# Experimental overview of charm Mixing and CP violation

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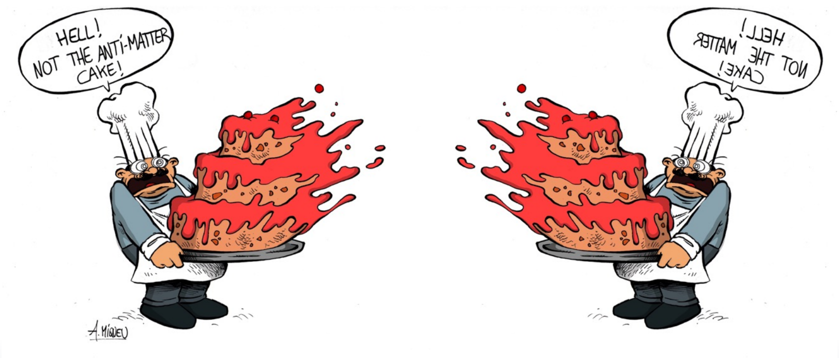
Implications of LHCb measurements and future prospects (19th October 2022)



# Mixing and CP-violation in the charm sector

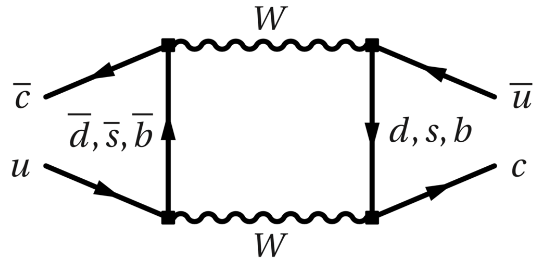
|  | $d$ | $s$ | $b$ |
|---|---|---|---|
| $\bar{d}$ | - | $K^0$ | $B_0$ |
| $\bar{s}$ | $\bar{K}^0$ | - | $B_s^0$ |
| $\bar{b}$ | $\bar{B}^0$ | $\bar{B}_s^0$ | - |

|  | $u$ | $c$ | $t$ |
|---|---|---|---|
| $\bar{u}$ | - | $D^0$ | - |
| $\bar{c}$ | $\bar{D}^0$ | - | - |
| $\bar{t}$ | - | - | - |

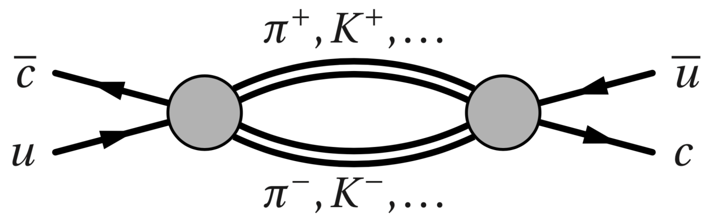
- The charm sector encompasses the only up-type quark decays of neutral mesons in which mixing and CP-violation (CPV) can be probed.
- CPV is predicted to be small $(\sim 10^{-3} - 10^{-4})$ by the Standard Model, so is mixing.

  → Room for new physics enhancements.
- These predictions are dominated by long distance contributions.

  → Experimental measurements are crucial to improve theoretical predictions.




Short Distance Contributions:
Heavily suppressed!




Long Distance Contributions:
Large theoretical uncertainties!

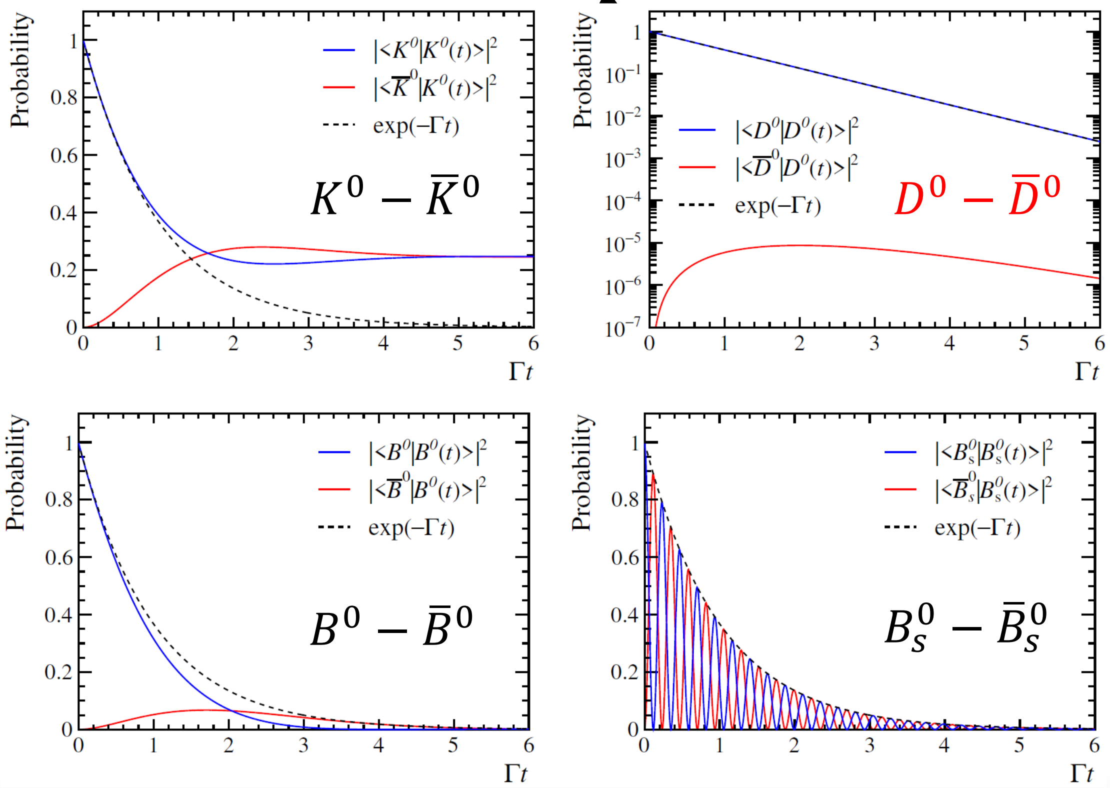
- Charm data samples are huge: ~ a few billion $D^0$ decays at LHCb with Run 1 + Run 2 data.

# Neutral meson mixing: very different systems

- Neutral charm mass eigenstates are superpositions of flavour eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$.
- Oscillations dynamics defined by two parameters: $x = \frac{m_2 - m_1}{\Gamma}$ and $y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$, where $\Gamma = \frac{\Gamma_1 + \Gamma_2}{\Gamma}$ ($D^0$ 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 | $x$ | $y$ |
|---|---|---|
| $K^0 - \bar{K}^0$ | $-0.946 \pm 0.004$ | $0.99650 \pm 0.00001$ |
| $D^0 - \bar{D}^0$ | $(4.07 \pm 0.44)\times10^{-3}$ | $(6.47 \pm 0.24)\times10^{-3}$ |
| $B^0 - \bar{B}^0$ | $-0.769 \pm 0.004$ | $(0.1 \pm 0.1)\times10^{-2}$ |
| $B_s^0 - \bar{B}_s^0$ | $26.89 \pm 0.07$ | $(12.9 \pm 0.6)\times10^{-2}$ |

