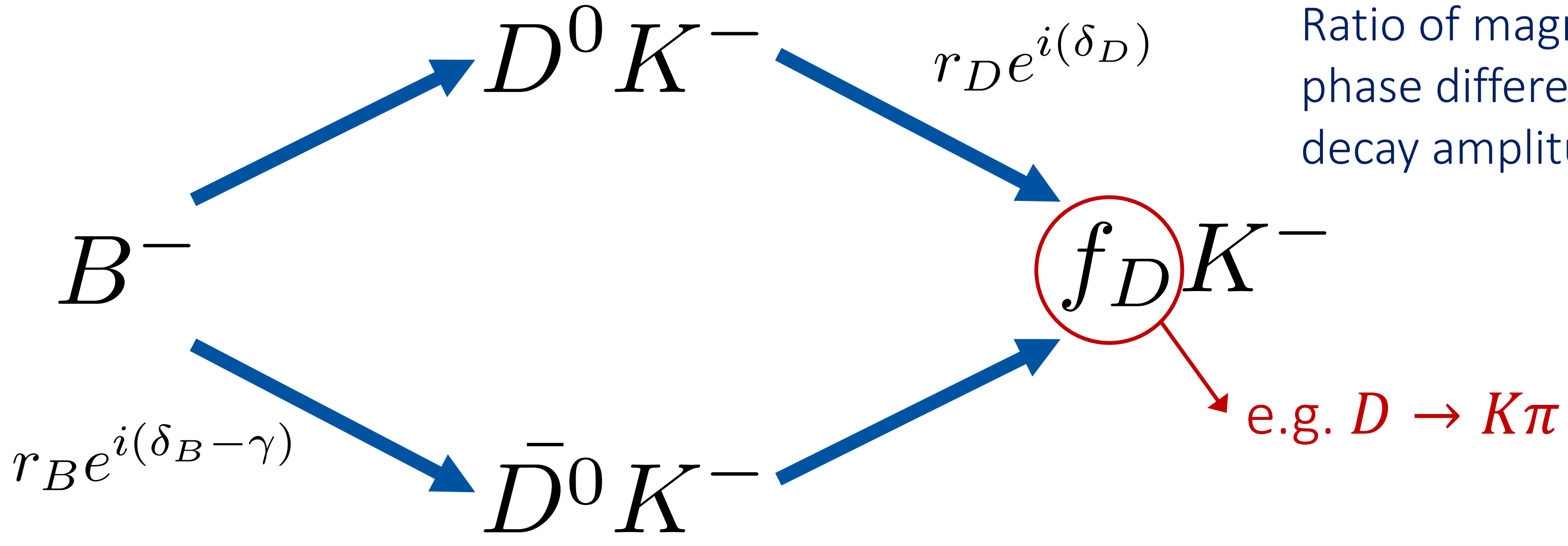
Ratio of magnitudes and phase difference for D decay amplitudes



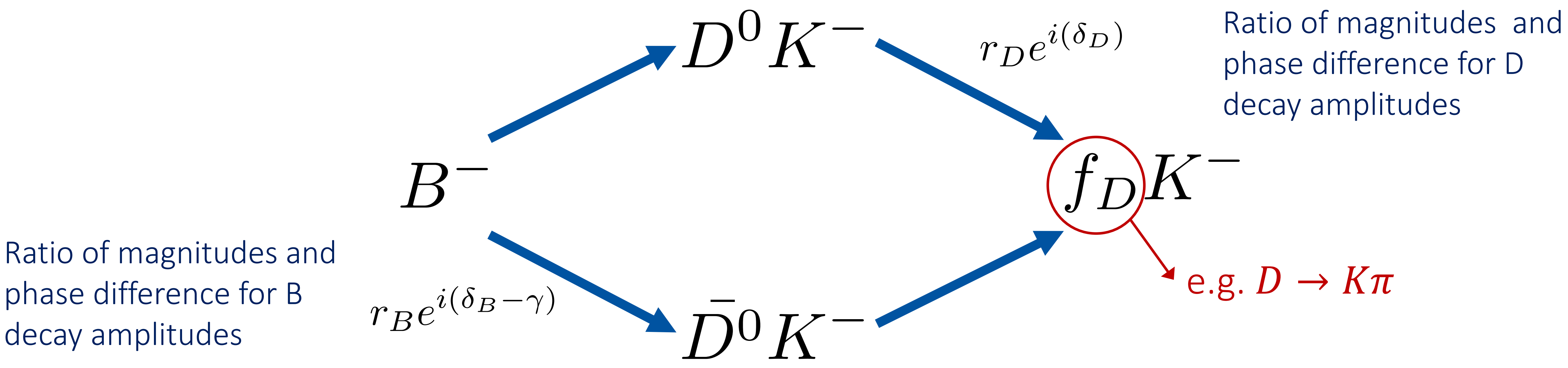
Ratio of magnitudes and phase difference for B decay amplitudes

$$\Gamma(B^{\pm} \to Dh^{\pm}) \propto |r_De^{-i\delta_D} + r_Be^{i(\delta_B \pm \gamma)}|^2 \Rightarrow r_D^2 + r_B^2 + 2r_Dr_B\cos(\delta_B + \delta_D \pm \gamma)$$

Measuring the CKM angle γ (II)

$$\gamma \equiv \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$$

- Exploit the effects of interference
  - Need at least two paths to the same final state: $b \to cW\ (V_{cb})$ and $b \to uW\ (V_{ub})$
  - Consider the golden mode $B^{\pm} \to DK^{\pm}$



B decay parameters independent of the D final state – we can over constrain the system

Measuring the CKM angle γ (III)

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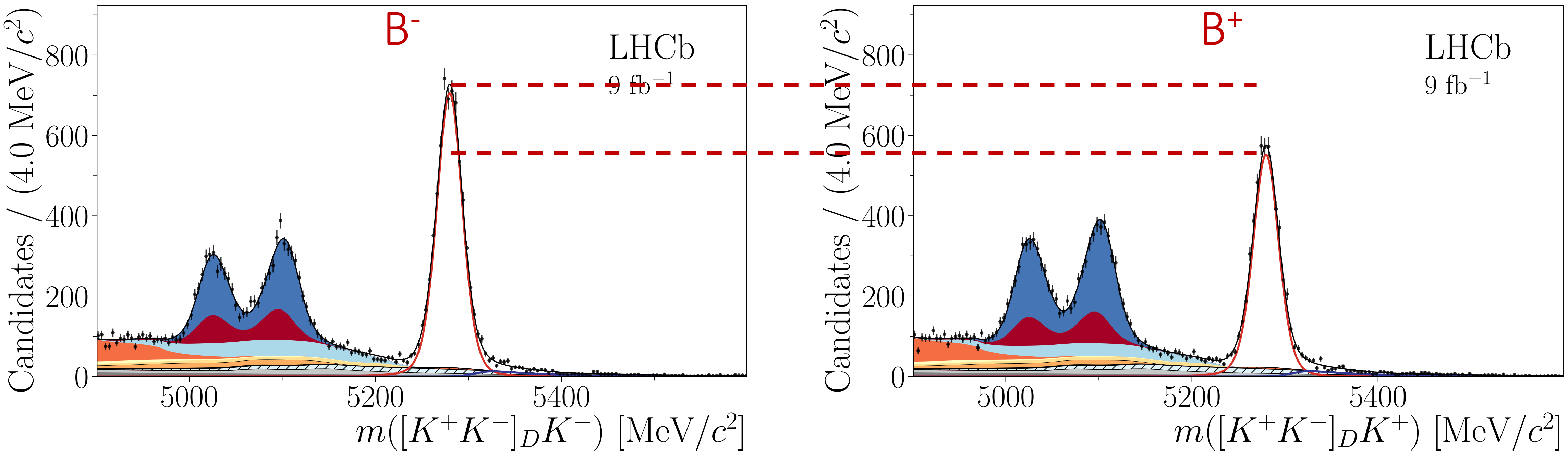
$$\gamma \equiv \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$$

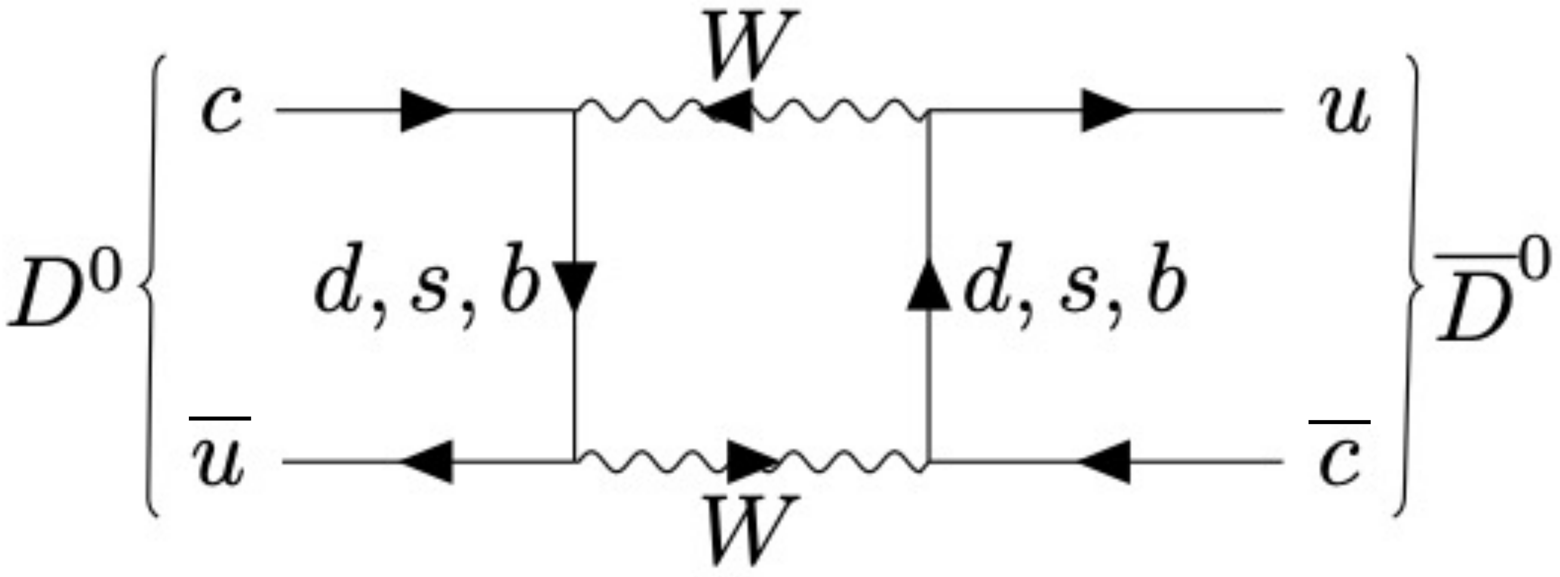
- Exploit the effects of interference
  - Need at least two paths to the same final state: $b \to cW\ (V_{cb})$ and $b \to uW\ (V_{ub})$
  - Consider the golden mode $B^{\pm} \to DK^{\pm}$



$$\Gamma(B^{\pm} \to Dh^{\pm}) \propto |r_D e^{-i\delta_D} + r_B e^{i(\delta_B \pm \gamma)}|^2 \Rightarrow r_D^2 + r_B^2 + 2 r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$

Introduction to charm mixing

- Flavour quantum numbers are not conserved by the weak interaction
  - Neutral mesons can oscillate between particle and antiparticle states



- Well known phenomenon since the 1950’s in the neutral kaon system
  - Also observed in the beauty and charm sectors
  - Sensitive probe for new interactions see, e.g., arXiv:1710.09644 **[hep-ph]**

Introduction to charm mixing (II)

- Flavour quantum numbers are not conserved by the weak interaction
  - Neutral mesons can oscillate between particle and antiparticle states

- Mass eigenstates related to the flavour eigenstates as

$$|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\overline{D}^0\rangle$$

- Mixing is then parameterised by

$$x \equiv (m_1 - m_2)/\Gamma \text{ and } y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$$

- Important parameters to measure in their own right
  - Expected to be small, O(%), in the SM, but could be enhanced by new physics effects

Measuring charm mixing

- Charm mixing parameters can be determined using two-body decays
  - E.g. Ratio of $D^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$ time-dependent decay rates

$$R^{\pm}(t) \approx R^{\pm} + \sqrt{R^{\pm}}y'^{\pm}\left(\frac{t}{\tau}\right) + \frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4}\left(\frac{t}{\tau}\right)^2$$

- Where

$$R^{\pm} = r_D^2(1 \pm A_D)$$

$$\phi \equiv \arg(q/p)$$

$$x'^{\pm} \equiv -|q/p|^{\pm 1}\left[x\cos(\delta_D^{K\pi} \pm \phi) + y\sin(\delta_D^{K\pi} \pm \phi)\right]$$

$$y'^{\pm} \equiv -|q/p|^{\pm 1}\left[y\cos(\delta_D^{K\pi} \pm \phi) - x\sin(\delta_D^{K\pi} \pm \phi)\right]$$

This is the same strong phase difference and ratio of amplitudes as shown in the B decay equation

Should we combine beauty and charm?

- Just seen that there are some common parameters
- Recall that many measurements of γ utilise decays of neutral D mesons
  - Must (and always have) include charm mixing anyway
  - Decay rate equation becomes

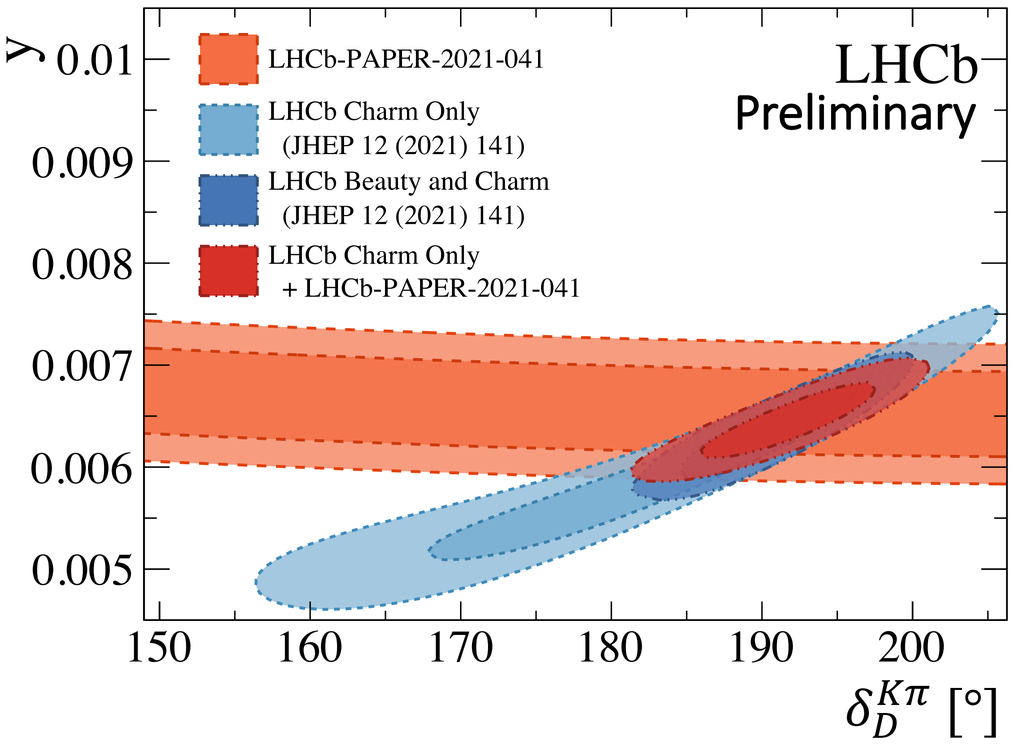
$$
\begin{aligned}
\Gamma(B^{\pm} \to Dh^{\pm}) \propto \; & r_D^2 + r_B^2 + 2 r_D r_B \cos(\delta_B + \delta_D \pm \gamma) \\
& - \alpha \left[(1 + r_B^2) r_D \cos(\delta_D) + (1 + r_D^2) r_B \cos(\delta_B \pm \gamma) \right] y \\
& + \alpha \left[(1 - r_B^2) r_D \sin(\delta_D) - (1 - r_D^2) r_B \sin(\delta_B \pm \gamma) \right] x
\end{aligned}
$$

- Particularly important in decays where r_B is comparable to x and y
- Beauty data samples now large enough that the strong phase δ_D can be measured more precisely than in charm measurements

Should we combine beauty and charm? (II)

- It also turns out there is a strong correlation between y and $\delta_D^{K\pi}$
  - Recall terms from the equation above, sensitivity to y driven by

$$y' \approx -y\cos\left(\delta_D^{K\pi}\right) + x\sin\left(\delta_D^{K\pi}\right)$$

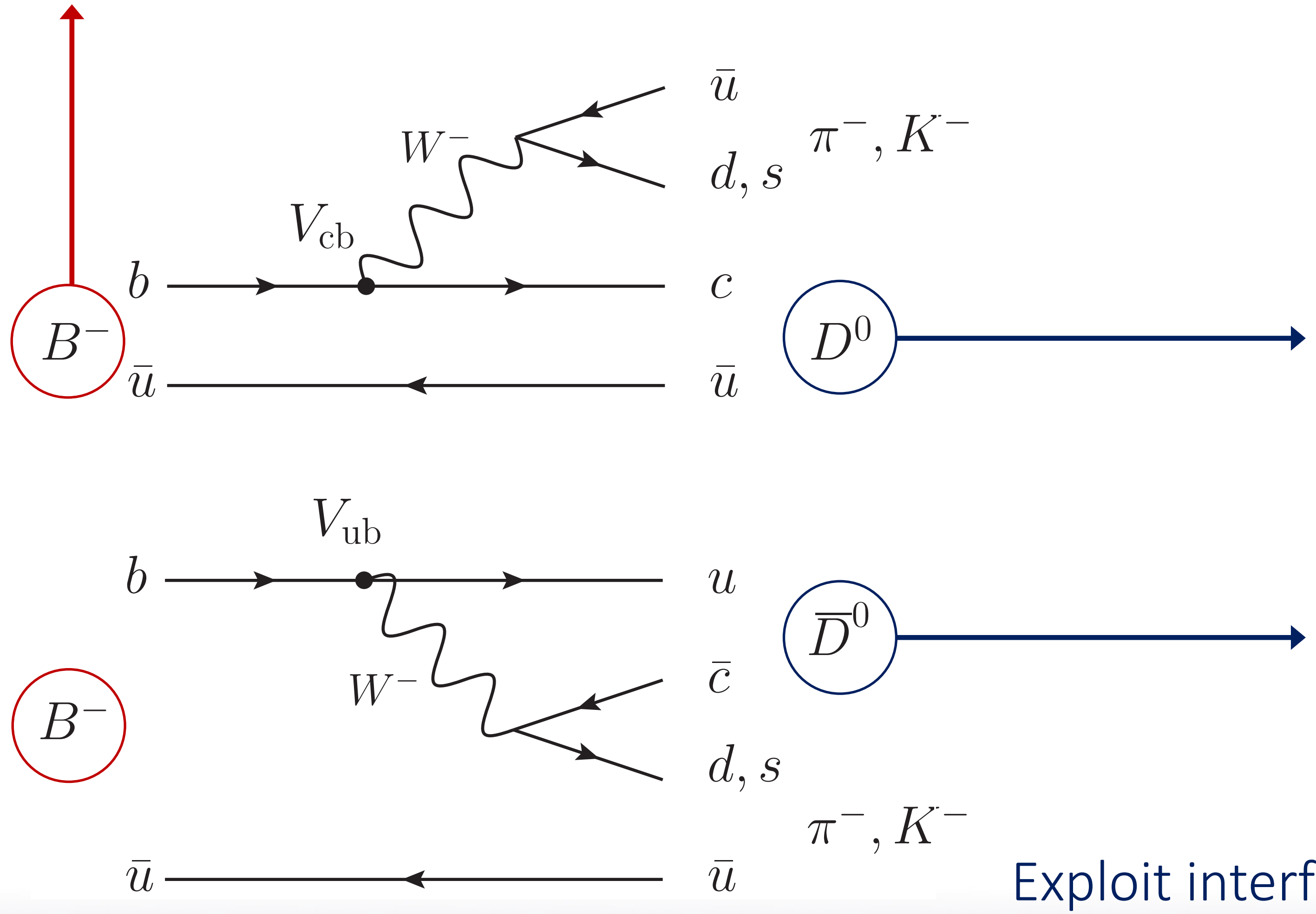


- Beauty samples can improve the precision on y by exploiting such correlations!

- A statistically robust determination of all these parameters requires the simultaneous approach

Inputs to the combination – time-independent beauty

$$B^\pm \to Dh^\pm,\ B^\pm \to D^*h^\pm,\ B^\pm \to DK^{*\pm},\ B^\pm \to Dh^\pm\pi^+\pi^-,\ B^0 \to DK^{*0}$$



Each B decay mode includes results from (some of) the following D decay modes

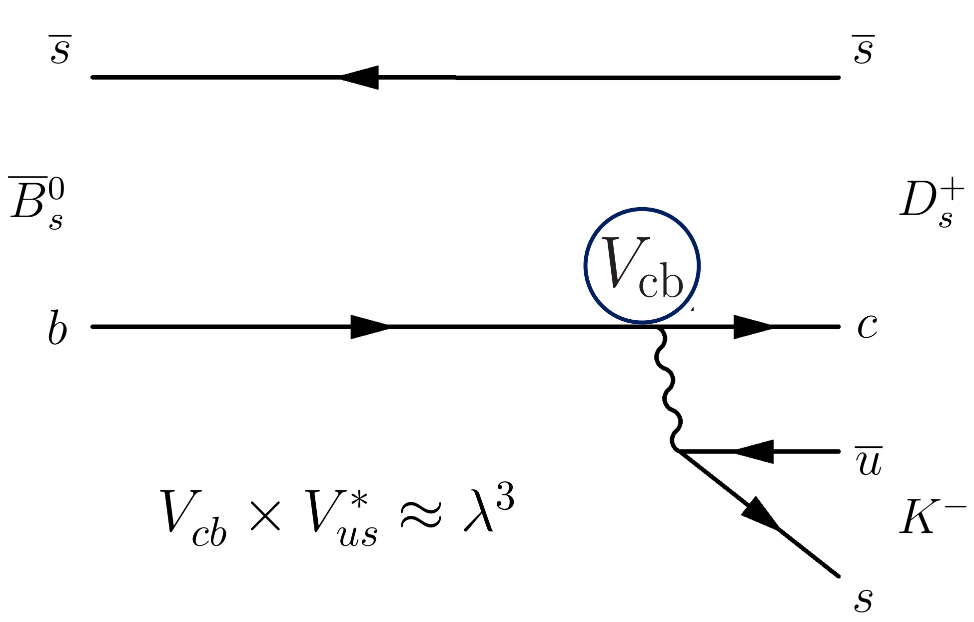
$$D \to h^+h^-$$
$$D \to h^+\pi^-\pi^+\pi^-$$
$$D \to h^+h^-\pi^0$$
$$D \to K^0_S h^+h^-$$
$$D \to K^0_S K^\pm\pi^\mp$$

Exploit interference between the two diagrams

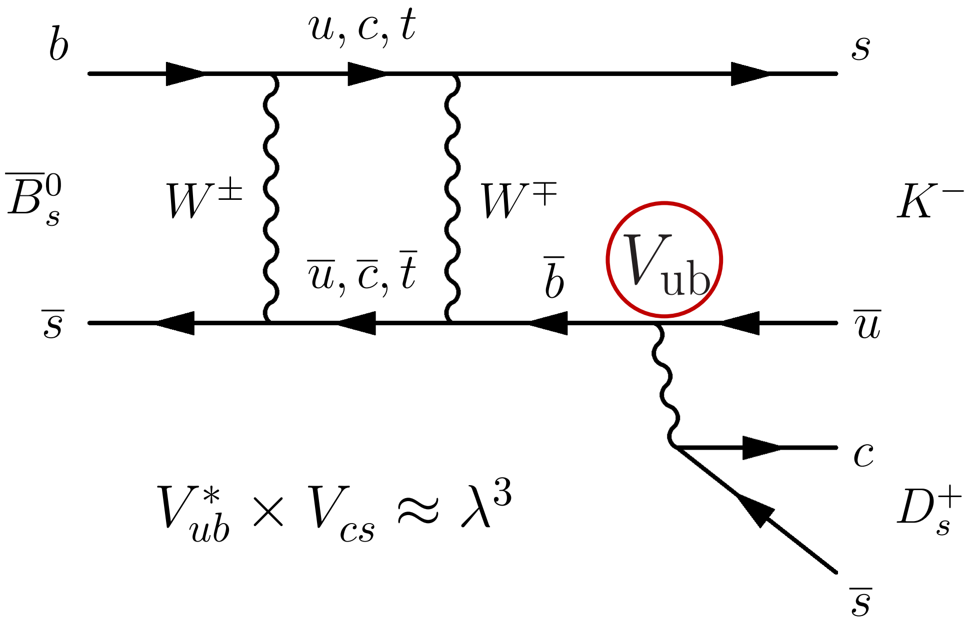
Inputs to the combination – time-dependent beauty

$$B^0 \to D^{\mp}\pi^{\pm},\ B_s^0 \to D_s^{\mp}K^{\pm} \text{ and } B_s^0 \to D_s^{\mp}K^{\pm}\pi^+\pi^-$$

- Quite different to the time dependent measurements
  - Interference effects arise from B meson mixing
  - Require knowledge of initial flavour via flavour tagging algorithms



$V_{cb} \times V_{us}^* \approx \lambda^3$



$V_{ub}^* \times V_{cs} \approx \lambda^3$

Exploit interference between the two diagrams

Inputs to the combination – charm

- The LHCb charm inputs included for the first time
  - Suite of mixing and/or CP violation measurements

Channel	Measurement
$D^0 \to h^+h^-$	ΔA_{CP}
$D^0 \to h^+h^-$	y_{CP}
$D^0 \to h^+h^-$	ΔY
$D^0 \to K^+\pi^-$	$R^{\pm},\ (x'^{\pm})^2,\ y'^{\pm}$
$D^0 \to K^{\pm}\pi^{\mp}\pi^+\pi^-$	$(x^2+y^2)/4$
$D^0 \to K^0_{\mathrm{S}}\pi^+\pi^-$	$x,\ y$
$D^0 \to K^0_{\mathrm{S}}\pi^+\pi^-$	$x_{CP},\ y_{CP},\ \Delta x,\ \Delta y$

Inputs to the combination – auxiliary inputs

- Include some inputs measured from statistically independent samples

Decay	Parameters	Source
$B^\pm \to DK^{*\pm}$	$\kappa_{B^\pm}^{DK^{*\pm}}$	LHCb
$B^0 \to DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb
$B^0 \to D^\mp\pi^\pm$	β	HFLAV
$B_s^0 \to D_s^\mp K^\pm(\pi\pi)$	ϕ_s	HFLAV
$D \to h^+h^-\pi^0$	$F_{\pi\pi\pi^0}^+$, $F_{K\pi\pi^0}^+$	CLEO-c
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{4\pi}^+$	CLEO-c
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII
$D \to K_\mathrm{S}^0K^\pm\pi^\mp$	$r_D^{K_\mathrm{S}^0K\pi}$, $\delta_D^{K_\mathrm{S}^0K\pi}$, $\kappa_D^{K_\mathrm{S}^0K\pi}$	CLEO
$D \to K_\mathrm{S}^0K^\pm\pi^\mp$	$r_D^{K_\mathrm{S}^0K\pi}$	LHCb

Several input measurements rely on CLEO-c + BESIII results for c_i and s_i from $D^0 \to K_\mathrm{S}^0\pi^+\pi^-$ decays

Almost there – the combination

- Performed using the Gammacombo package https://gammacombo.github.io
  - General purpose combination framework
- Default results use a frequentist approach (with the so called PLUGIN method)
  - 151 observables used to determine 52 parameters
  - Checked with a Bayesian approach

See JHEP 12 (2021) 141 for more details!

- Likelihood effectively a product of Gaussians

$$\mathcal{L}(\vec{\alpha}) = \prod_i f_i(\vec{A}_i^{\text{obs}} | \vec{\alpha})$$

$$f_i(\vec{A}_i^{\text{obs}} | \vec{\alpha}) \propto \exp\left(-\frac{1}{2} (\vec{A}_i(\vec{\alpha}) - \vec{A}_i^{\text{obs}})^T \, V_i^{-1} \, (\vec{A}_i(\vec{\alpha}) - \vec{A}_i^{\text{obs}}) \right)$$

Results - γ

- Headline result

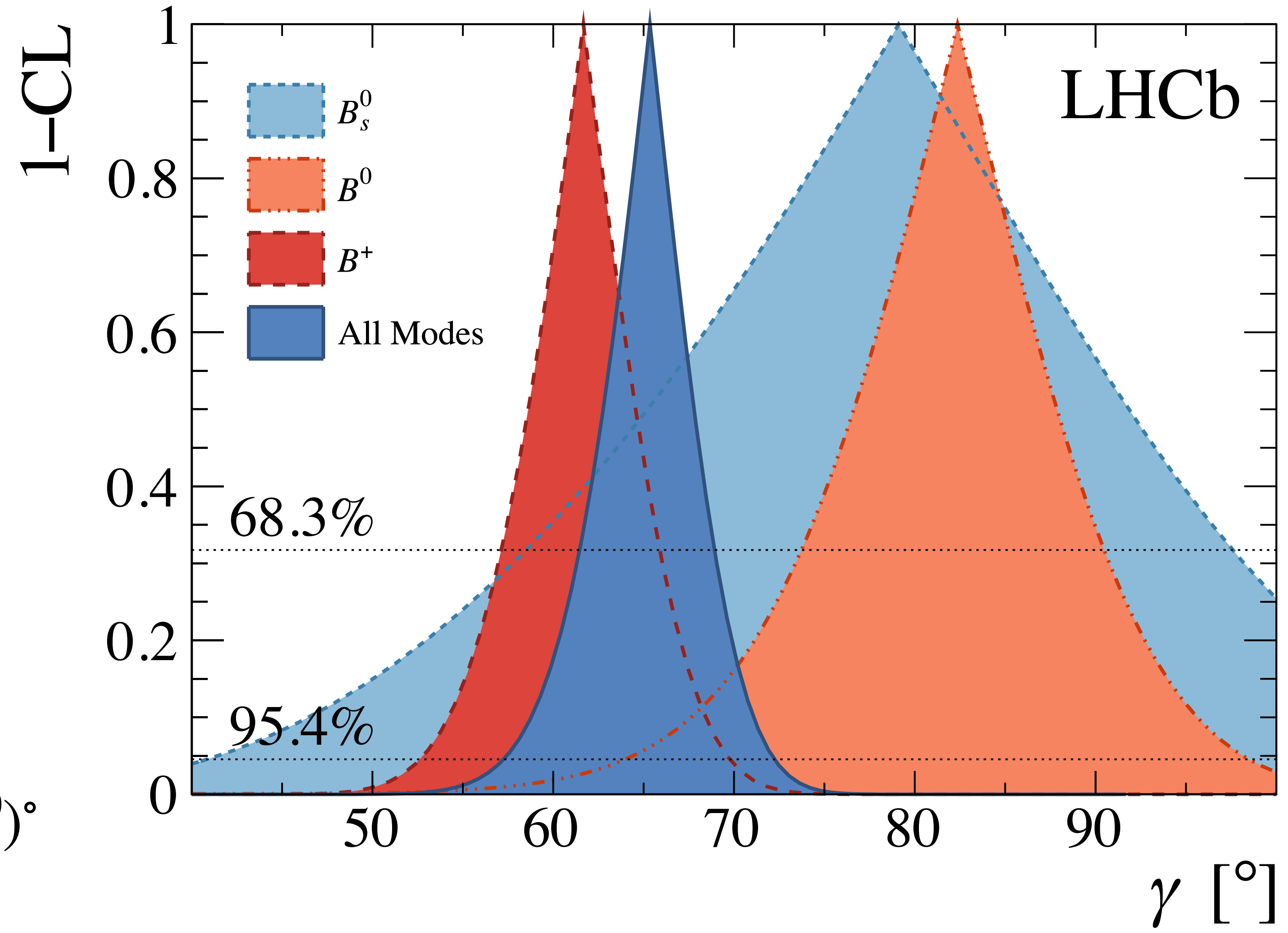
$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$

- Around two sigma tension between B^+ and B^0 results
  - Looking forward to full Run 1+2 results from the B^0 sector

- Excellent agreement with indirect results

$$\gamma = (65.8 \pm 2.2)^\circ \ , \quad \gamma = (65.55^{+0.90}_{-2.65})^\circ$$

UT Fit   CKM fitter



Results - charm

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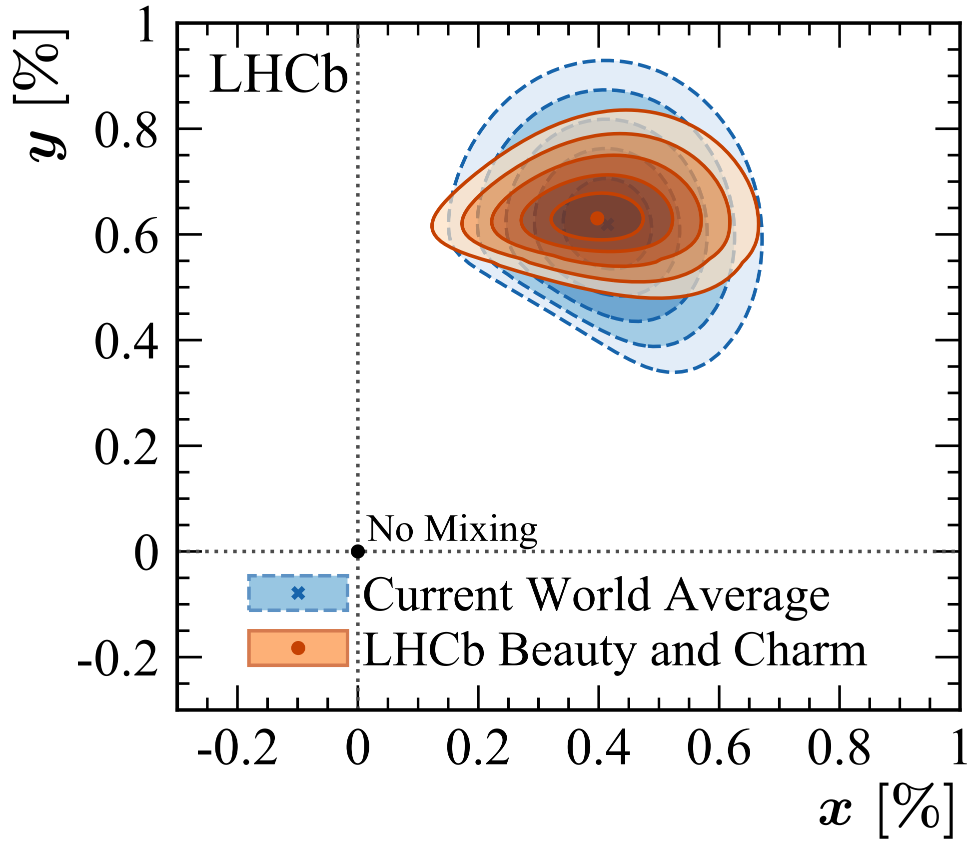
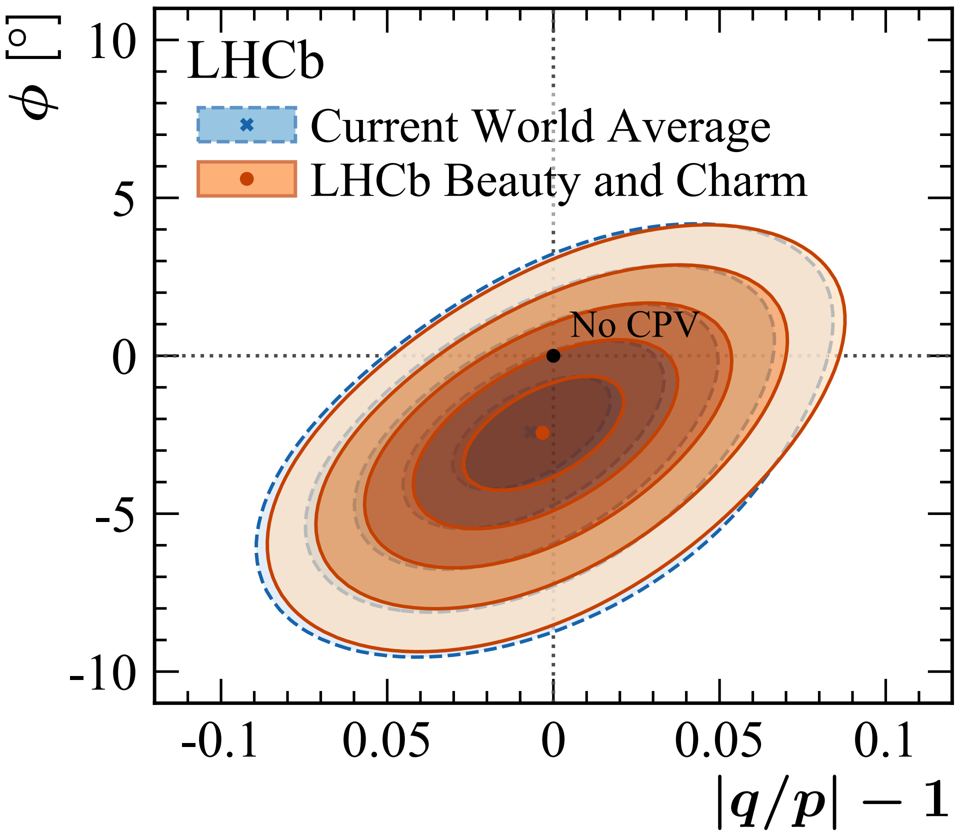
$x \equiv (m_1 - m_2)/\Gamma$ and $y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$

$\phi \equiv \arg(q/p)$





$$x = (0.400\,^{+0.052}_{-0.053})\%$$

$$y = (0.630\,^{+0.033}_{-0.030})\%$$

Factor of 2 more precise in y!

$$|q/p| = 0.997 \pm 0.016$$

$$\phi = (-2.4 \pm 1.2)^\circ$$

Hint of CPV in charm mixing?

Results - breakdowns

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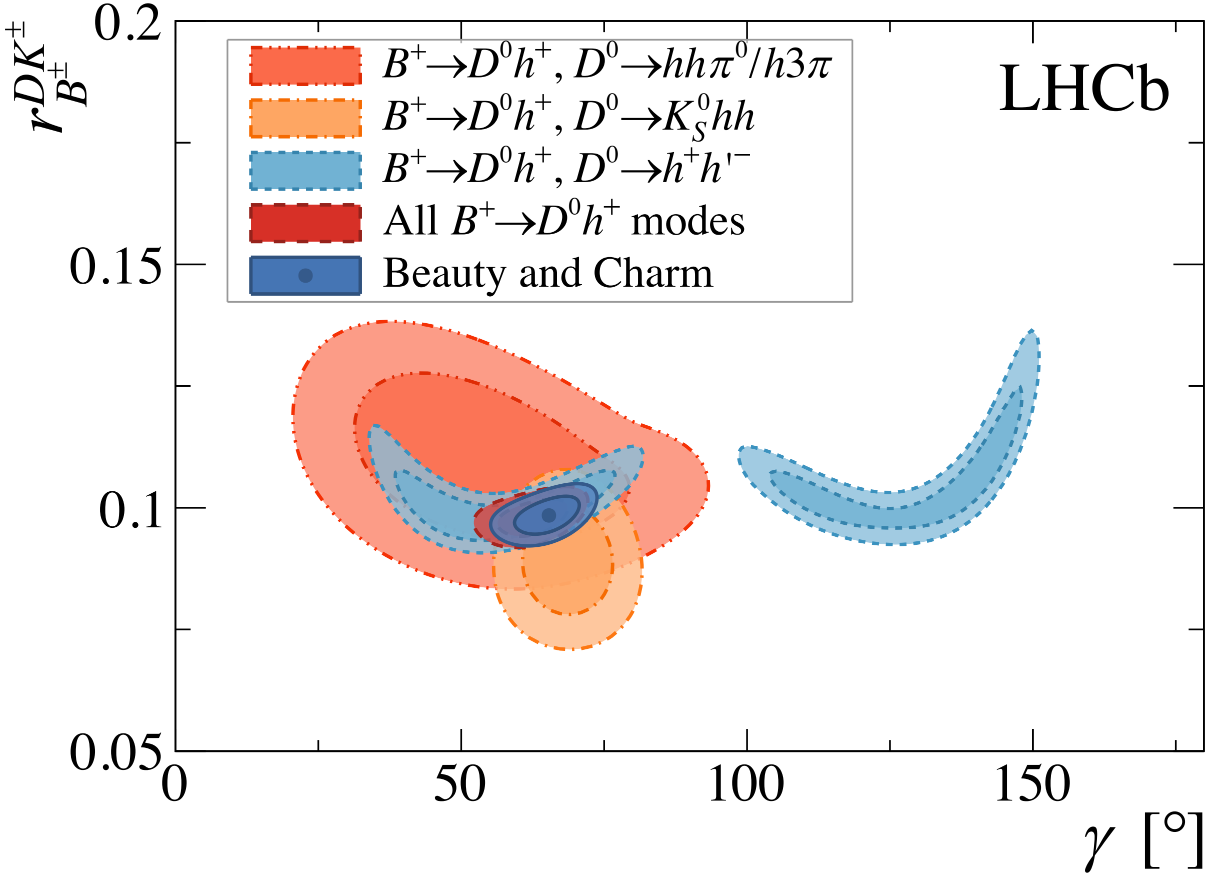
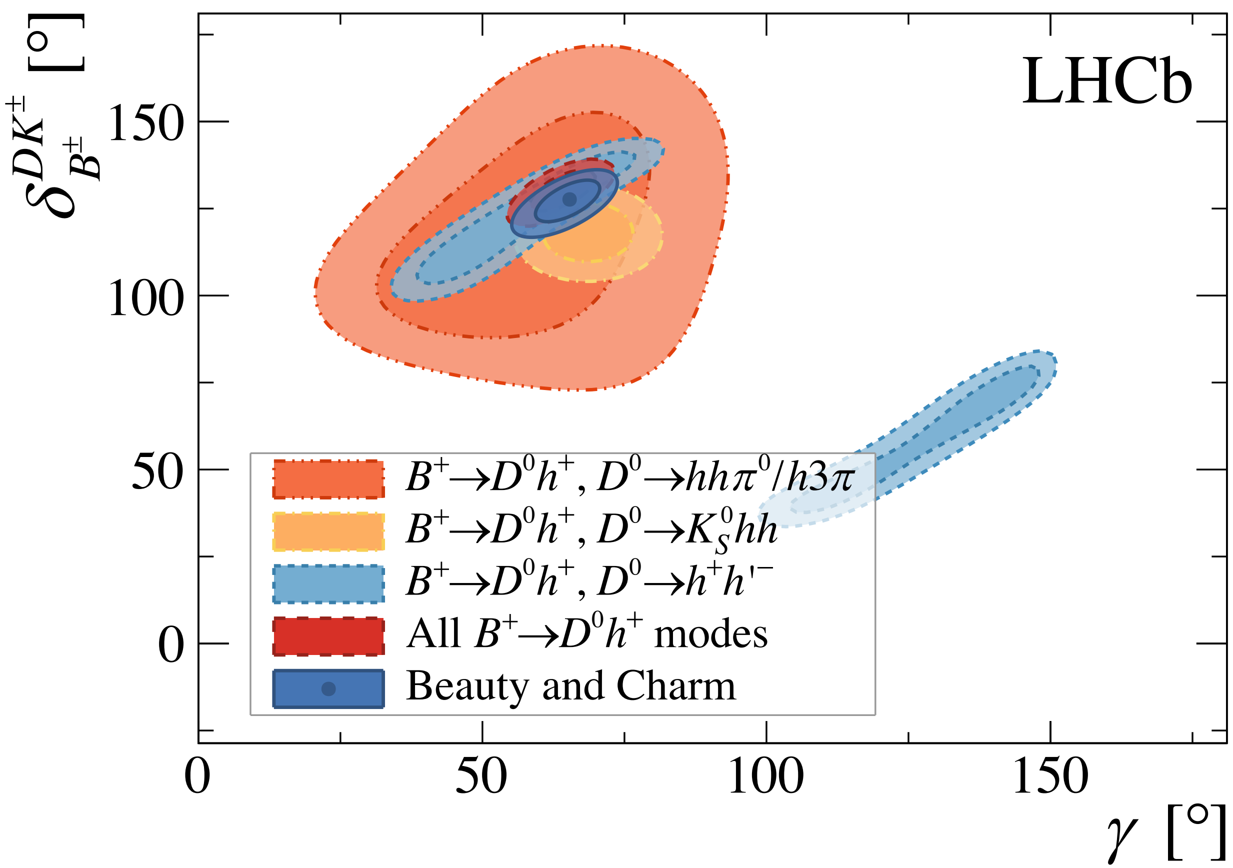