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

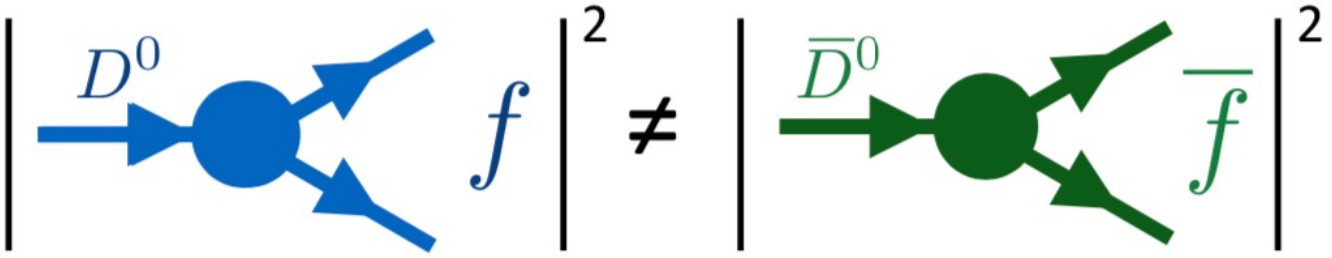

$B_s^0 - \bar{B}_s^0$ system

# 3 types of CPV

## DIRECT

**Decay**

$|A_f| \neq |\bar{A}_{\bar{f}}|$

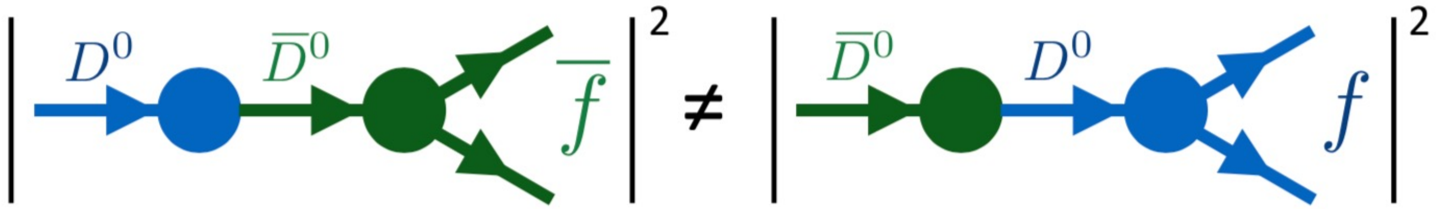



CPV in the decay observed at $5.3\sigma$ by the LHCb collaboration in March 2019! 🍾

## INDIRECT

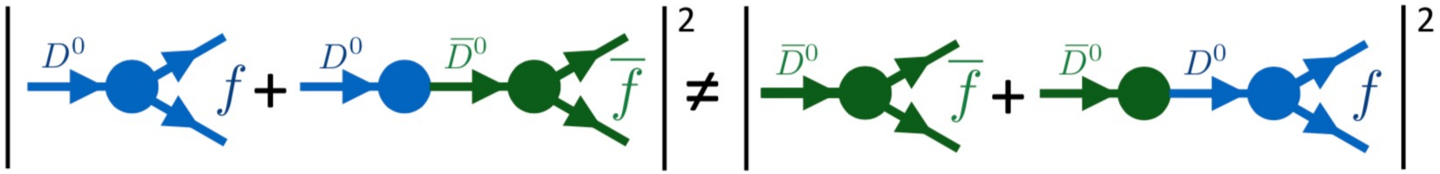
**Mixing**

$|q| \neq |p|$



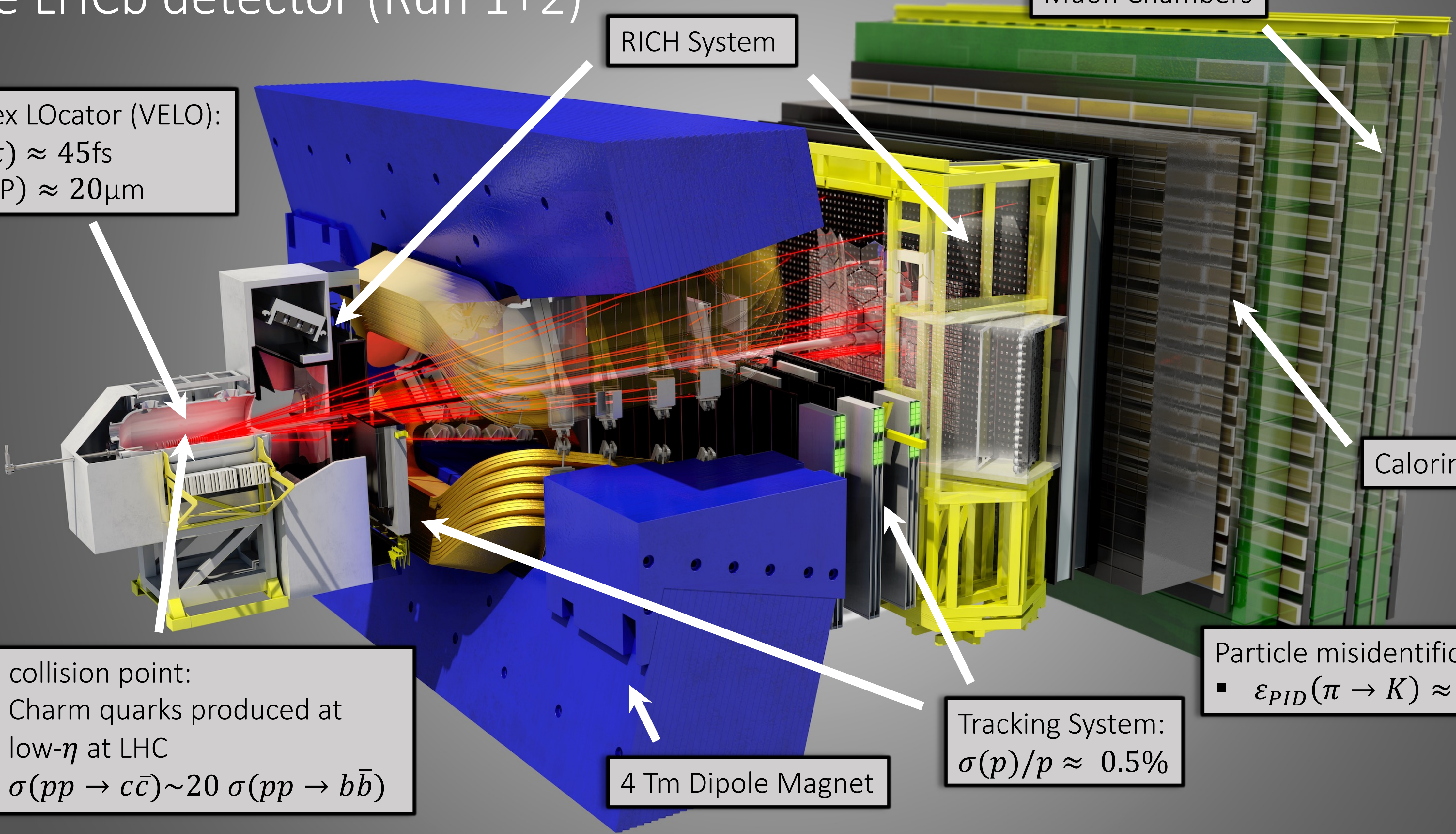

**Interference mixing-decay**

$\phi = \arg\left(\frac{q\bar{A}_f}{pA_f}\right) \neq 0$




Still no evidence of CPV

# The LHCb detector (Run 1+2)



Muon Chambers

RICH System

VErtex LOcator (VELO):
- $\sigma(t) \approx 45\text{fs}$
- $\sigma(\text{IP}) \approx 20\mu\text{m}$

Calorimeters

Particle misidentification:
- $\varepsilon_{PID}(\pi \to K) \approx 3\%$

pp collision point:
- Charm quarks produced at low-$\eta$ at LHC
- $\sigma(pp \to c\bar{c}) \sim 20\, \sigma(pp \to b\bar{b})$

4 Tm Dipole Magnet

Tracking System:
$\sigma(p)/p \approx 0.5\%$

# Outline of the talk

- Measurement of the time-integrated CP asymmetry in $D^0 \to K^-K^+$ decays [LHCb-PAPER-2022-024]

- Model-independent measurement of charm mixing parameters in $\bar{B} \to D^0(\to K_S^0\pi^+\pi^-)\mu^-\bar{\nu}_\mu X$ decays [LHCb-PAPER-2022-020]

- Measurement of the charm mixing parameter $y_{CP} - y_{CP}^{K\pi}$ using two-body $D^0$ decays [Phys. Rev. D 105, 092013]

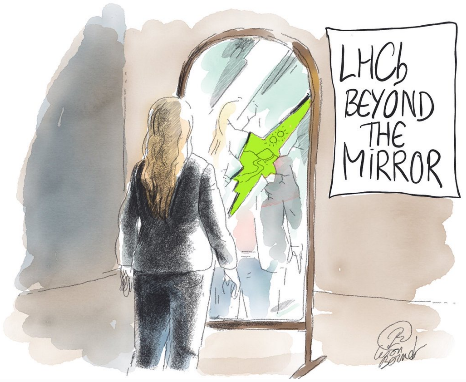
- New combination! [LHCb-CONF-2022-003]

# Measurement of the time-integrated CP asymmetry in $D^0 \to K^- K^+$ decays [LHCb-PAPER-2022-024]

# Measurement of the time-integrated CP asymmetry in $D^0 \to K^-K^+$ decays [LHCb-PAPER-2022-024]

$$A_{CP}(KK) = \frac{\int \varepsilon(t)[\Gamma(D^0 \to K^-K^+)(t) - \Gamma(\overline{D}^0 \to K^+K^-)(t)]\mathrm{d}t}{\int \varepsilon(t)[\Gamma(D^0 \to K^-K^+)(t) + \Gamma(\overline{D}^0 \to K^+K^-)(t)]\mathrm{d}t} = a^d_{KK} + \frac{\langle t \rangle_{KK}}{\tau_D} \Delta Y_{KK}$$

- $a^d_{KK} \approx 1 - \left|\frac{\bar{A}_{KK}}{A_{KK}}\right|$ probes CPV in the decay.
- $\Delta Y_{KK} \approx x\phi - y\left(\left|\frac{q}{p}\right| - 1\right)$ probes CPV in the mixing + interference between mixing and decay.
- CPV has been observed in $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) = (-15.4 \pm 2.9)\times 10^{-4}$. Phys. Rev. Lett. 122 (2019) 211803
- Strategy: Measure $A_{CP}(KK)$ and then retrieve $a^d_{KK}$ and $a^d_{\pi\pi}$ using $\Delta A_{CP}$ and $\Delta Y$ [Phys. Rev. D 104, 072010] results.
- Dataset: Run 2 (2015-2018, 6 fb$^{-1}$).



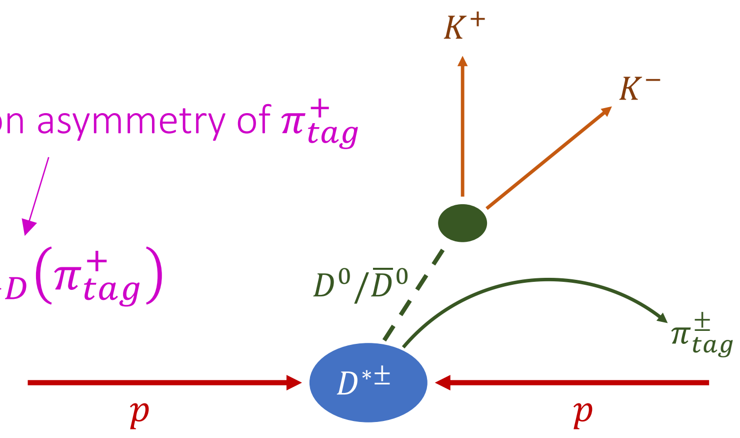

Credit: Lison Bernet

# $A_{CP}(KK)$: Experimental challenges

- $\overset{(-)}{D}{}^0 \to K^-K^+$ obtained from prompt $D^{*\pm} \to \overset{(-)}{D}{}^0\pi^{\pm}_{tag}$. Charge of $\pi^{\pm}_{tag}$ tags $D^0$ flavour.
- We experimentally measure:

$$A(KK) = \frac{N(D^{*+} \to D^0\pi^{\pm}_{tag}) - N(D^{*-} \to \bar{D}^0\pi^{-}_{tag})}{N(D^{*+} \to D^0\pi^{\pm}_{tag}) + N(D^{*-} \to \bar{D}^0\pi^{-}_{tag})} = A_{CP}(KK) + A_P(D^{*+}) + A_D(\pi^{+}_{tag})$$

Production asymmetry of $D^{*+}$ — Detection asymmetry of $\pi^{+}_{tag}$ — what we want




- Strategy to treat nuisance asymmetries: use Cabibbo-favoured $D^0/D^+_{(s)}$ decays (where CPV$\approx 0$):
  - $D^+$ method ($C_{D^+}$):

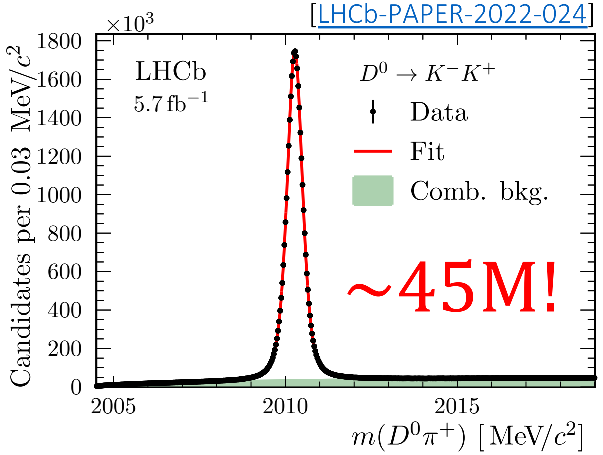
$$A_{CP}(KK) = +A(D^{*\pm} \to (D^0 \to K^-K^+)\pi^{\pm}_{tag}) - A(D^{*\pm} \to (D^0 \to K^-\pi^+)\pi^{\pm}_{tag})$$
$$+A(D^+ \to K^-\pi^+\pi^+) - [A(D^+ \to \bar{K}^0\pi^+) - A(\bar{K}^0)]$$

Neutral Kaon asymmetry: detection + mixing + CPV

  - $D_s^+$ method ($C_{D_s^+}$, gain of $\sim 40\%$ precision on final result):

$$A_{CP}(KK) = +A(D^{*\pm} \to (D^0 \to K^-K^+)\pi^{\pm}_{tag}) - A(D^{*\pm} \to (D^0 \to K^-\pi^+)\pi^{\pm}_{tag})$$
$$+A(D_s^+ \to \phi\pi^+) - [A(D_s^+ \to \bar{K}^0K^+) - A(\bar{K}^0)]$$

[LHCb-PAPER-2022-024]




* Particles with same colour are weighted to have identical kinematic distributions

# A new precise measurement of CPV in the decay!

Final results:

$C_{D^+}$: $A_{CP}(KK) = [13.6 \pm 8.8(\text{stat}) \pm 1.6(\text{sys})]\times 10^{-4}$,
$C_{D_s^+}$: $A_{CP}(KK) = [\ 2.8 \pm 6.7(\text{stat}) \pm 2.0(\text{sys})]\times 10^{-4}$.