Ratio of magnitudes between the B decay amplitudes



Strong phase difference between the B decay amplitudes

Results - breakdowns

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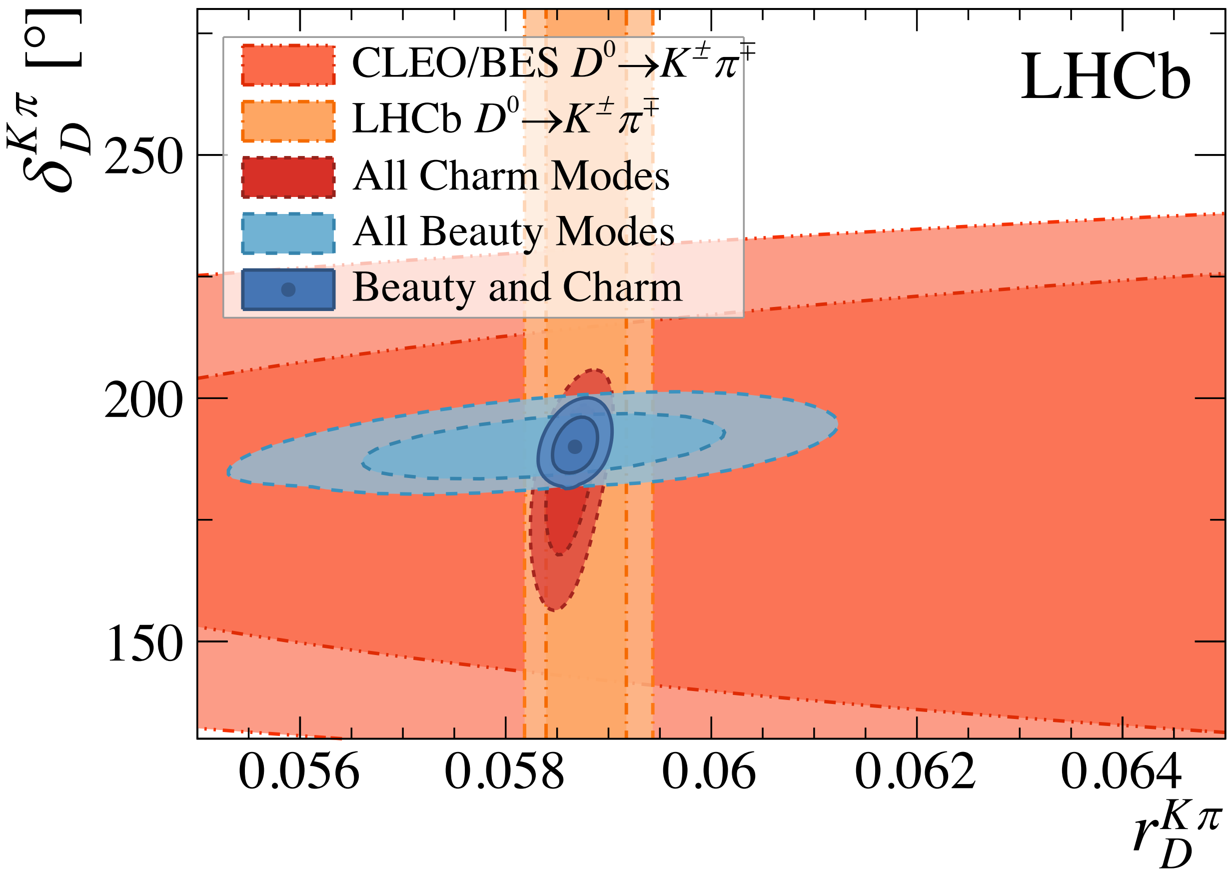
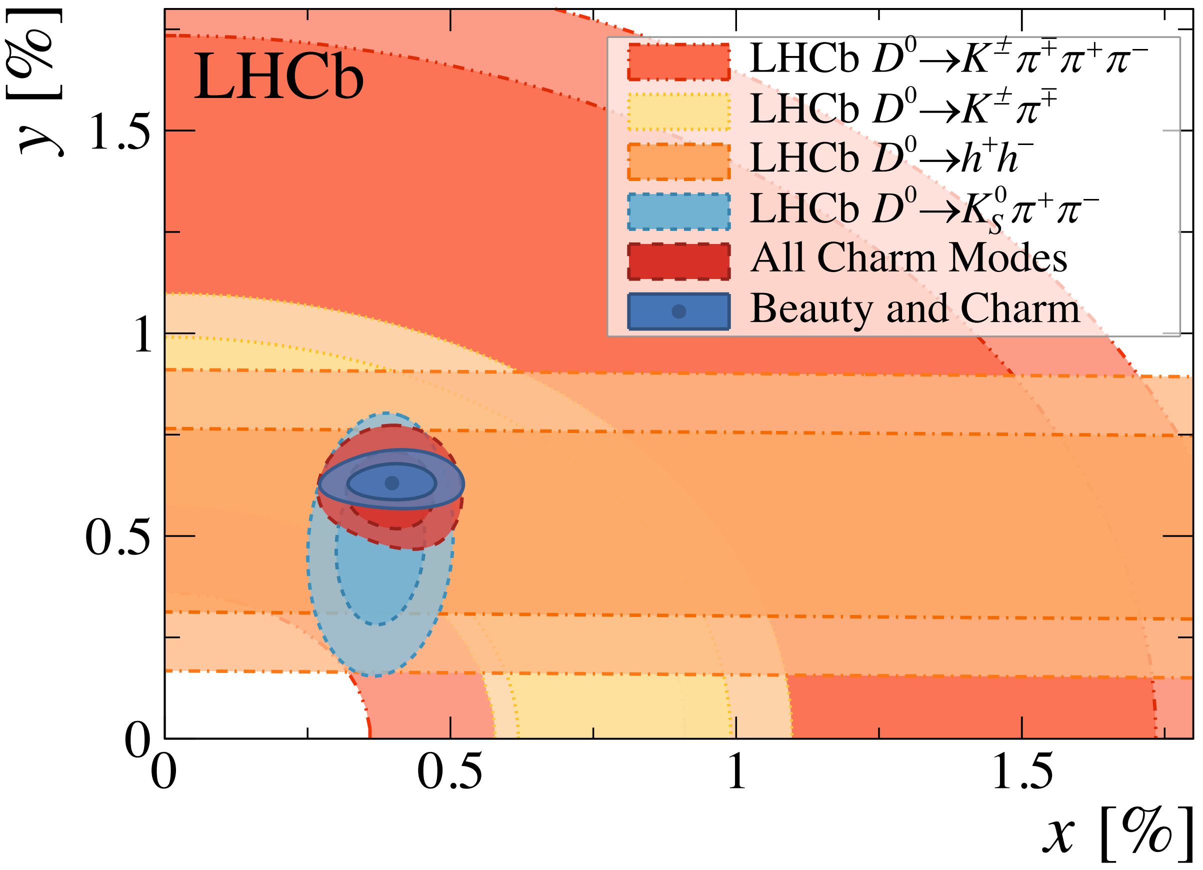


Ratio of magnitudes and strong phase difference between the D decay amplitudes



Charm mixing parameters

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Recently published in JHEP!

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  - LHCb-PAPER-2021-041

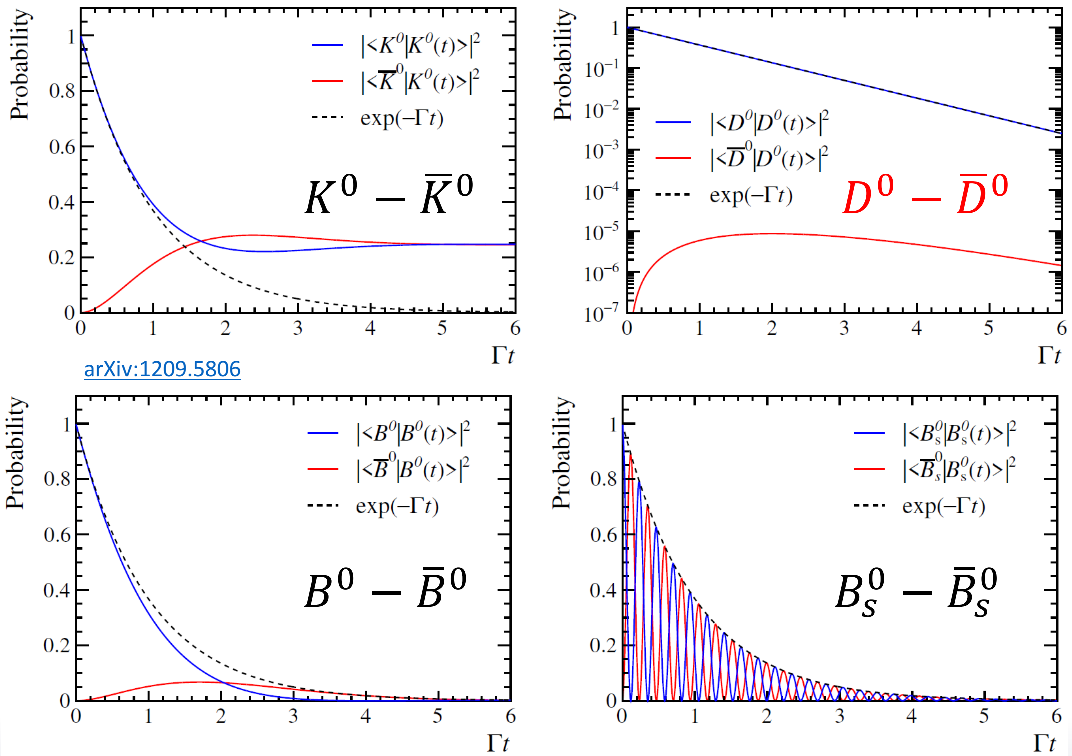
Shown for the first time today!

Neutral meson mixing: very different systems!

- Recap: D^0 mixing due to mass eigenstates $\neq$ flavour eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$.
- Mixing (oscillations) defined by two parameters: $x = \frac{m_1 - m_2}{\Gamma}$ and $y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$, where $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$ (D^0 decay width).

$$Prob(D^0 \to \bar{D}^0, t) = \left|\frac{q}{p}\right|^2 \frac{e^{-\Gamma t}}{2}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

Log scale in the charm sector!



Experimental knowledge of x and y [HFLAV and PDG]

System	x	y
$K^0 - \bar{K}^0$	-0.946 ± 0.004	0.99650 ± 0.00001
$D^0 - \bar{D}^0$	$(4.09^{+0.48}_{-0.49})\times 10^{-3}$	$(6.15^{+0.56}_{-0.55})\times 10^{-3}$
$B^0 - \bar{B}^0$	-0.769 ± 0.004	$(0.1 \pm 0.1)\times 10^{-2}$
$B_s^0 - \bar{B}_s^0$	26.89 ± 0.07	$(12.9 \pm 0.6)\times 10^{-2}$

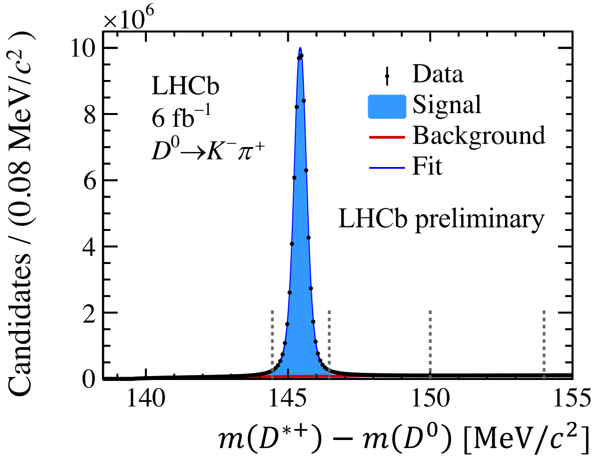
$D^0 - \bar{D}^0$ system

$B_s^0 - \bar{B}_s^0$ system

Charm mixing and experimental lifetimes

- D^0 mixing can be studied through golden decay modes $D^0 \to K^-\pi^+$ and $D^0 \to f$ ($f = K^-K^+$ and $\pi^-\pi^+$):
  - $D^0 \to K^-\pi^+$: *CP-mixed* state with $\tau(D^0 \to K^-\pi^+) \approx 1/\Gamma$
  - $D^0 \to f$: *CP-even* state with $\tau(D^0 \to f) < \tau(D^0 \to K^-\pi^+)$
- LHCb: a few billion D^0 collected in LHC Run 1 and Run 2 (9fb^{-1}).

→ Big data samples of $D^0 \to K^-\pi^+$ and $D^0 \to f$ decays!



The $y_{CP}^{f} - y_{CP}^{K\pi}$ observable (known as "y_{CP}" in the literature)

- Goal: Study lifetime ratio $D^0 \to K^-\pi^+ / D^0 \to f$ via the quantity $y_{CP}^{f} - y_{CP}^{K\pi}$:

$$\frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to f)} - 1 = y_{CP}^{f} - y_{CP}^{K\pi}$$

$f = K^-K^+$ and $\pi^-\pi^+$

The $y_{CP}^{f} - y_{CP}^{K\pi}$ observable (known as "y_{CP}" in the literature)

- Goal: Study lifetime ratio $D^0 \to K^-\pi^+ / D^0 \to f$ via the quantity $y_{CP}^{f} - y_{CP}^{K\pi}$:

$$\frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to f)} - 1 = y_{CP}^{f} - y_{CP}^{K\pi} \approx y\left(1 + \sqrt{R_D}\right)$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \approx 0.6\%$$

$$R_D = \frac{\mathcal{B}(D^0 \to K^+\pi^-)}{\mathcal{B}(D^0 \to K^-\pi^+)}, \quad \sqrt{R_D} \approx 6\%$$

- Hence, measuring precisely $y_{CP}^{f} - y_{CP}^{K\pi}$ allows to constrain y!
- y is small and hard to predict. Experimental determination of y is important to improve charm sector predictions.

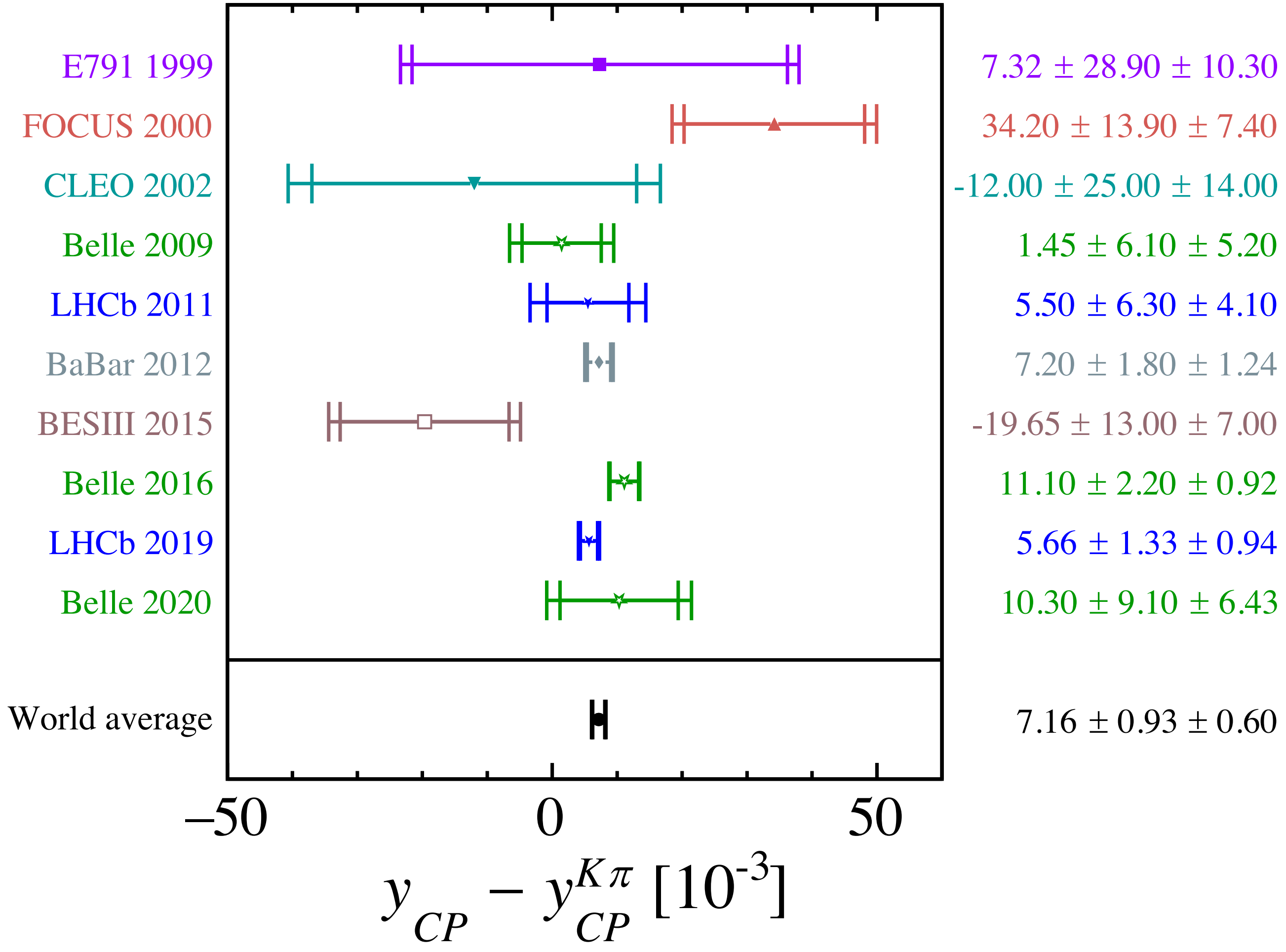
* Note: $y_{CP} - y_{CP}^{K\pi}$ was previously called y_{CP}. The term $-y_{CP}^{K\pi} \approx +0.4\times10^{-3}$ was included because of $D^0 \to K^-\pi^+ / D^0 \to K^+\pi^-$ mixing [arXiv:2106.02014].

$f = K^-K^+$ and $\pi^-\pi^+$

Measurement of $y_{CP} - y_{CP}^{K\pi}$ (known as "y_{CP}" in the literature)

- $y_{CP} - y_{CP}^{K\pi}$: average of $y_{CP}^{KK} - y_{CP}^{K\pi}$ and $y_{CP}^{\pi\pi} - y_{CP}^{K\pi}$.
- Analysis: Measure $y_{CP} - y_{CP}^{K\pi}$ with LHCb Run 2 data set (2015-2018, 6 fb^{-1}).
- Use two-body D^0 meson decays produced at the pp interaction point.
- Statistical uncertainty of $\sim 0.25\times 10^{-3}$ can be achieved (4× world average!)

Current status of $y_{CP} - y_{CP}^{K\pi}$



Measuring $y_{CP}^{KK} - y_{CP}^{K\pi}$ at LHCb

- The decay time ratio $R^{KK}(t)$ is defined as:

$$R^{KK}(t) = \frac{dN(D^0 \to K^-K^+, t)}{dN(D^0 \to K^-\pi^+, t)} \propto e^{-(y_{CP}^{KK} - y_{CP}^{K\pi})t/\tau_{D^0}} \frac{\varepsilon(K^-K^+, t)}{\varepsilon(K^-\pi^+, t)}$$

$\tau_{D^0} = (410.1 \pm 1.5)$fs [PDG]

- Hence, $y_{CP}^{KK} - y_{CP}^{K\pi}$ is obtained with an exponential fit to $R^{KK}(t)$ once the time-dependent nuisance efficiencies $\varepsilon(h^-h'^+, t)$ have been treated.
- Treatment of $\varepsilon(h^-h'^+, t)$: data-driven approach. Must control $\varepsilon(h^-h'^+, t)$ at $\sim 0.1 \times 10^{-3}$ level!

* Same logic for $y_{CP}^{\pi\pi} - y_{CP}^{K\pi}$, where K^-K^+ is replaced by $\pi^-\pi^+$.

Correction strategy: the biggest challenge

$R^{KK}(t) \propto e^{-(y_{CP}^{KK}-y_{CP}^{K\pi})t/\tau_{D^0}} \frac{\varepsilon(K^-K^+,t)}{\varepsilon(K^-\pi^+,t)}$

- Split time-dependent final state efficiencies into two components:

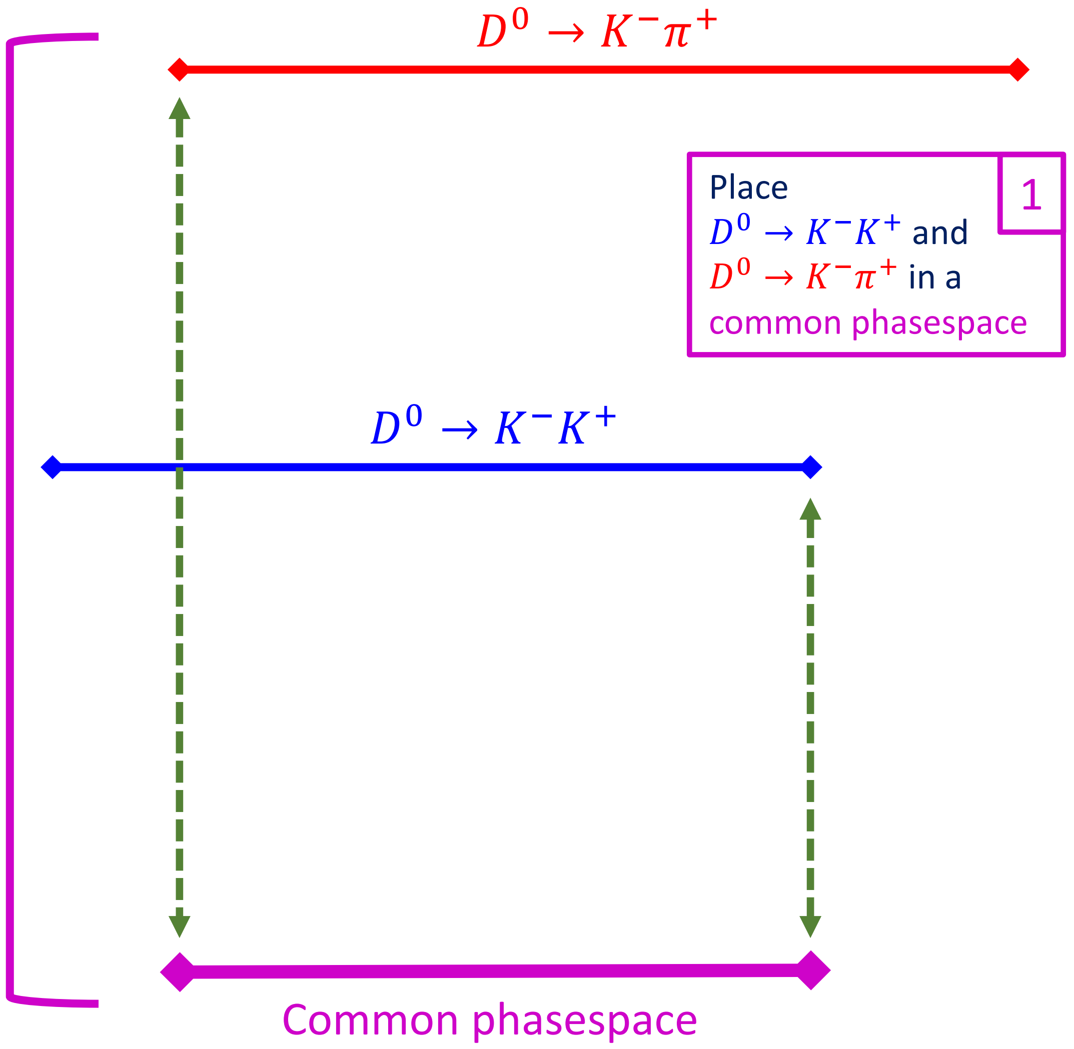
$$\varepsilon(h^-h'^+,t) \sim \varepsilon^{selection}(h^-h'^+,t)\varepsilon^{detection}(h^-h'^+,t)$$

- $\varepsilon^{selection}(h^-h'^+,t)$: time-dependent effects of kinematic requirements from data selection.

  - ➢ Strategy: equalise $\varepsilon^{selection}$.
    Addressed with the kinematic matching procedure
    by placing both decays in a common phasespace.

- $\varepsilon^{detection}(h^-h'^+,t)$: time-dependent effects linked to the interaction of kaons and pions with LHCb detector.

  - ➢ $\varepsilon^{detection}$ addressed with the kinematic weighting procedure.



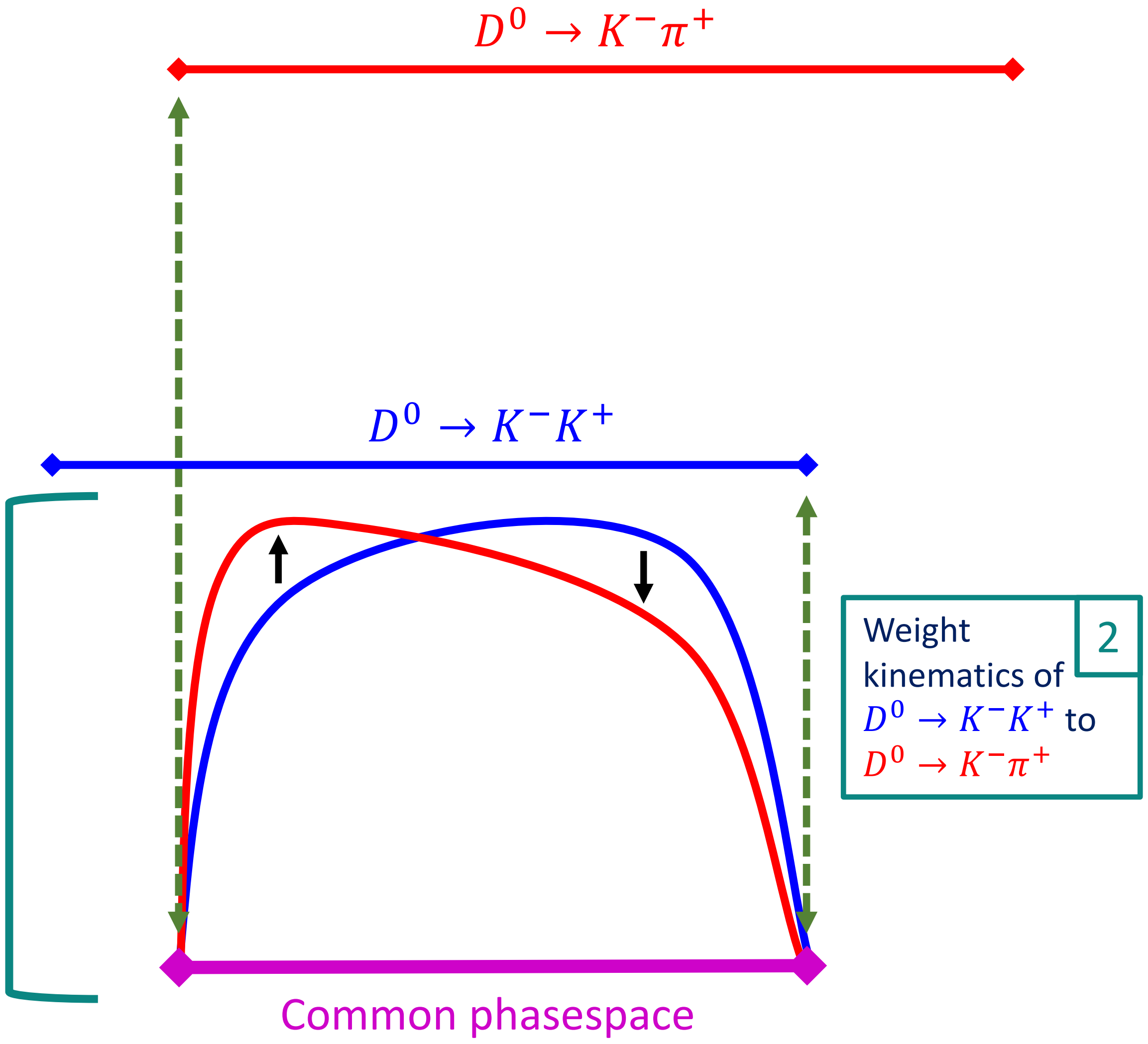
Correction strategy: the biggest challenge

$R^{KK}(t) \propto e^{-(y_{CP}^{KK}-y_{CP}^{K\pi})t/\tau_{D^0}} \frac{\varepsilon(K^-K^+,t)}{\varepsilon(K^-\pi^+,t)}$

- Split time-dependent final state efficiencies into two components:

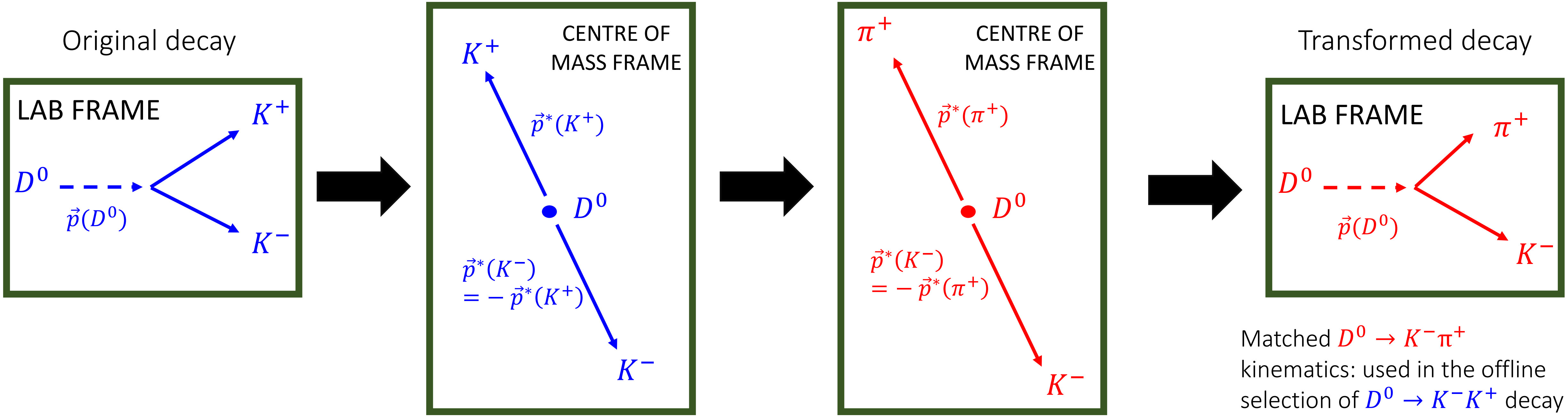
$$\varepsilon(h^-h'^+,t) \sim \varepsilon^{selection}(h^-h'^+,t)\varepsilon^{detection}(h^-h'^+,t)$$

- $\varepsilon^{selection}(h^-h'^+,t)$: time-dependent effects of kinematic requirements from data selection.
  - Strategy: equalise $\varepsilon^{selection}$.
    Addressed with the kinematic matching procedure by placing both decays in a common phasespace.
- $\varepsilon^{detection}(h^-h'^+,t)$: time-dependent effects linked to the interaction of kaons and pions with LHCb detector.
  - $\varepsilon^{detection}$ addressed with the kinematic weighting procedure.



Kinematic matching: Matching the kinematics of $D^0 \to K^-K^+$ to the ones of $D^0 \to K^-\pi^+$

We change $m(K^+)$ to $m(\pi^+)$ and scale both centre-of-mass momenta $|\vec{p}^*|$ accordingly.



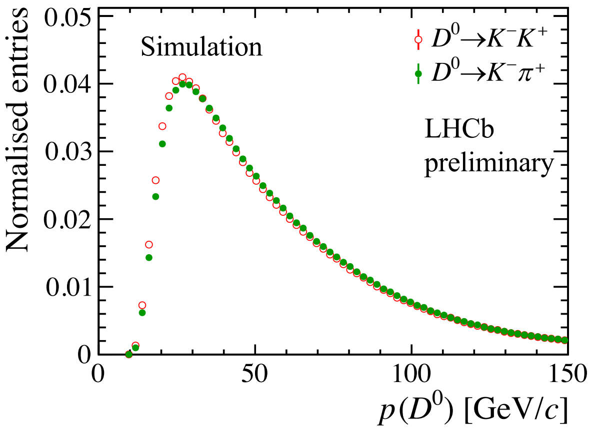
Matched $D^0 \to K^-\pi^+$ kinematics: used in the offline selection of $D^0 \to K^-K^+$ decay

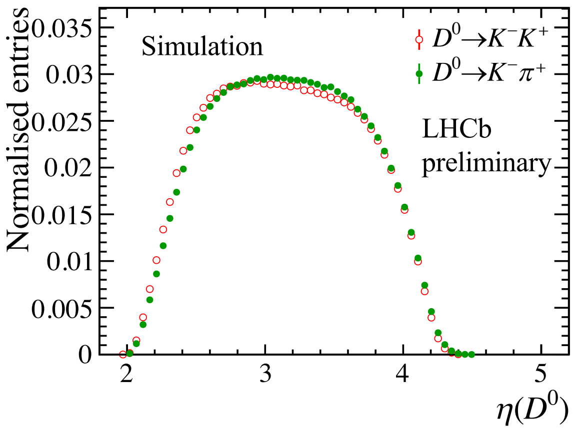
$$|\vec{p}^*| = \frac{\sqrt{(m_{D^0}^2 - (m_{p_1} + m_{p_2})^2)(m_{D^0}^2 - (m_{p_1} - m_{p_2})^2)}}{2m_{D^0}}$$

Kinematic matching: validation with fast simulation

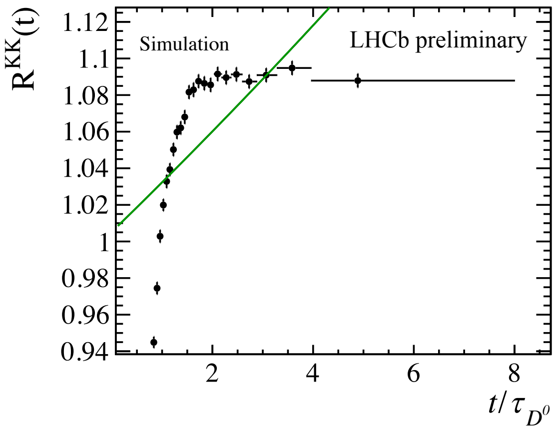
Generate few million fast simulation ([RapidSim]) candidates of $D^{*+} \to (D^0 \to K^-K^+)\pi^+_{tag}$ and $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+_{tag}$ with the same D^0 lifetime. Apply strong lifetime biasing requirements and verify that the matching procedure corrects for them.

Before kinematic matching

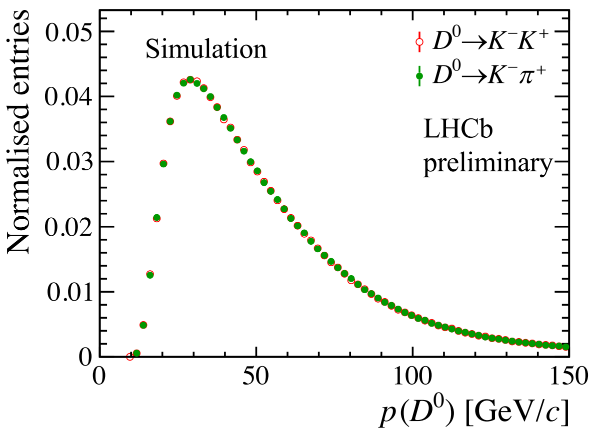


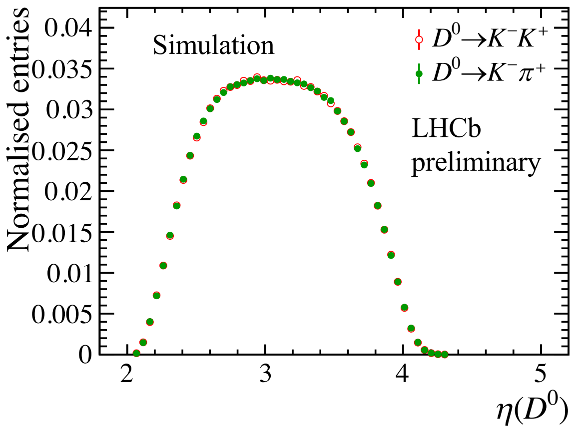


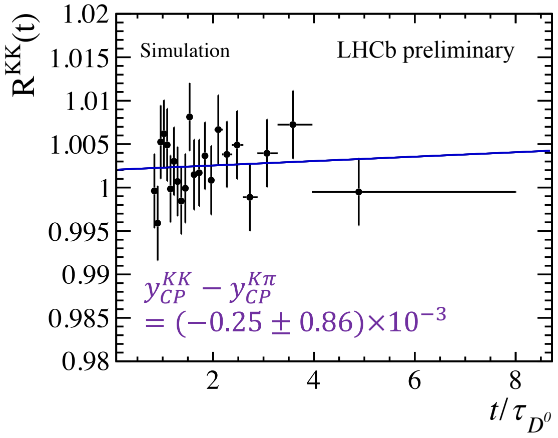
Decay time ratio



After kinematic matching



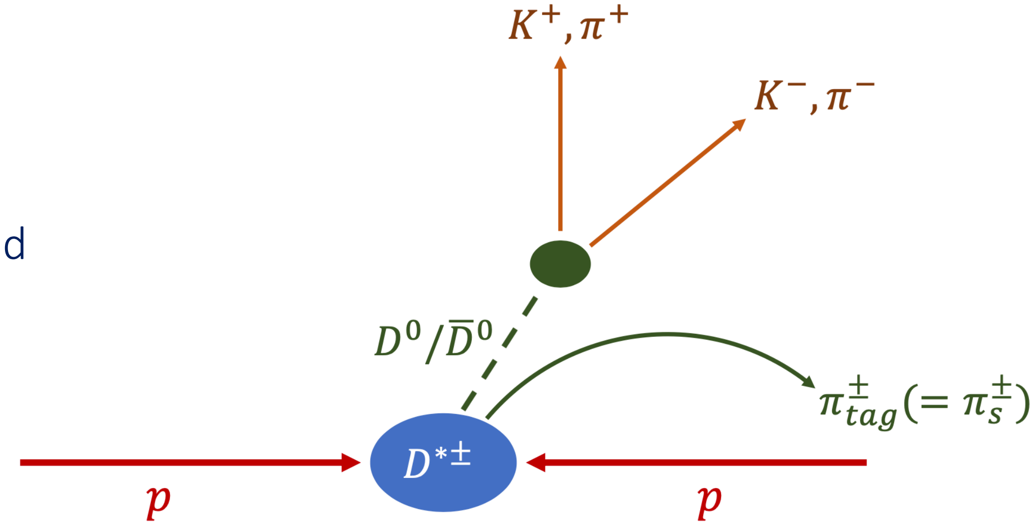


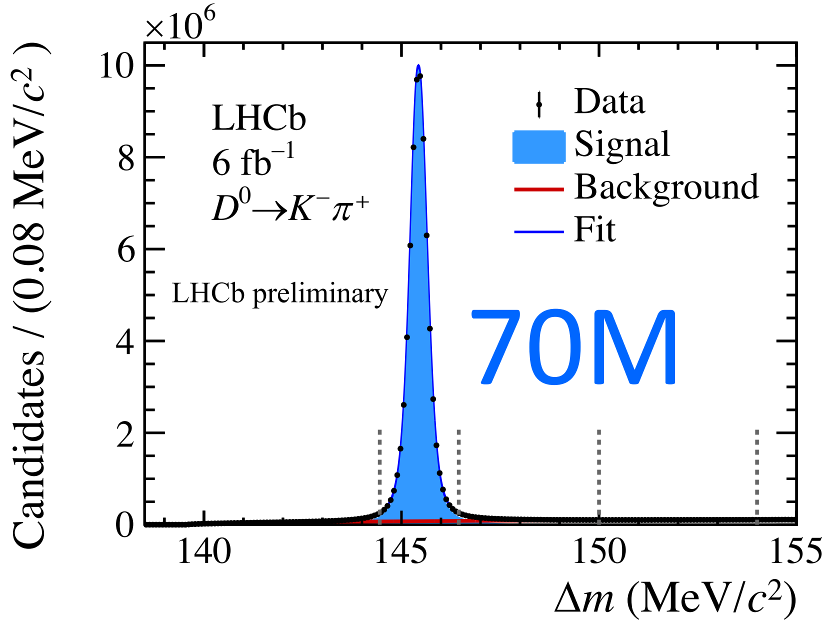


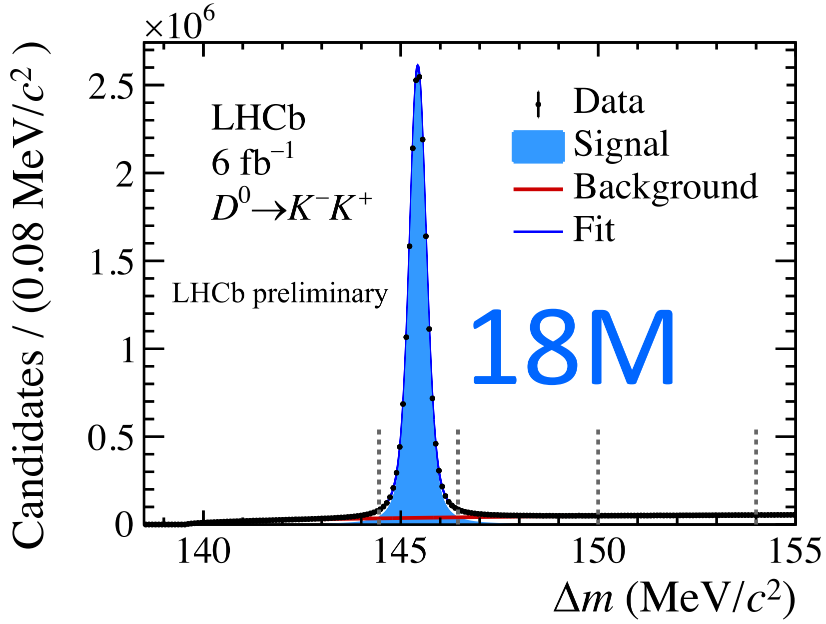
$y_{CP}^{KK} - y_{CP}^{K\pi}$ is compatible with zero. This is validated down to $\sim 0.2\times 10^{-3}$.