$\rho = 0.06$

Combination:

$$A_{CP}(KK) = [6.8 \pm 5.4(\text{stat}) \pm 1.6(\text{sys})]\times 10^{-4}.$$

Using $\Delta A_{CP}$ result, we get:

$$a^d_{KK} = (\ 7.7 \pm 5.7)\times 10^{-4}$$
$$a^d_{\pi\pi} = (23.2 \pm 6.1)\times 10^{-4}$$

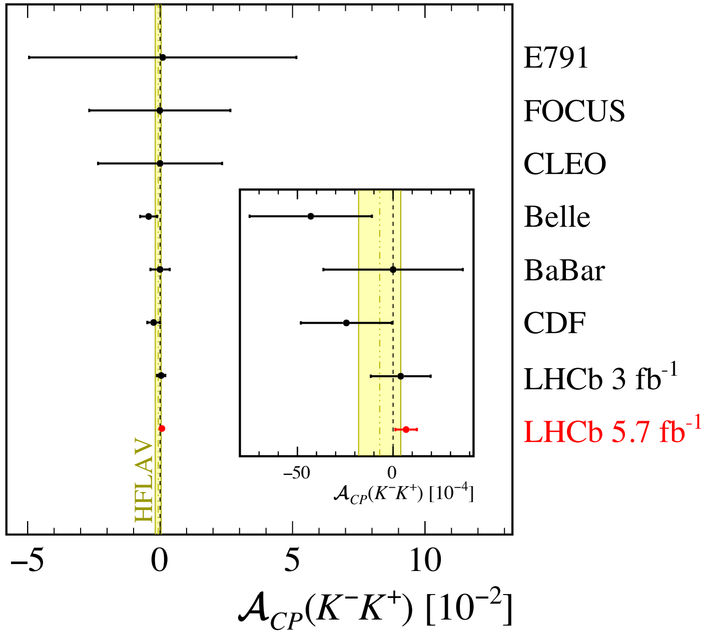
$\rho(a^d_{KK}, a^d_{\pi\pi}) = 0.88$

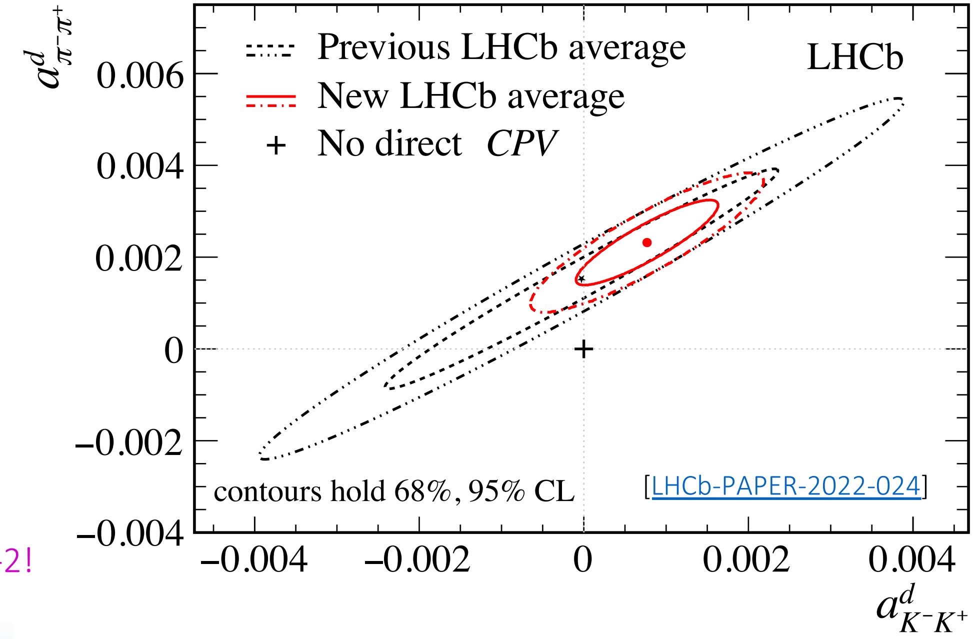
**First evidence of CP violation in $D^0 \to \pi^-\pi^+$ decays at $3.8\sigma$!**

LHCb prospects [arXiv:1808.08865] (stat uncertainties only)

| Sample ($\mathcal{L}$) | Tag | Yield $D^0 \to K^-K^+$ | Yield $D^0 \to \pi^-\pi^+$ | $\sigma(\Delta A_{CP})$ [%] | $\sigma(A_{CP}(hh))$ [%] |
|---|---|---|---|---|---|
| Run 1–2 (9 fb$^{-1}$) | Prompt | 52M | 17M | 0.03 | 0.07 |
| Run 1–3 (23 fb$^{-1}$) | Prompt | 280M | 94M | 0.013 | 0.03 |
| Run 1–4 (50 fb$^{-1}$) | Prompt | 1G | 305M | 0.007 | 0.015 |
| Run 1–5 (300 fb$^{-1}$) | Prompt | 4.9G | 1.6G | 0.003 | 0.007 |

We do better than our own propects for Run1-2!



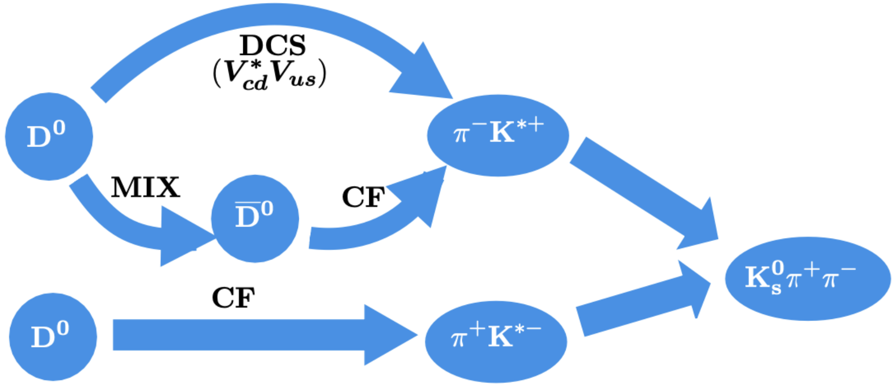
# Model-independent measurement of charm mixing parameters in $\bar{B} \to D^0(\to K_S^0\pi^+\pi^-)\mu^-\bar{\nu}_\mu X$ decays