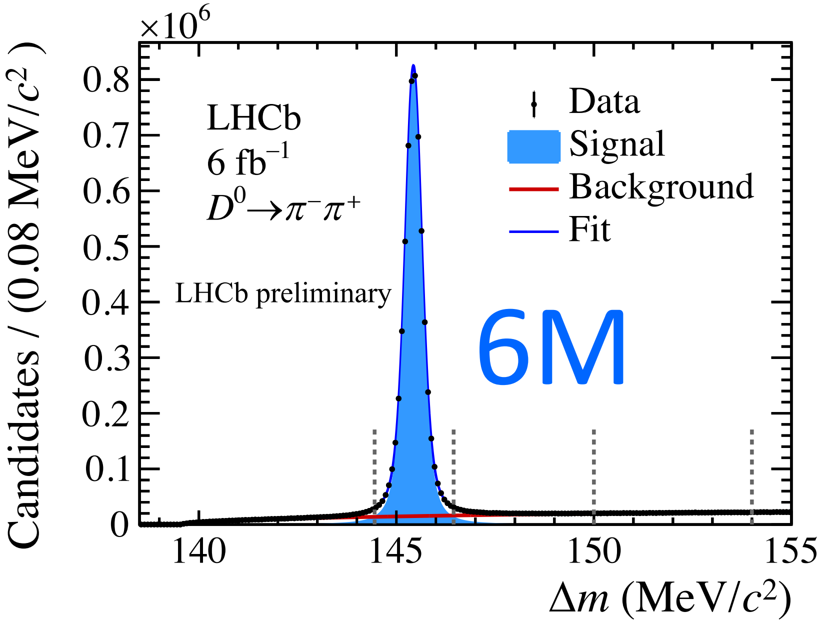
Signal selection: High yields, high purity, unbiased

- Use full Run 2 data (2015-2018). $D^0 \to h^- h'^+$ candidates obtained from $D^{*+} \to D^0 \pi^+_{tag}$ produced at pp interaction point (prompt D^{*+}).
- Trigger strategy: use trigger lines [LHCb-PUB-2015-026] specifically developed to minimise biases to the D^0 decay time distribution.
- Combinatorial background: Fit $\Delta m = m(h^- h^+ \pi^+_{tag}) - m(h^- h^+)$ and assign negative weights to pure background candidates (sideband subtraction).









Validation of the analysis procedure

- $D^0 \to \pi^-\pi^+$ and $D^0 \to K^-K^+$ are both CP-even, so we expect identical lifetimes ($y_{CP}^{CC} = 0$):

$$R^{CC}(t) = \frac{dN(D^0 \to \pi^-\pi^+, t)}{dN(D^0 \to K^-K^+, t)} \propto e^{-\, y_{CP}^{CC}\, t/\tau_{D^0}} \frac{\varepsilon(\pi^-\pi^+, t)}{\varepsilon(K^-K^+, t)}$$

- Good test since both final state particles are different, increasing differences linked to selection and detection efficiencies ($2\times$ stronger!).

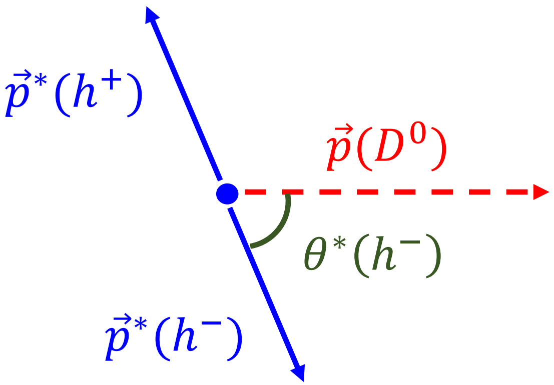
- Other important cross-checks:

  1. Measurement of $y_{CP} - y_{CP}^{K\pi}$ with fast simulation, where substantial biasing effects are introduced (shown previously in slide 35).

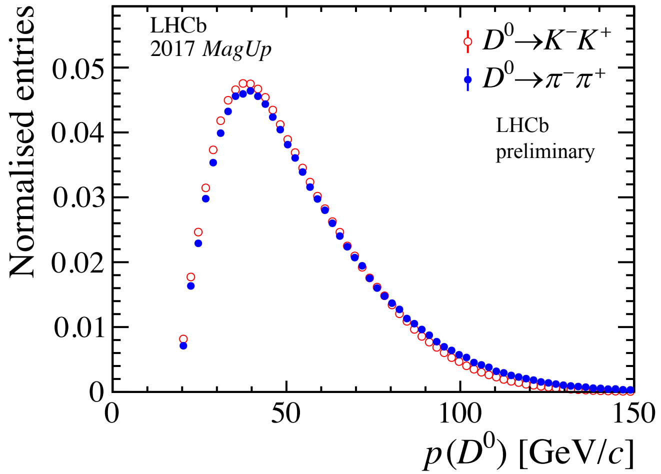
  2. Measurement of $y_{CP} - y_{CP}^{K\pi}$ with high-statistics LHCb simulation samples (validated down to 0.2×10^{-3}).

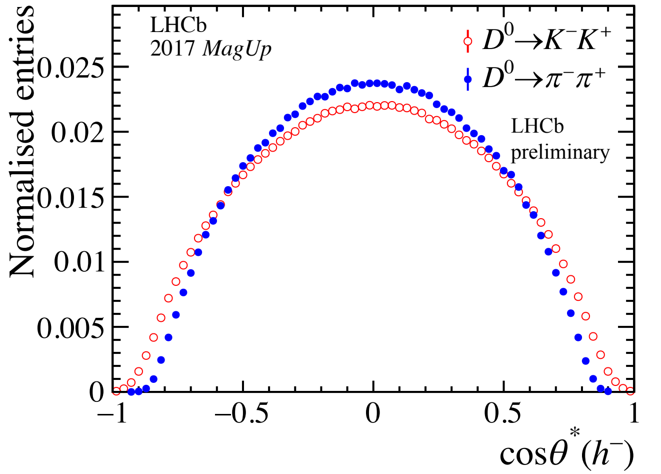
y_{CP}^{CC}: Consistency checks of $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$

- $\theta^*(h^-)$:
  - Angle between $\vec{p}(D^0)$ (lab frame) and $\vec{p}^*(h^-)$ (centre-of-mass frame).
  - Very sensitive to data selection.

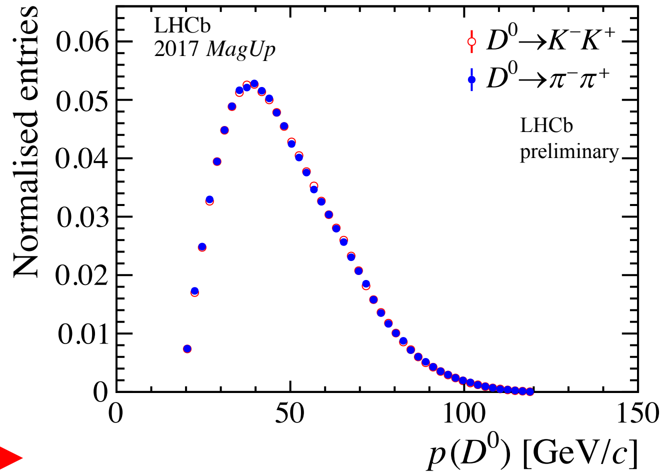


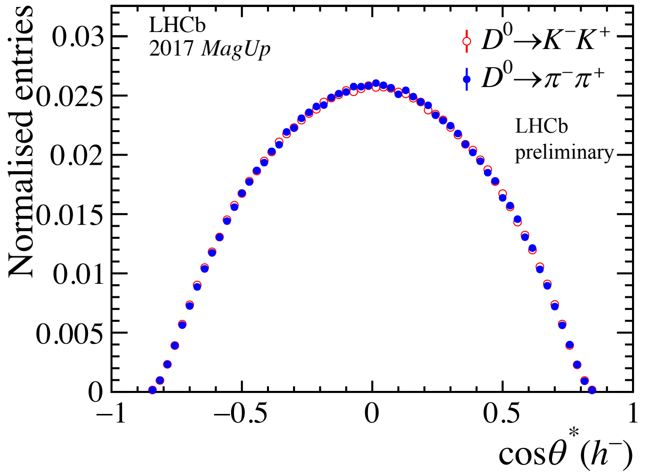
Raw: no correction





Matching + Weighting

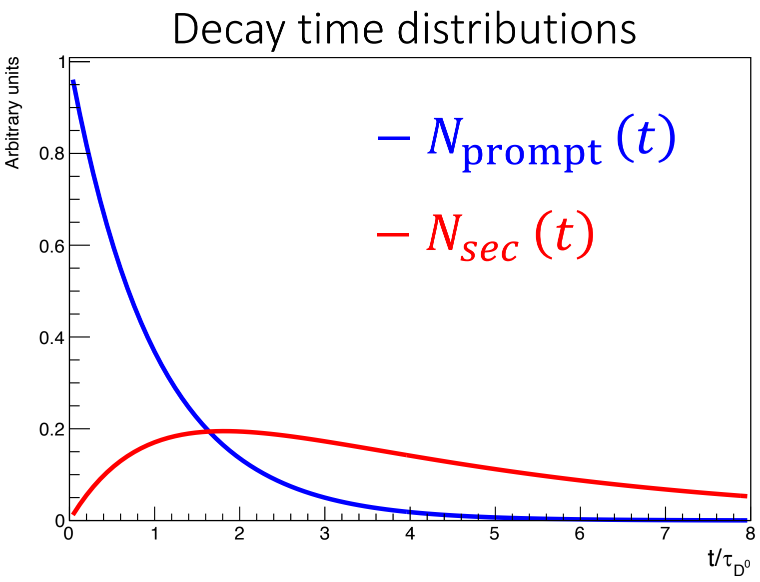


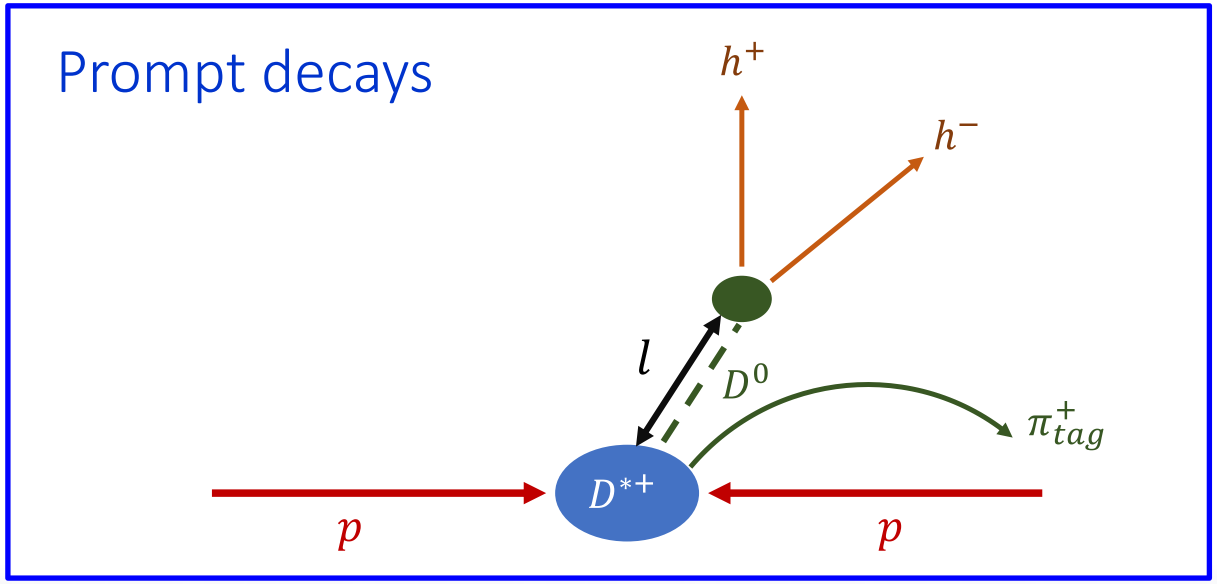


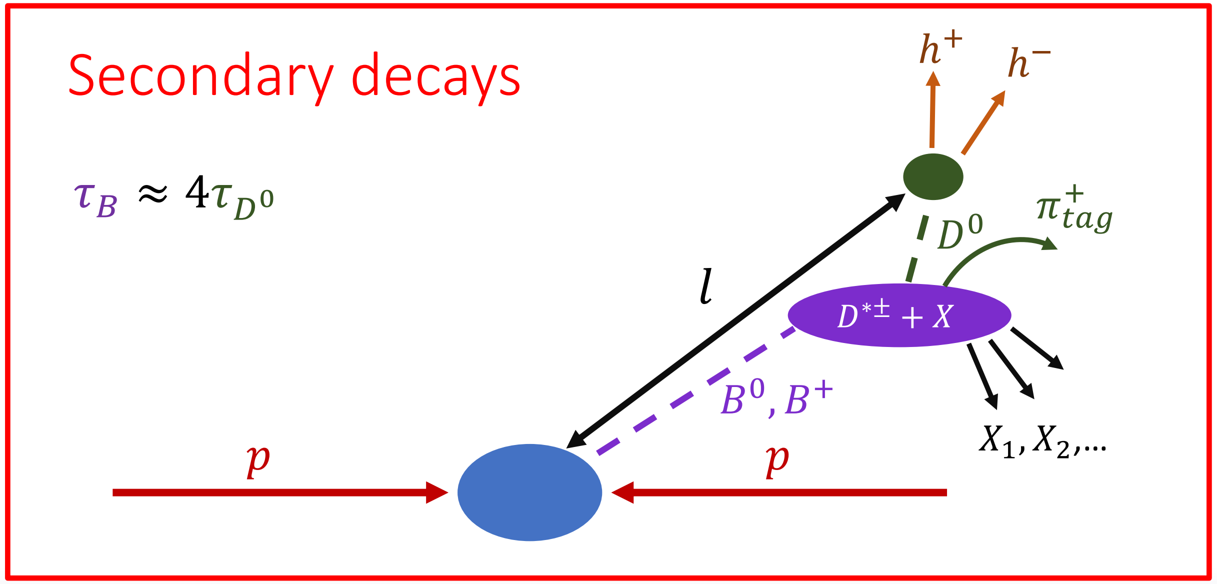
*Many other kinematic distributions are checked!

Challenging background: secondary D^{*+} decays

- Data samples are contaminated by secondary D^{*+} decays coming from B meson decays.
- Secondary decays: D^0 decay time t is biased since it's obtained using decay length l measured w.r.t pp interaction point (hence includes B decay flight).
- The fit model of $y_{CP}^{f} - y_{CP}^{K\pi}$ is carefully adjusted to include the contamination of secondary decays.



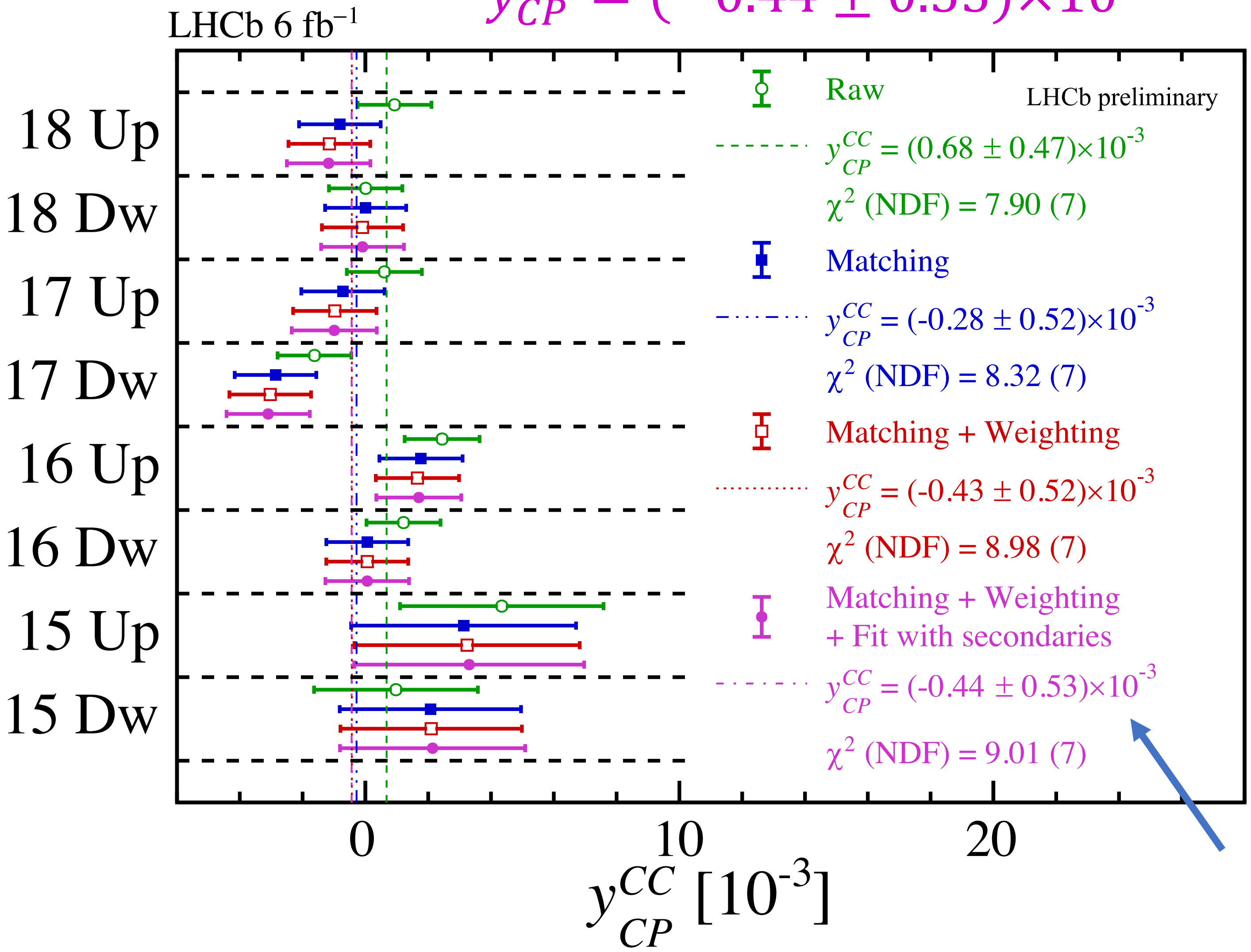




Results of y_{CP}^{CC}: Compatible with zero

Years and Magnet polarities

$y_{CP}^{CC} = (-0.44 \pm 0.53)\times 10^{-3}$

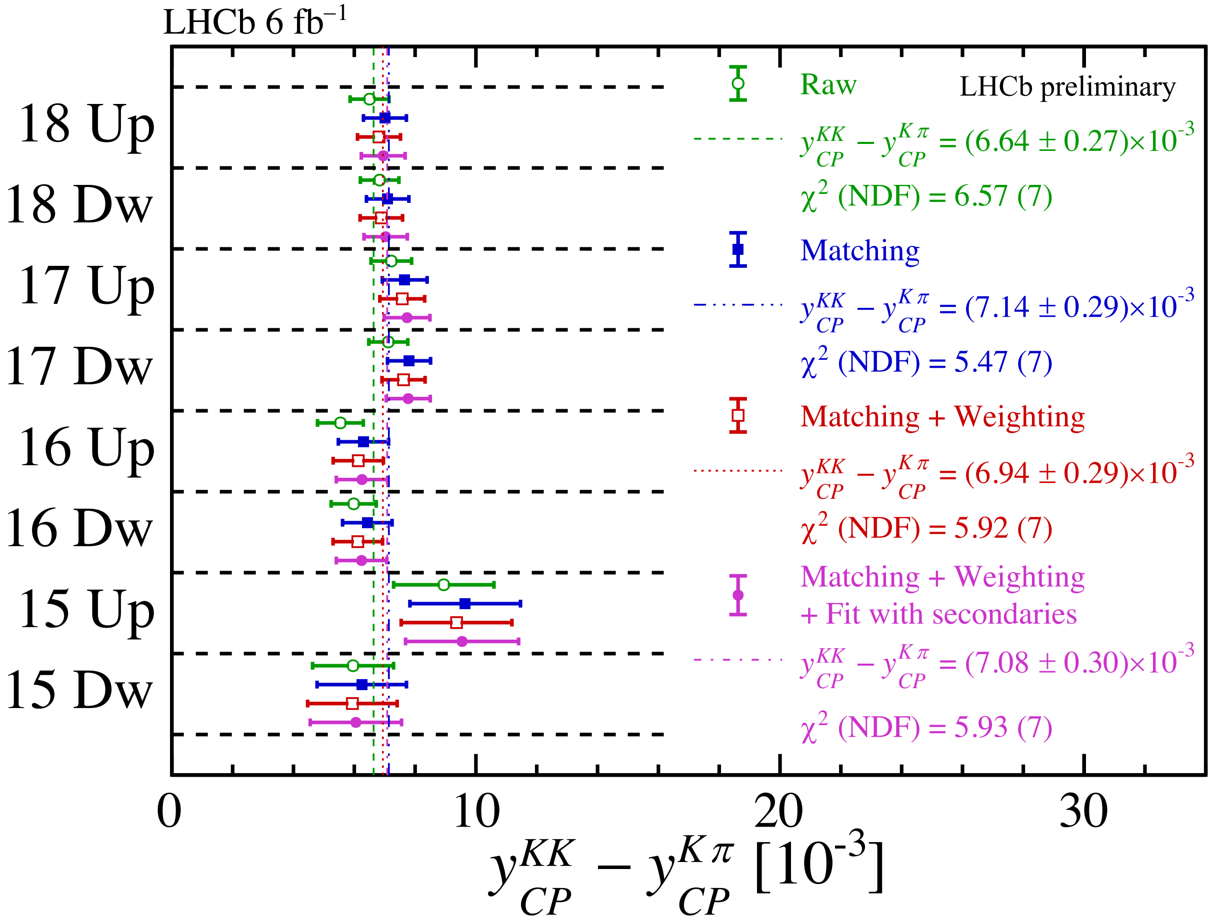


Averages over all data samples

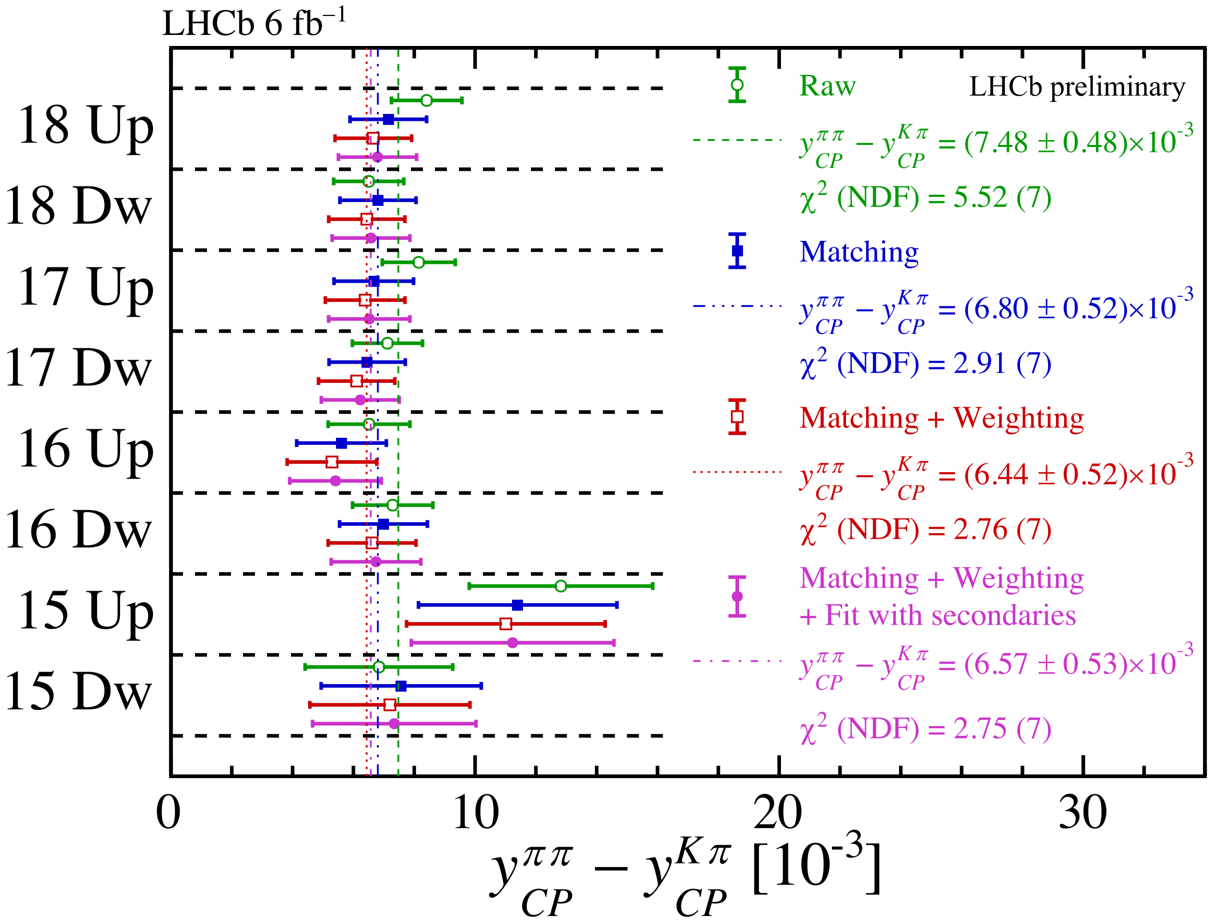
Results of $y_{CP}^{KK} - y_{CP}^{K\pi}$ and $y_{CP}^{\pi\pi} - y_{CP}^{K\pi}$

- Compatibility below 1σ between independent $y_{CP}^{KK} - y_{CP}^{K\pi}$ and $y_{CP}^{\pi\pi} - y_{CP}^{K\pi}$ measurements!

$$y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30)\times 10^{-3}$$



$$y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53)\times 10^{-3}$$



Systematic and statistical uncertainties

	$\sigma(y_{CP}^{KK} - y_{CP}^{K\pi})[10^{-3}]$	$\sigma(y_{CP}^{\pi\pi} - y_{CP}^{K\pi})[10^{-3}]$
Subtraction of combinatorial background	0.07	0.12
Treatment of secondary decays	0.03	0.03
Kinematic weighting procedure	0.02	0.08
Input D^0 decay time	0.03	0.03
Residual nuisance asymmetries	< 0.01	0.03
Partially or misreconstructed $D^{*+} \to D^0\pi^+$ candidates	0.11	0.02
Fit bias	0.03	0.03
TOTAL systematic uncertainty	0.14	0.16
Statististical uncertainty	0.30	0.53

Final value of $y_{CP} - y_{CP}^{K\pi}$

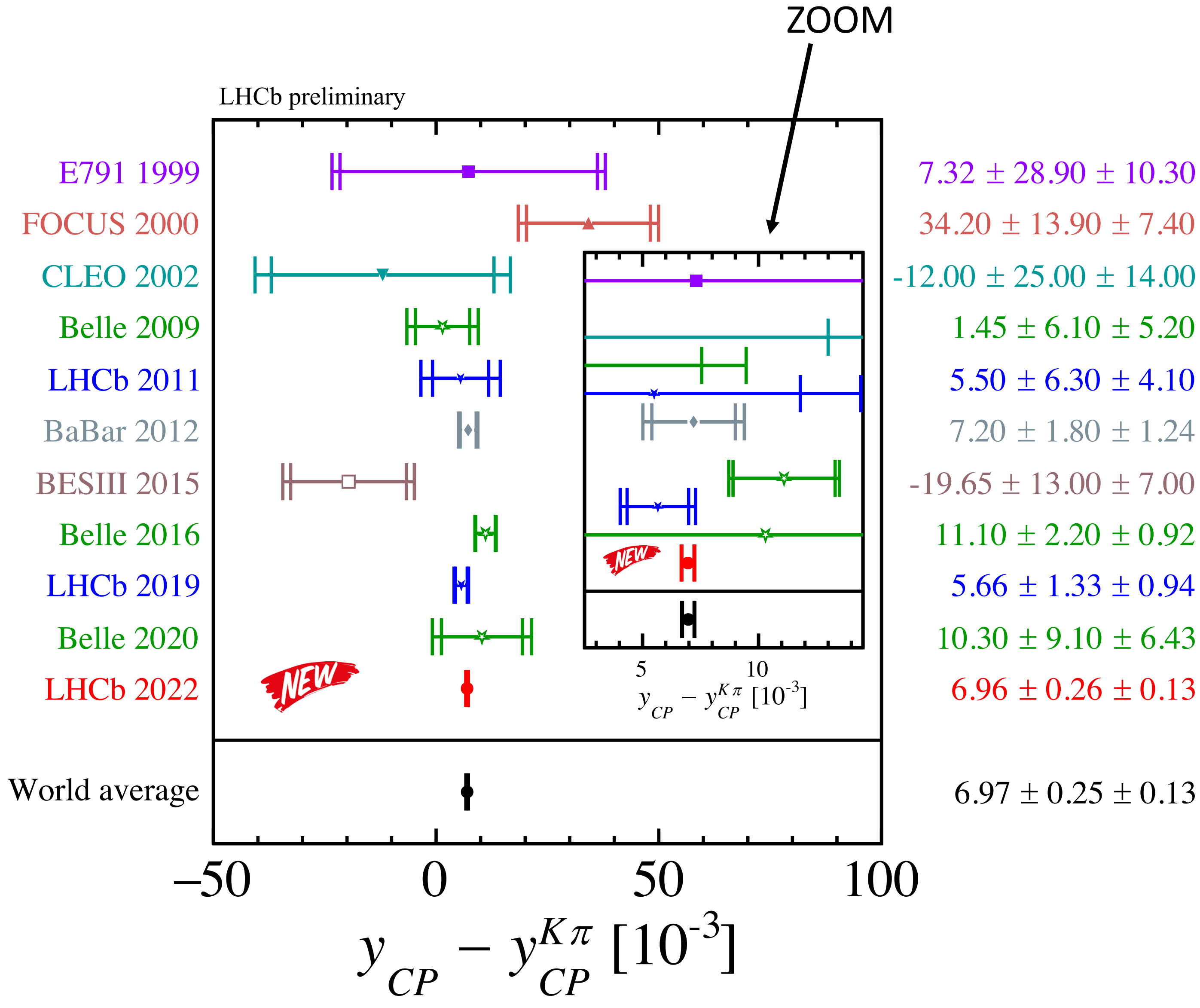
- Current world average value:

$$y_{CP} - y_{CP}^{K\pi} = (7.16 \pm 0.93_{stat} \pm 0.60_{syst})\times 10^{-3}$$

- $y_{CP}^{KK} - y_{CP}^{K\pi}$ and $y_{CP}^{\pi\pi} - y_{CP}^{K\pi}$ are combined (LHCb 2022):

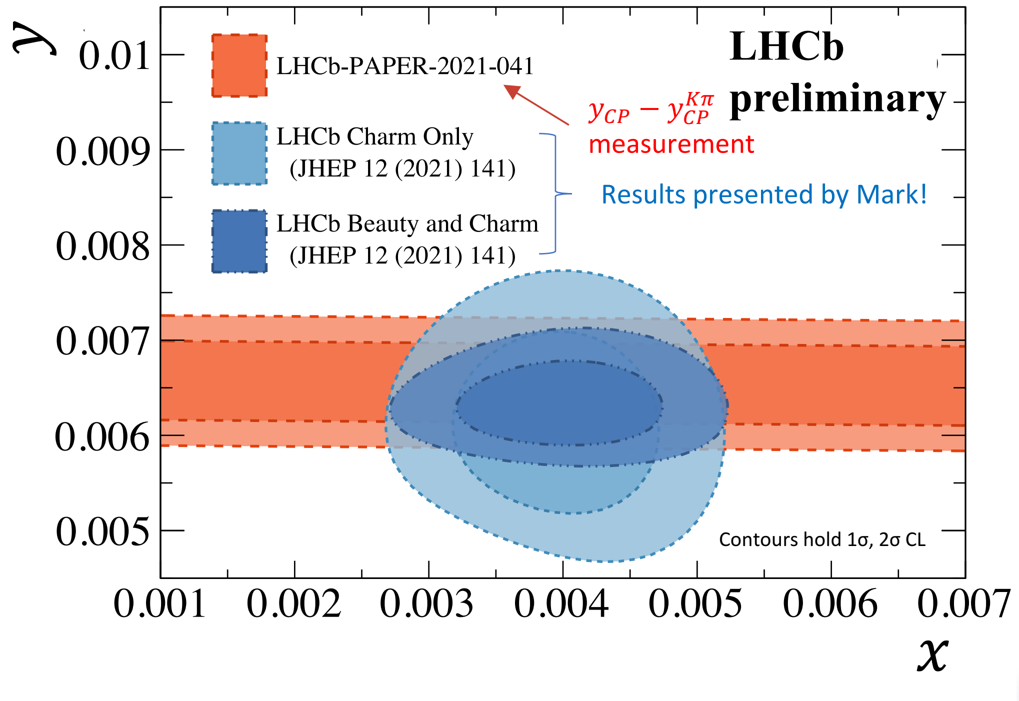
$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26_{stat} \pm 0.13_{syst})\times 10^{-3},$$

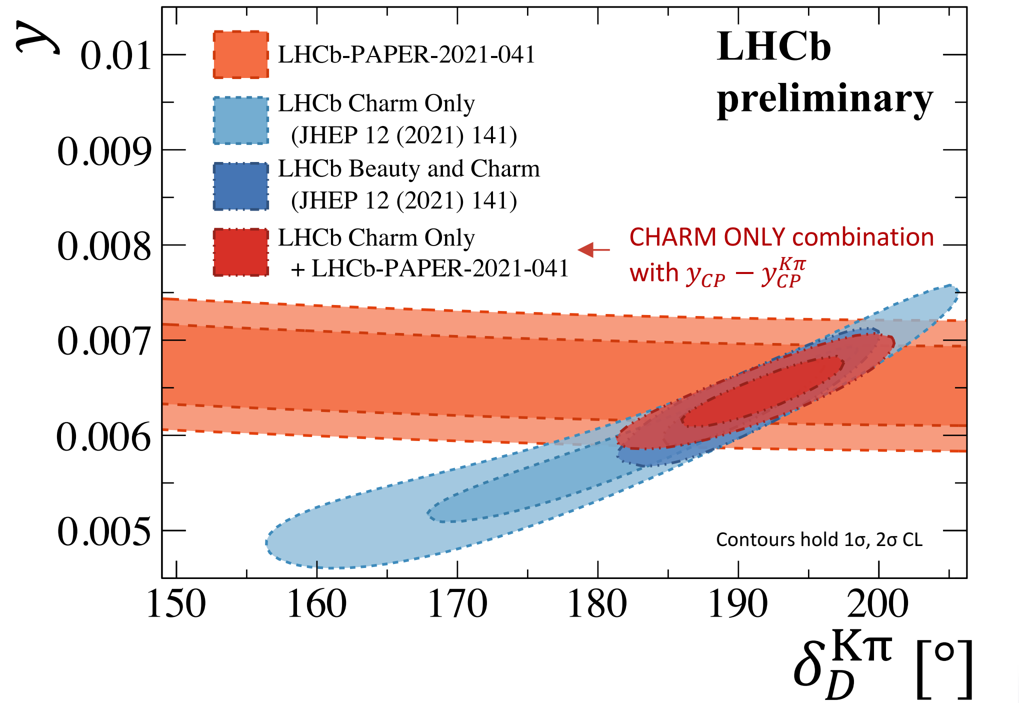
being 4× more precise than current world average value!



Impact of this measurement on charm averages

- The measurement (LHCb-PAPER-2021-041) is added to LHCb CHARM ONLY global fits. Improvements of mixing parameter $y = (\Gamma_1 - \Gamma_2)/2\Gamma$ and strong phase difference between $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$ decays $\delta_D^{K\pi}$.
- Using a LHCb CHARM ONLY combination:
  - $y = (6.46^{+0.24}_{-0.25})\times 10^{-3}$ Improvement by more than a factor of two!
  - $\delta_D^{K\pi} = (192.1^{+3.7}_{-4.0})°$ 3σ deviation from $180°$: Evidence for U-spin symmetry breaking in two-body D^0 decays!

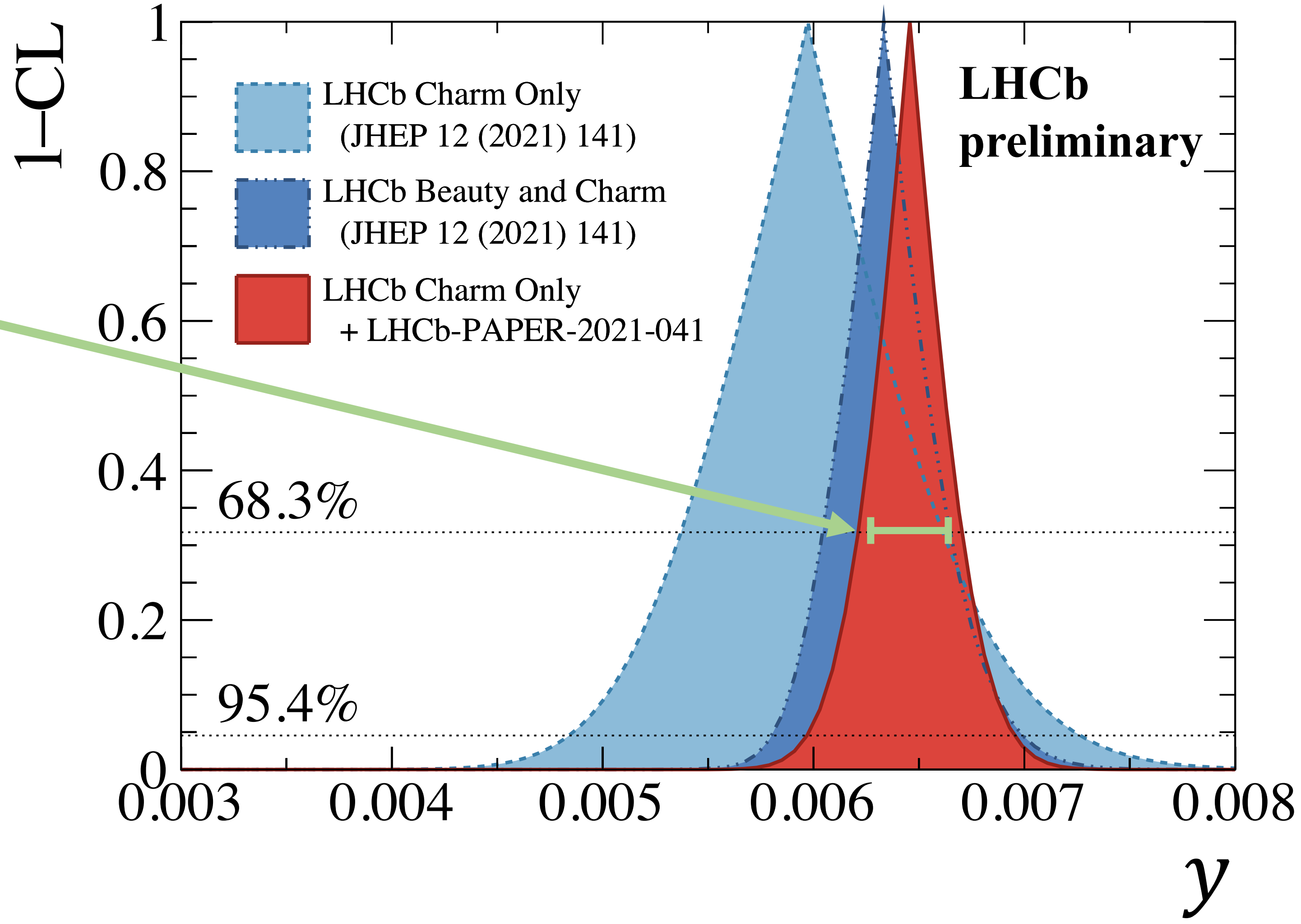




Charm mixing parameter y: Towards the future

- New measurement of $y_{CP} - y_{CP}^{K\pi}$ will be added to the LHCb Beauty and Charm combination soon!