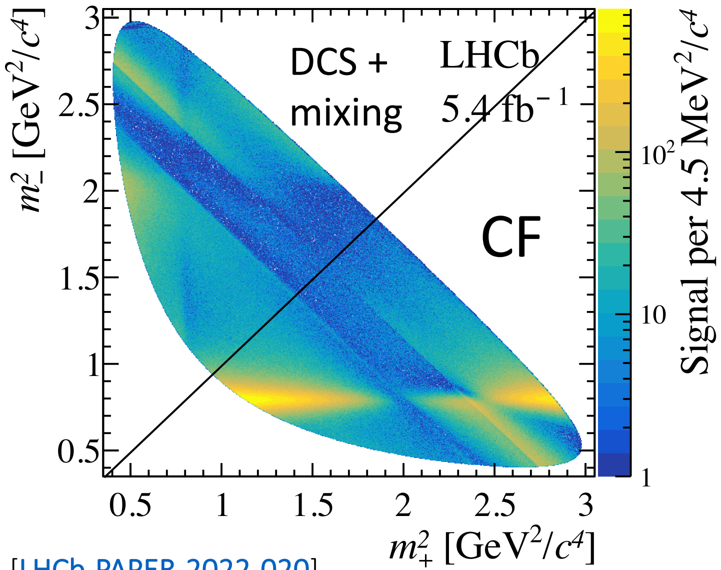
[LHCb-PAPER-2022-020]

accepted for publication by PRD

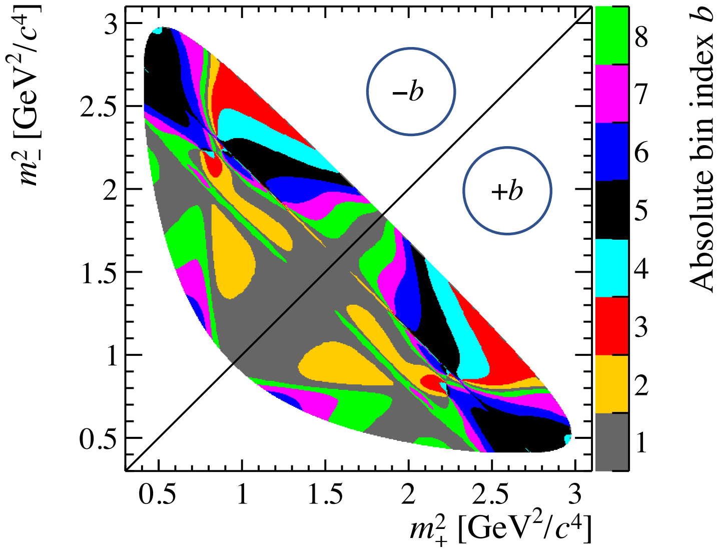
# $D^0 \to K_S^0\pi^+\pi^-$: a golden mode at LHCb

- $D^0 \to K_S^0\pi^+\pi^-$ displays a rich resonant structure.
- Bin-flip method [PhysRevD.99.012007]: model-independent approach which avoids the need for a fit of the decay amplitudes.
- Data binned in Dalitz regions $\pm b$. Binning scheme chosen to have approximately constant strong-phase differences between $D^0$ and $\bar{D}^0$ amplitudes.




[LHCb-PAPER-2022-020]




Simultaneous fit of the yield ratio $R_b^\pm$ ($\pm$ for initial $D^0/\bar{D}^0$) between $+b$ and $-b$ in bins of $D^0$ decay time $t$:

$$R_b^\pm(t) \approx r_b - \sqrt{r_b}[(1-r_b)c_b y - (1+r_b)s_b x]\Gamma t$$

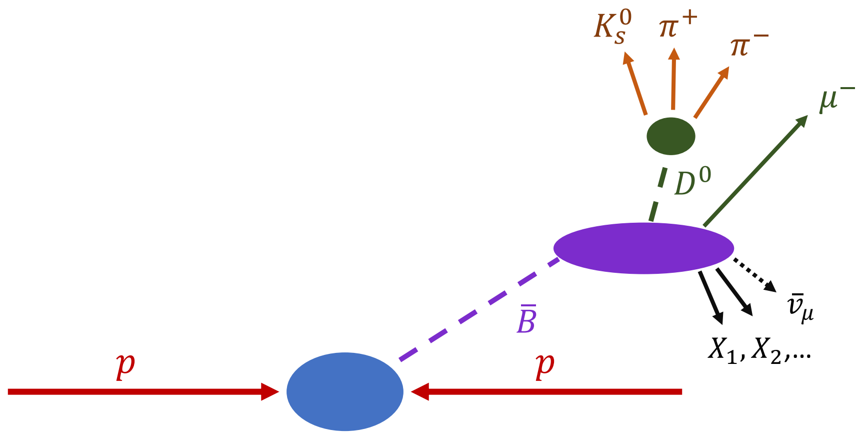
- $r_b \equiv R_b(t=0)$
- $c_b$ and $s_b$: parameters related to the strong phase differences between $\pm b$ regions (based on external inputs from CLEO and BESIII).



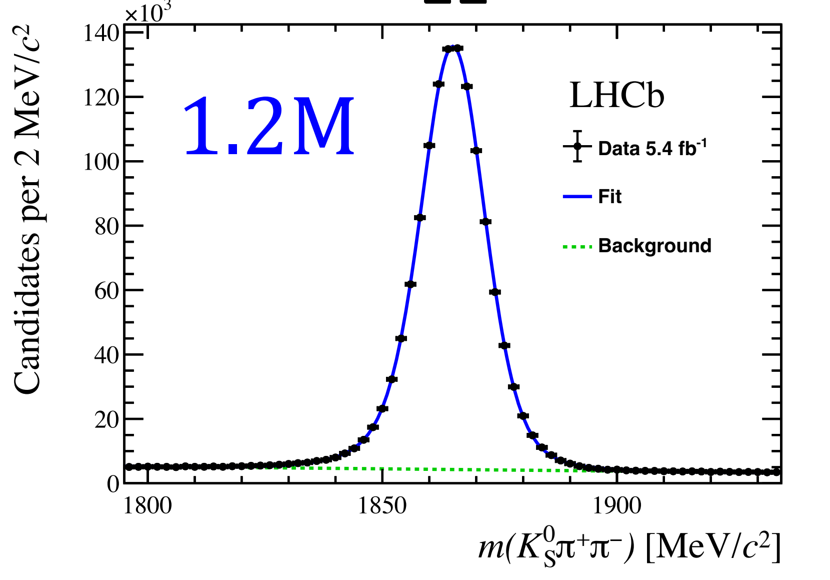
$m_\pm^2 = m^2(K_S^0\pi^\pm)$

# A complementary measurement to the prompt one!

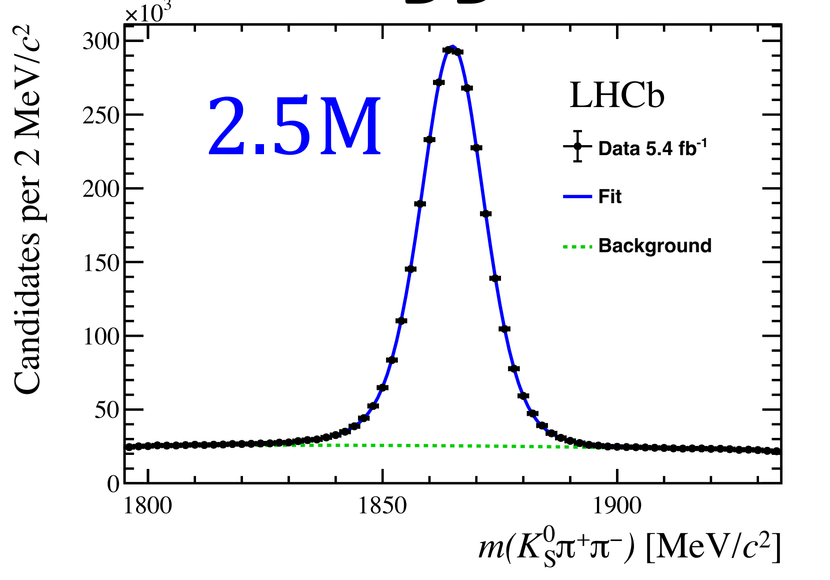
- Analysis with $D^0$ from semileptonic $\bar{B} \to D^0(\to K_S^0\pi^+\pi^-)\mu^-\bar{\nu}_\mu X$ decays (Run 2, $6\ \mathbf{fb^{-1}}$). Muon charge tags $D^0$ flavour.
- Complementary to prompt analysis using $D^{*+} \to D^0\pi^+$ decays [PRL 127 (2021) 111801]. Significantly less statistics but can probe low values of $D^0$ decay time.
- Data sample split in two: $K_S^0 \to \pi^+\pi^-$ can occur inside (two "long" tracks: LL) or outside (two "downstream" tracks: DD) the VELO region.




LL



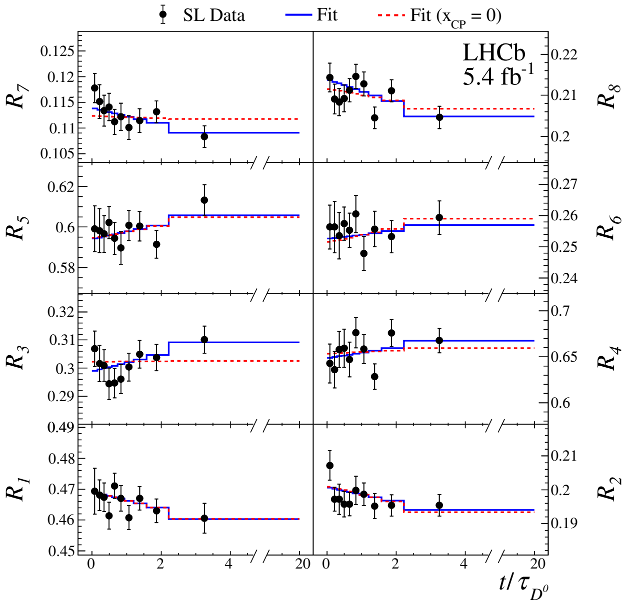

DD



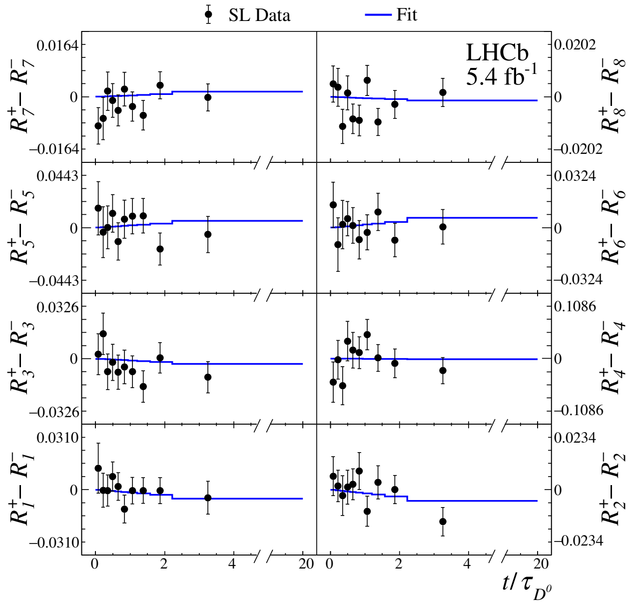

[LHCb-PAPER-2022-020]

# Final results: compatible with the prompt analysis!

**Mixing measurement: $D^0 + \bar{D}^0$**




**CPV measurement: $D^0 - \bar{D}^0$**



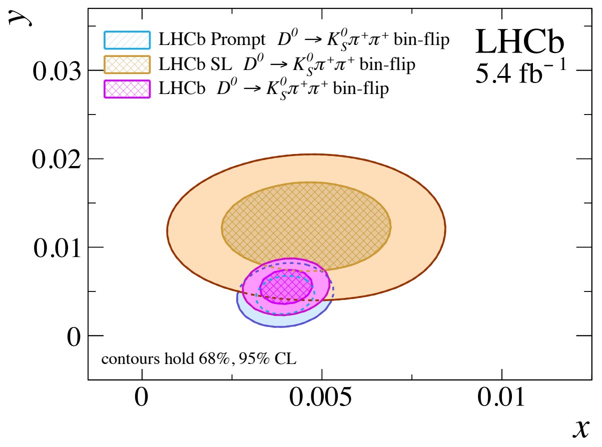

## Summary of uncertainties

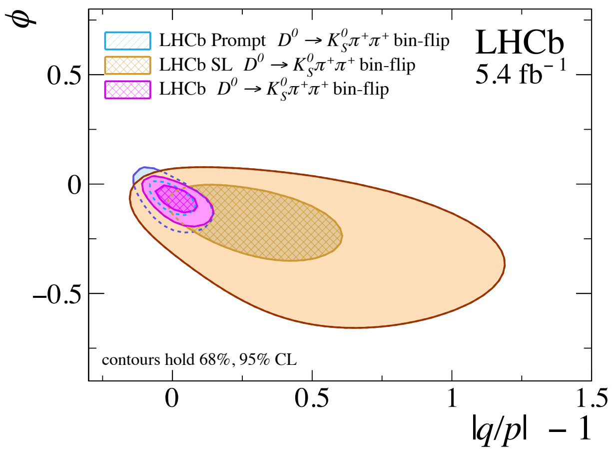
| Source | $x_{CP}$ $[10^{-3}]$ | $y_{CP}$ $[10^{-3}]$ | $\Delta x$ $[10^{-3}]$ | $\Delta y$ $[10^{-3}]$ |
|---|---|---|---|---|
| Reconstruction and selection | 0.06 | 0.79 | 0.28 | 0.24 |
| Detection asymmetry | 0.06 | 0.03 | 0.01 | 0.09 |
| Mass-fit model | 0.03 | 0.09 | 0.01 | 0.01 |
| Unrelated $D^0\mu$ combinations | 0.24 | 0.22 | 0.01 | 0.05 |
| Total systematic | 0.26 | 0.83 | 0.28 | 0.26 |
| Strong phase inputs | 0.32 | 0.68 | 0.16 | 0.21 |
| Statistical (w/o phase inputs) | 1.45 | 3.04 | 0.92 | 1.91 |
| Statistical | 1.48 | 3.12 | 0.93 | 1.92 |

Uncertainty on external strong phase inputs higher than total systematic → need for new BESIII inputs!