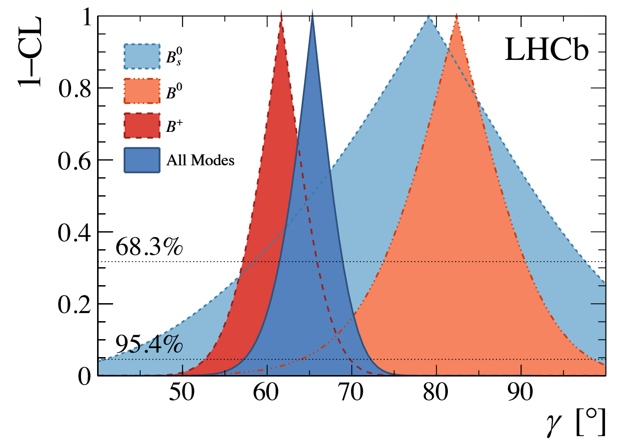
Expected future 1σ uncertainty with Beauty and Charm + $y_{CP} - y_{CP}^{K\pi}$ combination.



Conclusion

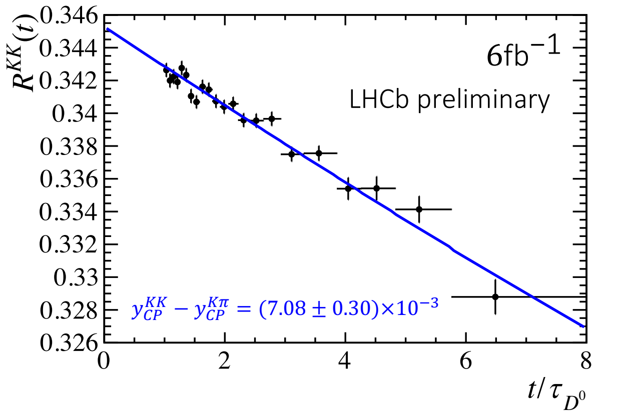
- Combination of LHCb measurements from Beauty and Charm sectors (JHEP 12 (2021) 141) to determine CKM angle γ:

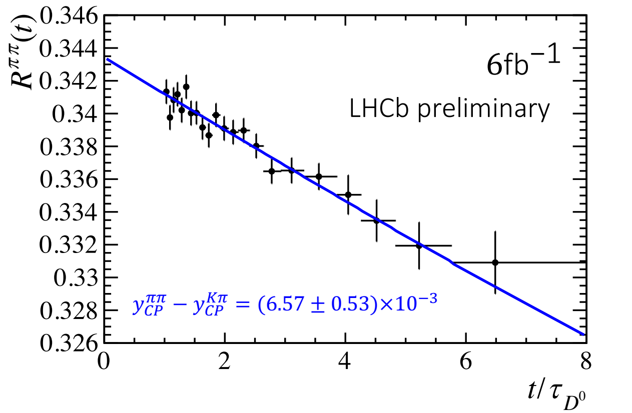
$$\gamma = (65.4^{+3.8}_{-4.2})^{\circ}$$



- Measurement of $y_{CP} - y_{CP}^{K\pi}$ shown for the first time today! The arXiv preprint will be available soon (LHCb-PAPER-2021-041).

$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26_{stat} \pm 0.13_{syst})\times 10^{-3}$$



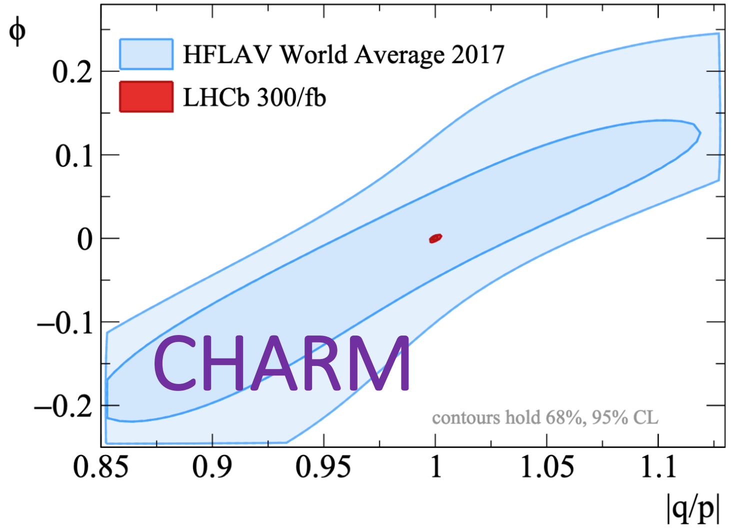


- JHEP 12 (2021) 141 and LHCb-PAPER-2021-041 allow to improve significantly the current knowledge of y.

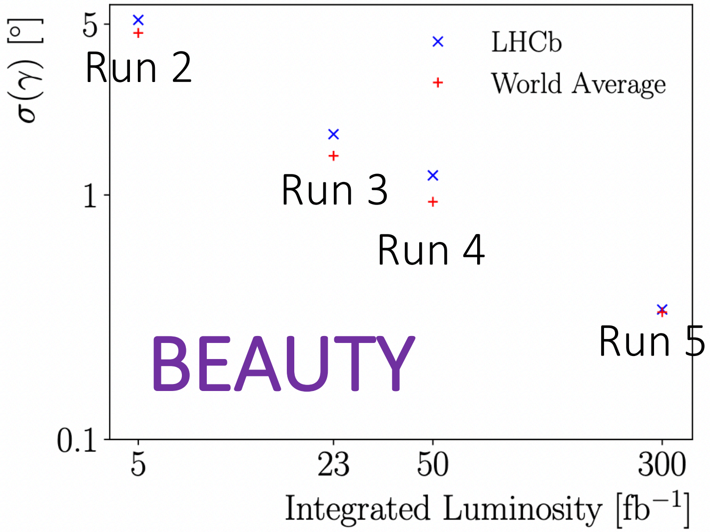
- Plenty of Beauty and Charm results will be released this year by LHCb.

Prospects for future LHCb measurements (Run 3-5)

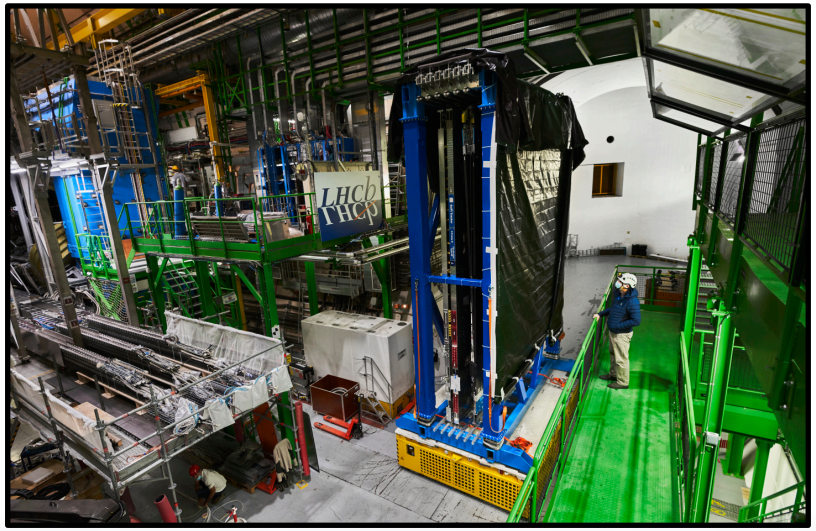
- Prospects based on [Physics case for an LHCb Upgrade II : arXiv:1808.08865](https://arxiv.org/abs/1808.08865) (2018).
- LHCb has a brand new detector for Run 3!



Prospects of CKM angle γ



Transportation of the new SciFi tracker (November 2021)



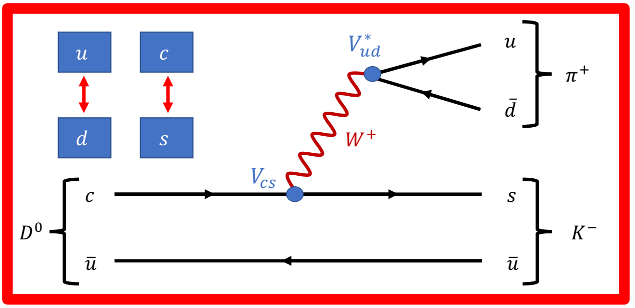
Arrival of the new VELO subdetector at LHCb (January 2022)

Backup slides

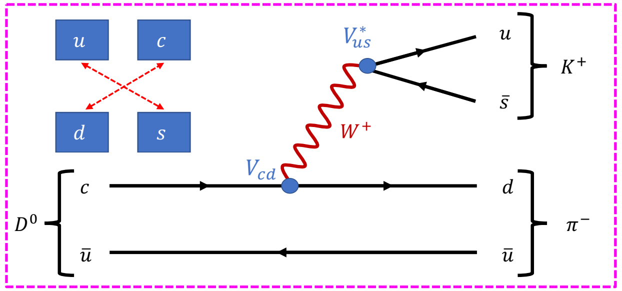
The mixing world of two-body D^0 mesons

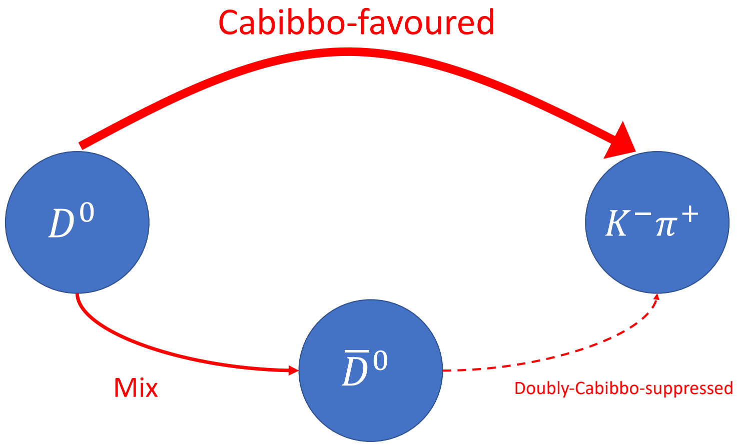
$D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$ world

Cabibbo-favoured (CF)



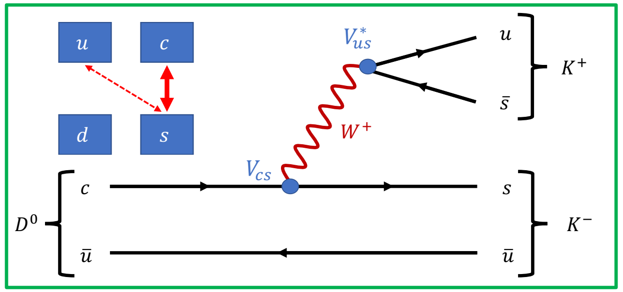
Doubly-Cabibbo-suppressed (DCS)

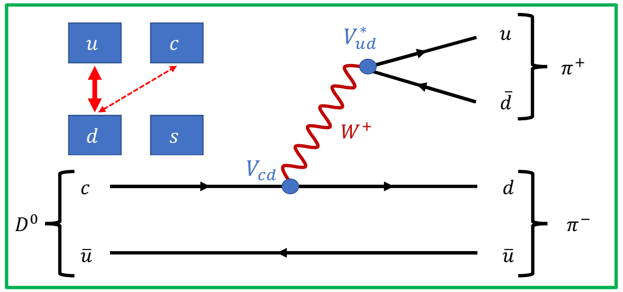


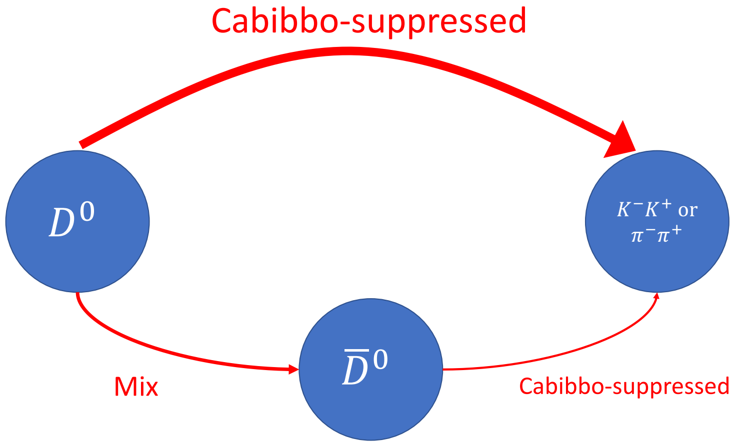


$D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ world

Cabibbo-suppressed (CS)







- The interference between $D^0 - \bar{D}^0$ mixing and decay leads to different *measured lifetimes* according to which final state is studied.
- Consequently, the *measured lifetimes* $\tau(D^0 \to K^-\pi^+)$ and $\tau(D^0 \to K^-K^+)(\tau(D^0 \to \pi^-\pi^+))$ are not equal.
- Therefore, comparing $\tau(D^0 \to K^-\pi^+)$ with $\tau(D^0 \to K^-K^+)(\tau(D^0 \to \pi^-\pi^+))$ provides key information on the $D^0 - \bar{D}^0$ mixing dynamics.

Introduction to y_{CP}: going a bit into details

- y_{CP} is defined for a given final state $f = K^+K^-$ or $f = \pi^+\pi^-$ as:

$y_{CP}^f = \frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)}{2\Gamma} - 1$, with $\hat{\Gamma}$ being an *effective decay width*, *i.e.* satisfying $\Gamma(D^0 \to f, t) = e^{-\hat{\Gamma}(D^0 \to f)t}$

- We expect y_{CP}^{KK} and $y_{CP}^{\pi\pi}$ to be compatible with each other below the 1×10^{-5} level (negligible).
- y_{CP} is related to y as:

$$y_{CP} \approx y \cos\phi_2^\Gamma$$

- ϕ_2^Γ is a quantum phase accounting for the violation of charge-parity (CP). Any deviation of y_{CP} from y would be a additional sign of CP violation in the charm sector.

- Current experimental data gives $\phi_2^\Gamma = (4.8^{+2.9}_{-2.8})\times10^{-2}$ rad, implying $|y_{CP} - y| \lesssim 3\times10^{-5}$ @ 95% CL. Hence, measuring y_{CP} can constraint significantly our knowledge of y.

*Sidenote: $y_{12} = \frac{2|\Gamma_{12}|}{\Gamma} \approx y$

Contribution from $y_{CP}^{K\pi}$ (a bit of technicality)

- There is no direct access to the width Γ. The proxy $2\Gamma \approx \hat{\Gamma}(D^0 \to K^-\pi^+) + \hat{\Gamma}(\bar{D}^0 \to K^+\pi^-)$ was therefore employed by previous measurements of y_{CP} and is also adopted in this measurement.
- The proxy induces a non-negligible bias to the measurement (similar in magnitude to the targeted uncertainty), as shown by Michael Morello and Tommaso Pajero (https://arxiv.org/abs/2106.02014). The bias is linked to $D^0 \to K^-\pi^+$ / $D^0 \to K^+\pi^-$ (RS/WS) mixing.
- Hence, we experimentally measure the quantity:

$$\frac{\hat{\Gamma}(D^0\to f)+\hat{\Gamma}(\bar{D}^0\to f)}{\hat{\Gamma}(D^0\to K^-\pi^+)+\hat{\Gamma}(\bar{D}^0\to K^+\pi^-)} - 1 = y_{CP} - y_{CP}^{K\pi}, \text{ where } y_{CP}^{K\pi} \approx -y\sqrt{R_D} \approx -y\sqrt{\frac{\mathcal{B}(D^0\to K^+\pi^-)}{\mathcal{B}(D^0\to K^-\pi^+)}} \approx -3.5\times 10^{-4}$$

Mixing and *CP* violation in $D \to K^-\pi^+$ decays

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(Dated: June 4, 2021)

The theoretical parametrisation of mixing and time-dependent *CP* violation for D^0 decays into two charged hadrons and the experimental methods to measure them are reviewed. While these phenomena are usually neglected in the literature for $D^0 \to K^-\pi^+$ decays, this approximation is not always justified at the current level of experimental precision. In particular, neglecting the deviations of the decay rate of $D^0 \to K^-\pi^+$ decays from an exponential function is shown to produce a bias on the measurement of the parameter y_{CP}, when this is performed by relying on $D^0 \to K^-\pi^+$ decays as control channel, whose size is around 40% of the precision of the current world average. Finally, the sensitivity to *CP* violation in the mixing achievable by studying $D^0 \to K^-\pi^+$ and untagged $D \to K^-\pi^+$ decays is estimated.

$$y_{CP}^{f} = \frac{\hat{\Gamma}(D^0\to f)+\hat{\Gamma}(\bar{D}^0\to f)}{2\Gamma} - 1.$$

Equalising $\varepsilon^{selection}$: kinematic matching procedure

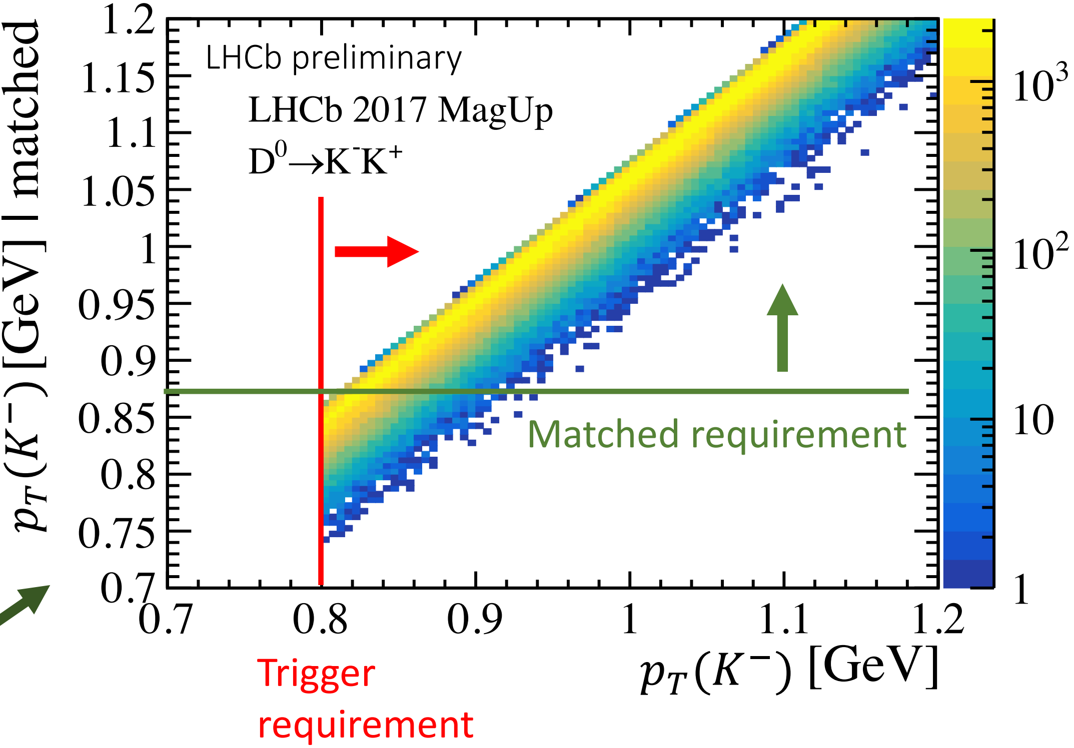
- All D^0 candidate selection procedures at LHCb include requirements on kinematic variables of daughter candidates (like $p, p_T, \eta, \mathrm{IP}$ …).
  → For two different final states, such requirements will place them in two distinct kinematic phasespaces. This biases the measurement.

- Kinematic matching procedure: event-by-event **procedure** that matches the daughter kinematic variables of one of the decays to the other one (e.g. match $D^0 \to K^-K^+$ to $D^0 \to K^-\pi^+$).
  → **Both decays are placed in the same phasespace**.

- Technically, the matched decay has new topological variables (called *matched*), which are the new variables used as part of the offline selection.