Combination of prompt and semileptonic analyses

$$x = (4.01 \pm 0.49) \times 10^{-3}$$
$$y = (5.50 \pm 1.30) \times 10^{-3}$$
$$|q/p| = 1.012^{+0.050}_{-0.048}$$
$$\phi = -0.060^{+0.037}_{-0.044}$$



# Measurement of the charm mixing parameter $y_{CP} - y_{CP}^{K\pi}$ using two-body $D^0$ decays [Phys. Rev. D 105, 092013]

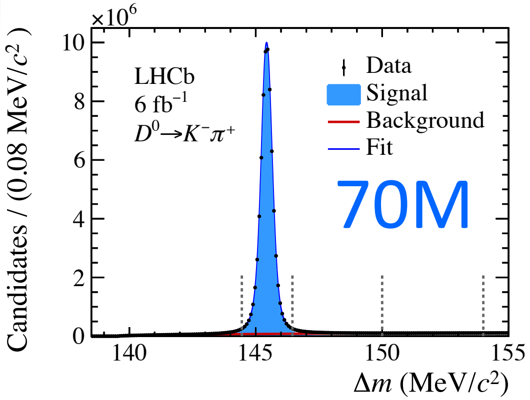
# The $y_{CP}^{f} - y_{CP}^{K\pi}$ observable

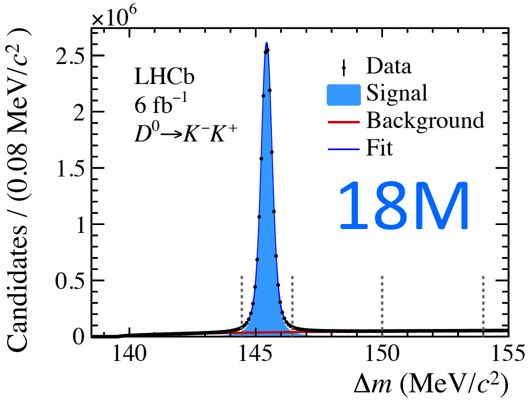
- Goal: Study lifetime ratio $D^0 \to K^-\pi^+ / D^0 \to f$ ($f = K^-K^+, \pi^-\pi^+$):

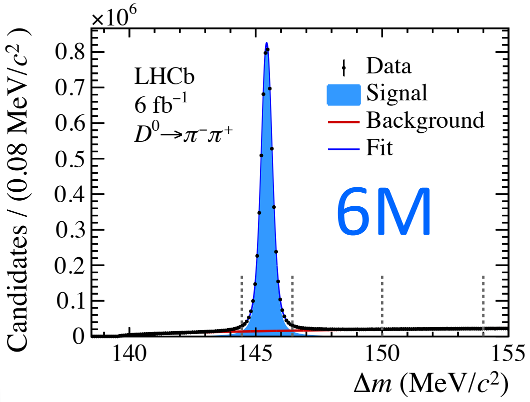
$$\frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to f)} - 1 = y_{CP}^{f} - y_{CP}^{K\pi} \approx y\left(1 + \sqrt{R_D}\right)$$

$$y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma} \approx 0.6\% \qquad \sqrt{R_D} = \sqrt{\frac{\mathcal{B}(D^0 \to K^+\pi^-, t=0)}{\mathcal{B}(D^0 \to K^-\pi^+, t=0)}} \approx 6\%$$

- Hence, measuring precisely $y_{CP}^{f} - y_{CP}^{K\pi}$ allows to constrain $y$!
- $y_{CP}^{f} - y_{CP}^{K\pi}$ obtained with fit to $R^f(t) = \frac{dN(D^0 \to f, t)}{dN(D^0 \to K^-\pi^+, t)} \propto e^{-(y_{CP}^{f} - y_{CP}^{K\pi})t/\tau_{D^0}} \frac{\varepsilon(f,t)}{\varepsilon(K^-\pi^+,t)}$.
- Biggest challenge: equalise the time-dependent efficiencies to make them cancel out in $R^f(t)$.
- Use full Run 2 data using prompt $D^{*+} \to D^0\pi^+_{tag}$ decays.



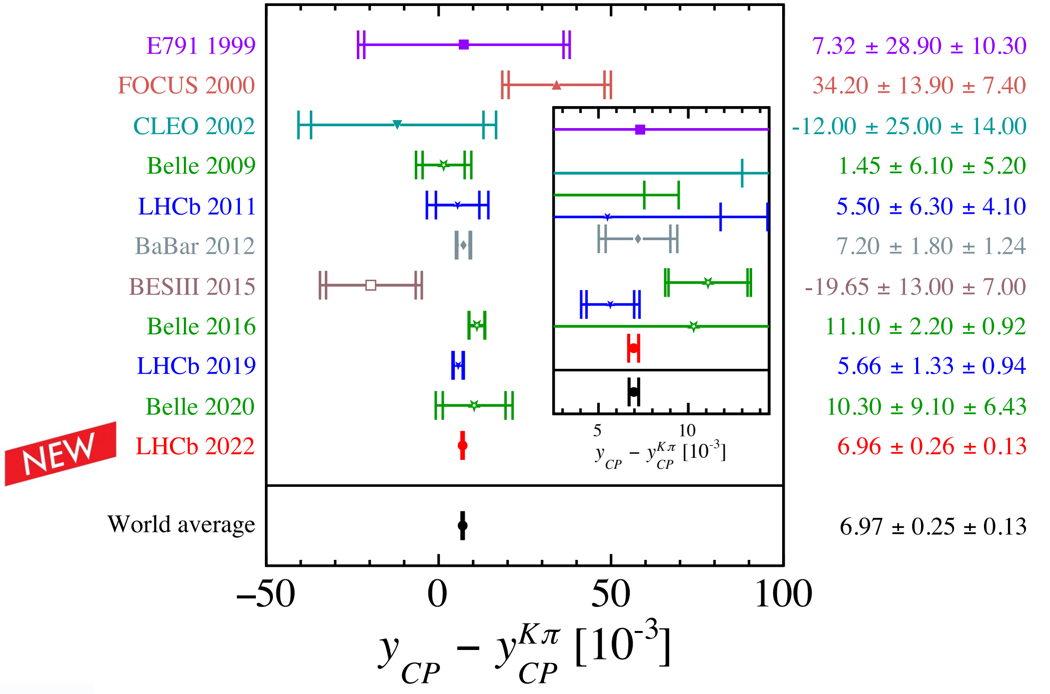

* Note: $y_{CP} - y_{CP}^{K\pi}$ was previously called $y_{CP}$. Term $-y_{CP}^{K\pi} \approx +0.4\times10^{-3}$ was included because of $D^0 \to K^-\pi^+ / D^0 \to K^+\pi^-$ mixing [JHEP03(2022)162].

# Results: largely dominating the world average

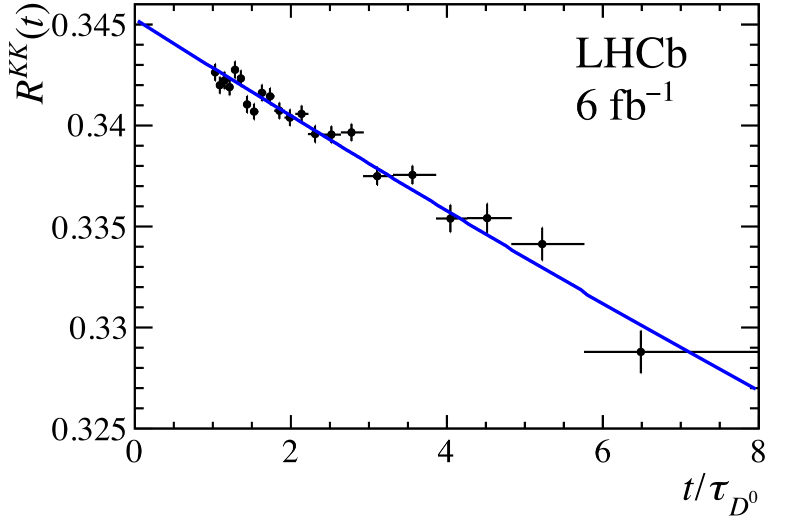
- The measured values are (slope of $R^f(t)$):