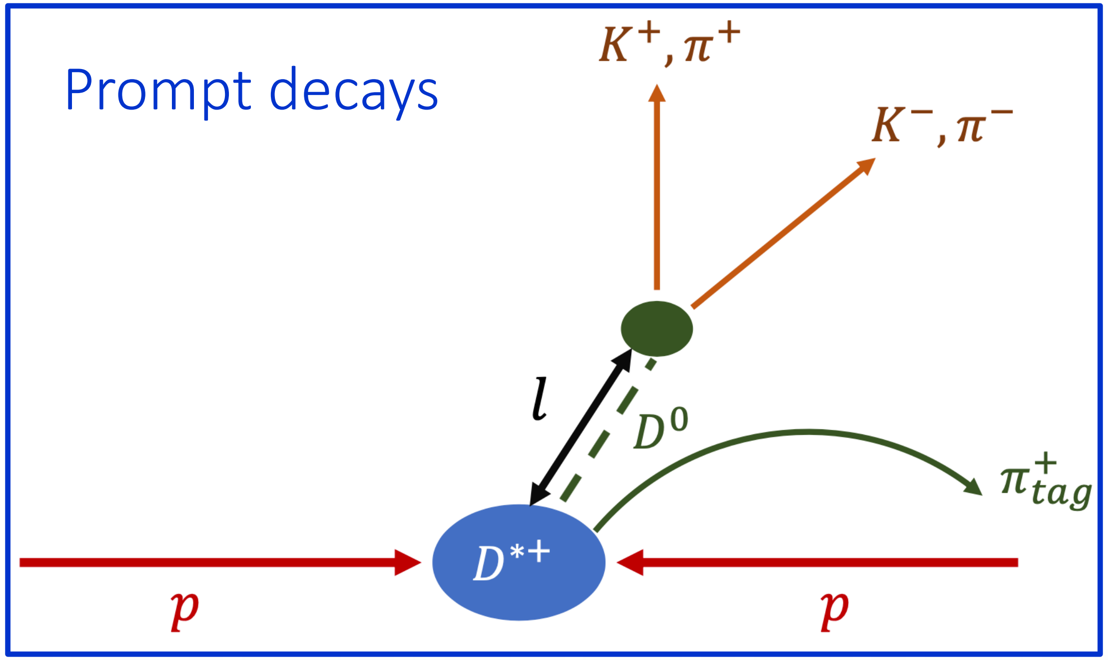
- The requirements of the offline selection are set to be effectively tighter than the trigger requirements, hence cancelling their biasing effects.

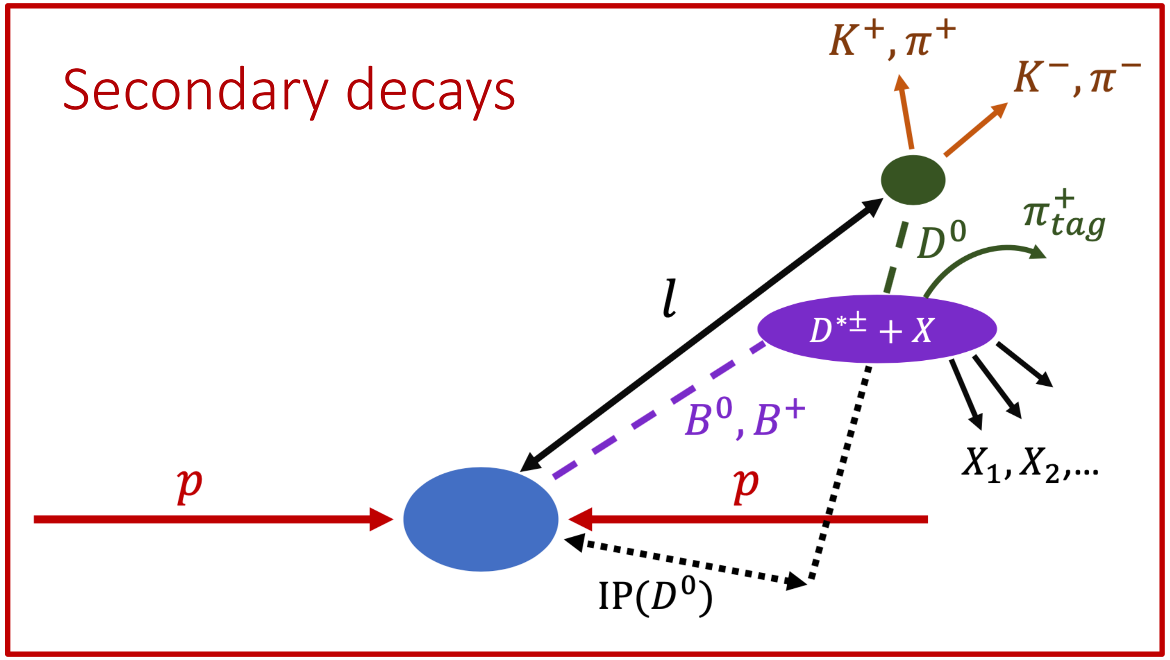
$D^0 \to K^-K^+$ to $D^0 \to K^-\pi^+$ matching: example



Challenging background: secondary D^0 decays

- The samples are contaminated by the presence of secondary D^0 decays coming from B meson decays.
- Decay times are measured as: $t = l\frac{m_D}{p_D}$ where the decay length l is measured w.r.t the PV. For secondary decays, t will be estimated as significantly larger than the proper D^0 decay time ($\tau_B \approx 4\tau_{D^0}$).
- Prompt decays have IP$(D^0) \approx 0$µm (IP = Impact Parameter) whereas secondary decays IP$(D^0) > 0$ → the requirement IP$(D^0) < 50$µm is applied to remove a large fraction of secondary decays.





Treatment of secondary D^{*+} decays

- Let's split the total decay time ratio $R^{hh}_{tot}(t)$ according to its prompt and secondary parts:

$$R^f_{tot}(t) = \left(1 - f_{sec}(t)\right)R^f_{prompt}(t) + f_{sec}(t)R^f_{sec}(t).$$

$f_{sec}(t) = \frac{N^f_{sec}(t)}{N^f_{sec}(t)+N^f_{prompt}(t)}$: fraction of secondary decays.

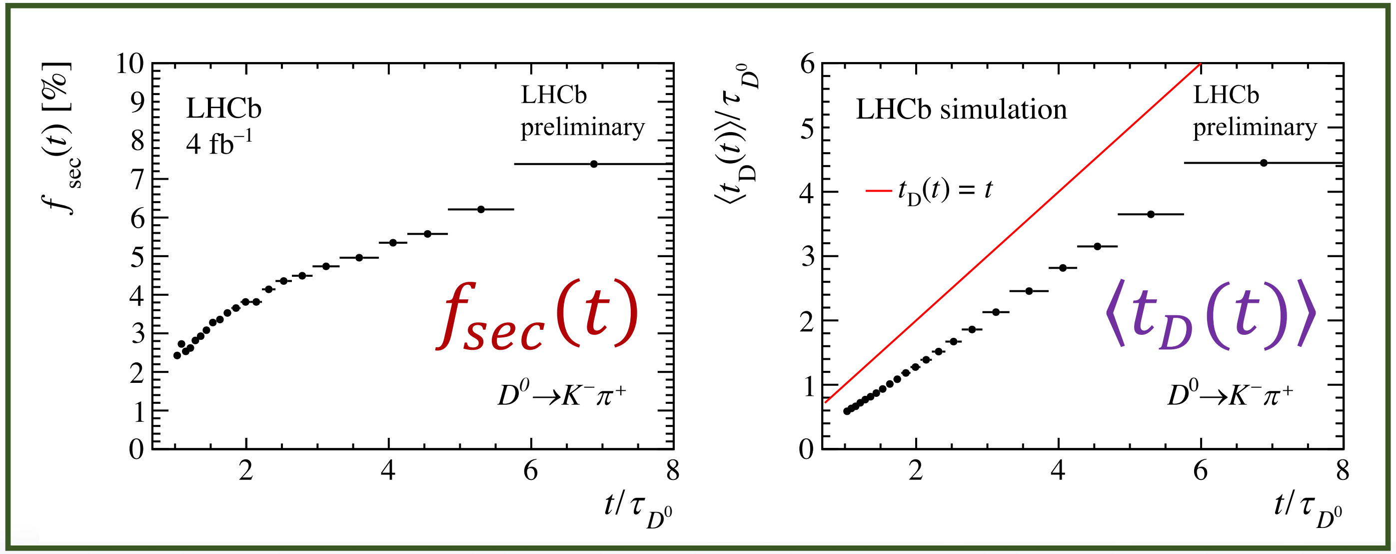
- To treat the presence of secondary decays, we change the fit model according to

$$R^f_{tot}(t) = R_0\left(\left(1 - f_{sec}(t)\right)e^{-(y^f_{CP}-y^{K\pi}_{CP})t/\tau_{D^0}} + f_{sec}(t)e^{-(y^f_{CP}-y^{K\pi}_{CP})\langle t_D(t)\rangle/\tau_{D^0}}\right),$$

where $\langle t_D(t)\rangle$ is the average true D^0 decay time in each bin of reconstructed decay time t for a pure sample of secondary decays.

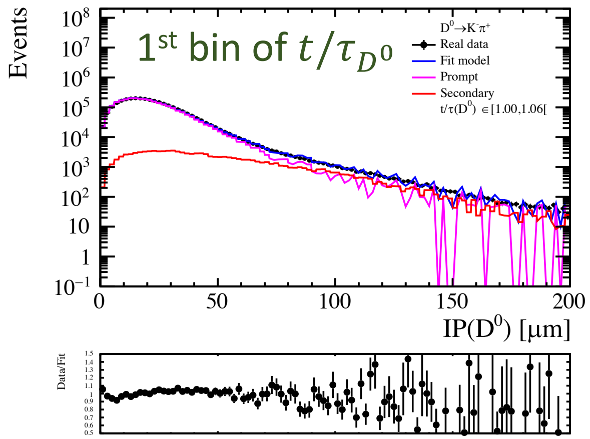
The **two ingredients** $f_{sec}(t)$ and $\langle t_D(t/\tau_{D^0})\rangle$ are obtained with the help of Monte Carlo simulations.

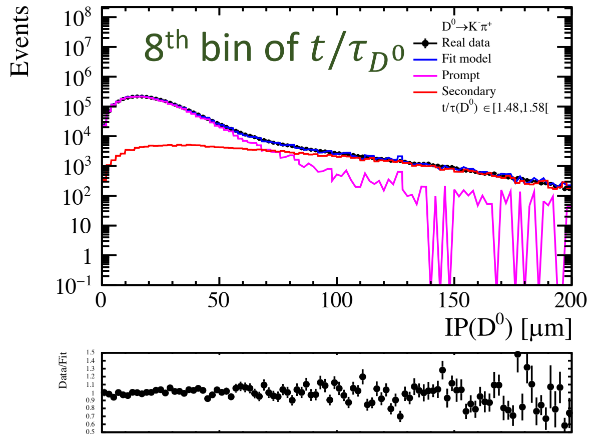
- With this method, $y^f_{CP} - y^{K\pi}_{CP}$ is measured with both prompt and secondary decays!

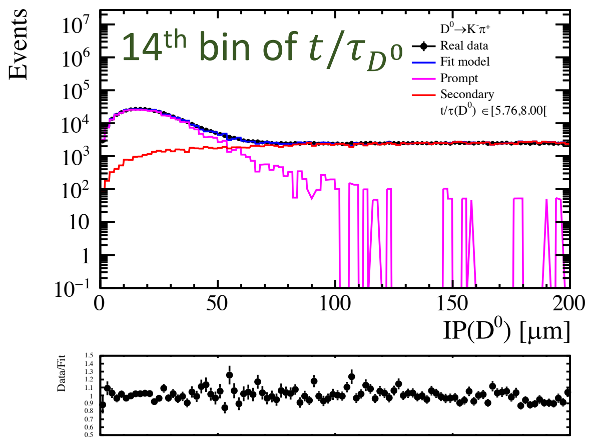


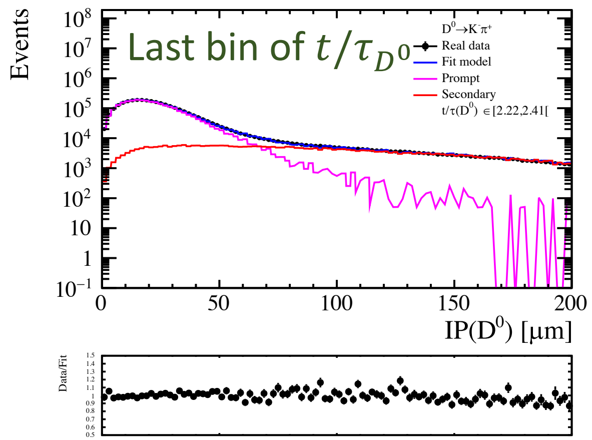
$f_{sec}(t)$: Fraction of secondary decays in each bin of t/τ_{D^0}

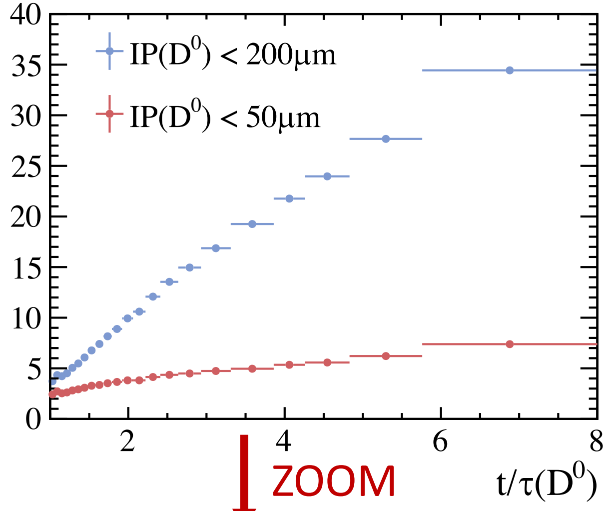
- Fit $\mathrm{IP}(D^0)$ in real data using prompt and secondary MC templates in each bin of D^0 decay time.





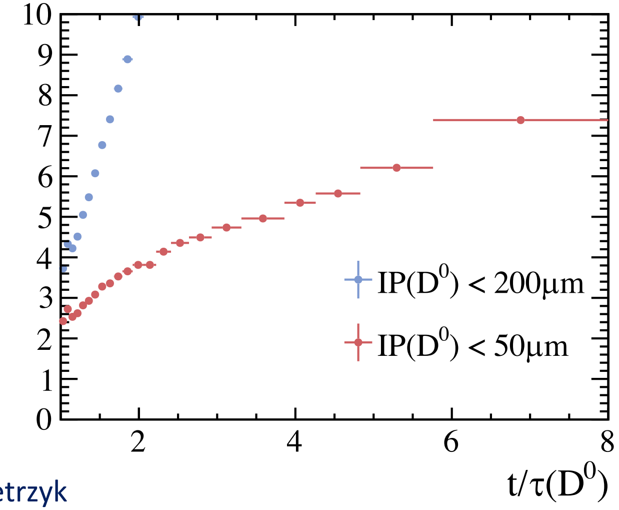






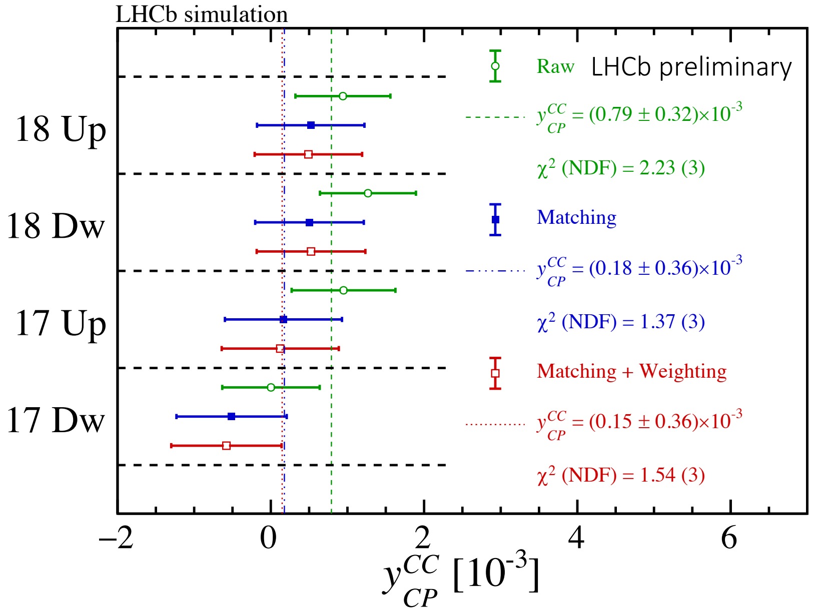
Decrease from 35% to 7% at high decay times with $\mathrm{IP}(D^0) < 50\mu m$.

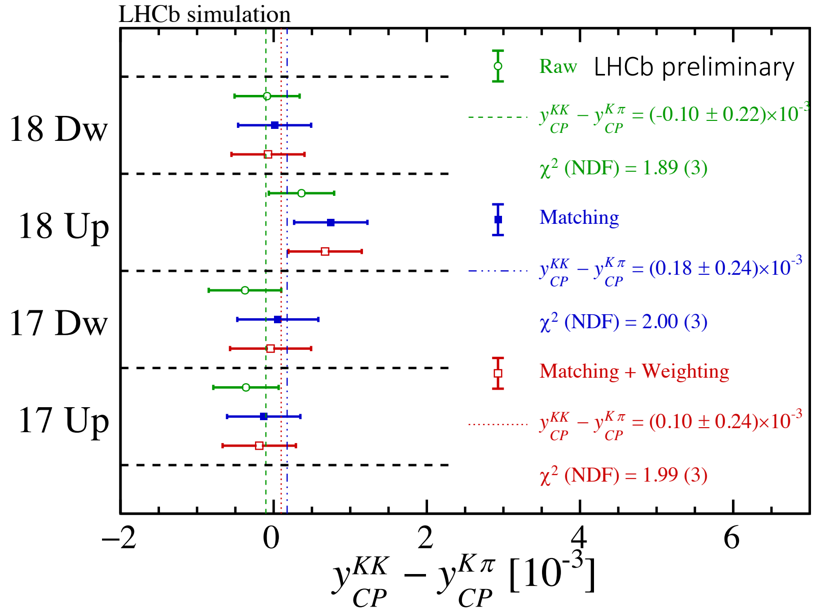
ZOOM

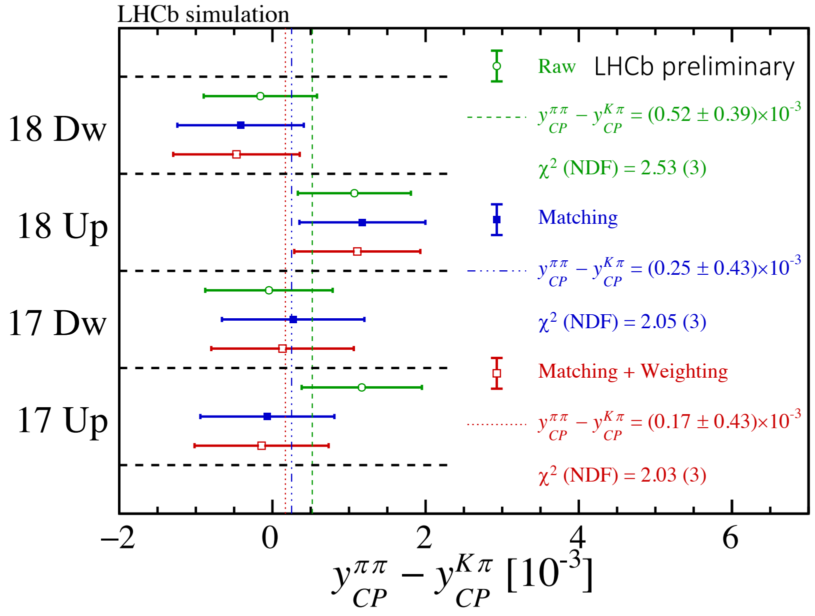


Validation of the measurement with LHCb simulation

- Use of large samples of LHCb simulation with the same data selection to test the analysis procedure.
- Since the effect of mixing is not simulated, we expect all results to be compatible with zero.
- After both matching and weighting procedures (in red), all three measurements are compatible with zero!







Determination of the systematic uncertainties in a few words

- **Subtraction of the combinatorial background:** repeat the measurements with alternative configurations for the sideband subtraction strategy and by propagating the uncertainties on the outputs.
- **Treatment of secondary decays:** Consider the imprecision related to the determinations of $f_{sec}(t)$ and $\langle t_D \rangle(t)$, which rely on Monte Carlo simulation (sum of five different contributions to the final systematic uncertainty).
- **Kinematic reweighting procedure:** Test four alternative choices of input kinematic variables to the reweighting algorithm, and study the reweighting of the target decay to the matched one.
- **Input $\boldsymbol{D^0}$ decay time:** Propagation of the uncertainty on the world average value of τ_{D^0} to the measurement.
- **Residual nuisance asymmetries:** Include potential biases related to the contributions from the flavour of the D^0 (which can arise from $\pi^{\pm}_{tag}$ detection asymmetries and $\boldsymbol{D^{*+}}$ production asymmetries).
- **Partially or misreconstructed $\boldsymbol{D^{*+} \rightarrow D^0 \pi^+}$ candidates (peaking backgrounds):** Generate RapidSim samples to fit the $m(h^- h^+)$ distributions in data, allowing a determination of the peaking background fractions for each decay mode. Then assess their impact to the measurement as a systematic uncertainty.
- **Fit bias:** Some potential biases from the fit model can appear at the second order of t/τ_{D^0} (based on very recent work in arXiv:2106.02014). Toy studies are performed to assess a systematic uncertainty.

Improvements of y and $\delta_D^{K\pi}$