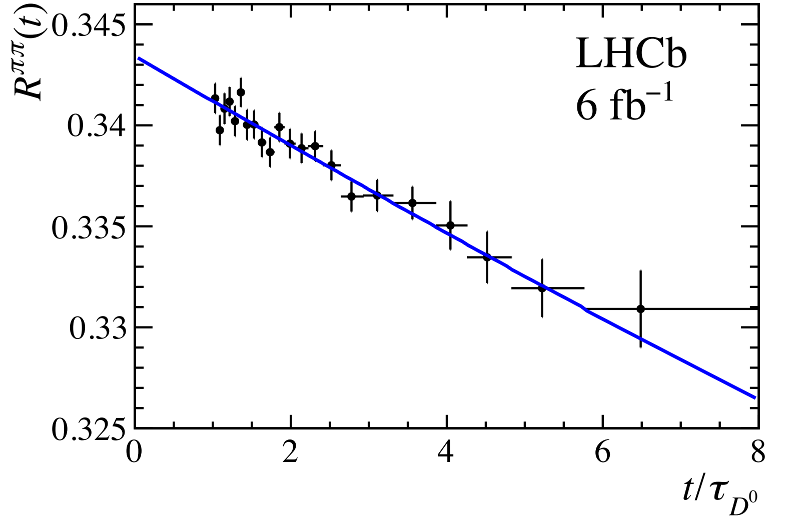
$$y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30_{\text{stat}} \pm 0.14_{\text{sys}})\times 10^{-3}$$
$$y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53_{\text{stat}} \pm 0.16_{\text{sys}})\times 10^{-3}$$

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




Four times more precise than previous world average value!



NEW

# Simultaneous determination of the CKM angle $\gamma$ and parameters related to mixing and CP violation in the charm sector [LHCb-CONF-2022-003]

- Shown in [LHCb-PAPER-2021-033] that a common beauty + charm combination can improve precision on charm mixing and CPV averages.
- Focus on charm results (see Peilian Li's talk at 11:45 for results of $\gamma$).
- New inputs with respect to LHCb-PAPER-2021-033:
    - $\gamma$ in $B^\pm \to D(\to K^\pm\pi^\mp\pi^+\pi^-)h^\pm$ [LHCb-PAPER-2022-017].
    - $\gamma$ in $B^\pm \to D(\to h^\pm h'^\mp\pi^0)h^\pm$ [JHEP 07 (2022) 099].
    - $A_{CP}(KK)$ in $D^0 \to K^-K^+$ [LHCb-PAPER-2022-024]. $A_{CP}$ new to combination.
    - $y_{CP} - y_{CP}^{K\pi}$ in $D^0 \to h^-h'^+$ [Phys. Rev. D 105, 092013].
    - $x_{CP}, y_{CP}, \Delta x, \Delta y$ in $D^0 \to K_S^0\pi^+\pi^-$ [LHCb-PAPER-2022-020].
- New external constraints:
    - CP-even fraction $F^+$ in $D^0 \to \pi^+\pi^-\pi^+\pi^-$ from BESIII [arXiv:2208.10098].
    - Two independent measurements of strong phase difference $\delta_D^{K\pi}$ between $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$ from CLEO [Phys. Rev. D 86 (2012) 112001] and BESIII [arXiv:2208.09402].

LHCb

LHCb-CONF-2022-003
October 7, 2022

**Simultaneous determination of the CKM angle $\gamma$ and parameters related to mixing and *CP* violation in the charm sector**

LHCb collaboration†

**Abstract**

A combination of measurements sensitive to the *CP* violation angle $\gamma$ of the Cabibbo–Kobayashi–Maskawa unitarity triangle, to the charm mixing parameters that describe oscillations between $D^0$ and $\overline{D}^0$ mesons, and to *CP* asymmetries in the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays is performed. All relevant beauty and charm results obtained with the data collected with the LHCb detector at CERN's Large Hadron Collider to date are included. The charm mixing parameters are determined to be $x = (0.398\,^{+0.050}_{-0.049})\%$ and $y = (0.636\,^{+0.020}_{-0.019})\%$, while the *CP* asymmetries in the decay are determined to be $a^{\mathrm{d}}_{K^+K^-} = (9.0 \pm 5.7) \times 10^{-4}$ and $a^{\mathrm{d}}_{\pi^+\pi^-} = (24.0 \pm 6.2) \times 10^{-4}$, with a correlation of $\rho = 0.88$. The angle $\gamma$ is found to be $\gamma = (63.8\,^{+3.5}_{-3.7})^\circ$ and is the most precise determination from a single experiment.



†LHCb Implications Workshop, CERN, 19–21 October 2022. Contact authors: Matthew Kenzie, matthew.william.kenzie@cern.ch, Tommaso Pajero, tommaso.pajero@cern.ch, Mark Whitehead, mark.peter.whitehead@cern.ch.

# New charm combinations

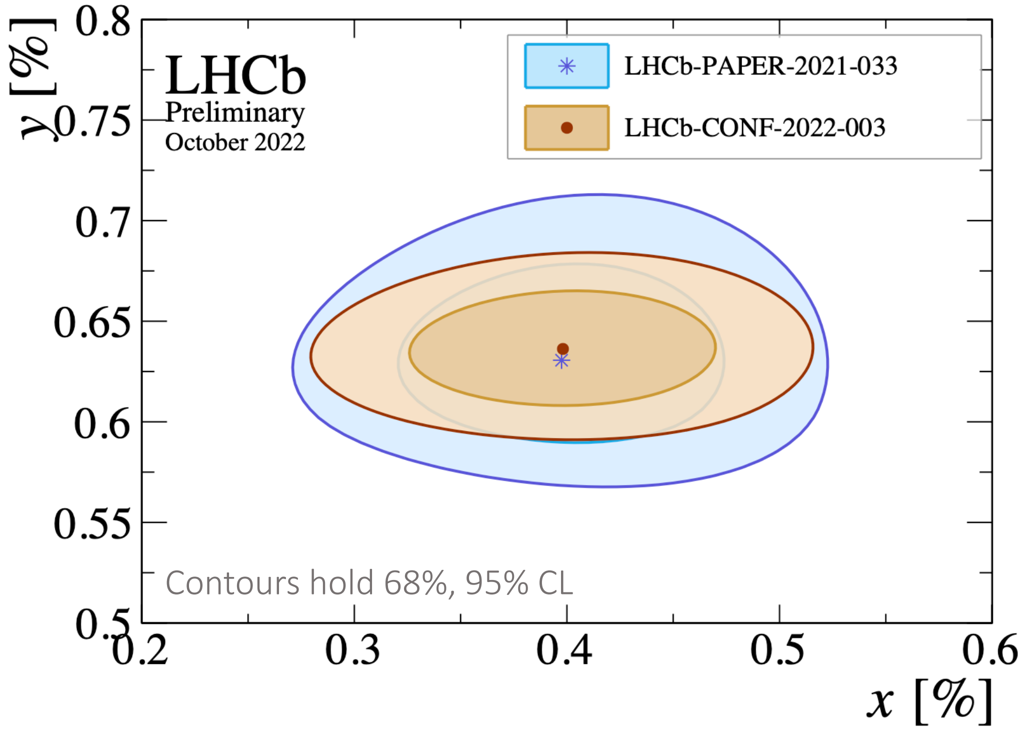
- With respect to LHCb-PAPER-2021-033, improvement of $y$ by 40%, thanks to new measurement of $y_{CP} - y_{CP}^{K\pi}$.
- $\delta_D^{K\pi} \neq 180°$ at $3.6\sigma$ → Evidence of U-spin symmetry breaking.

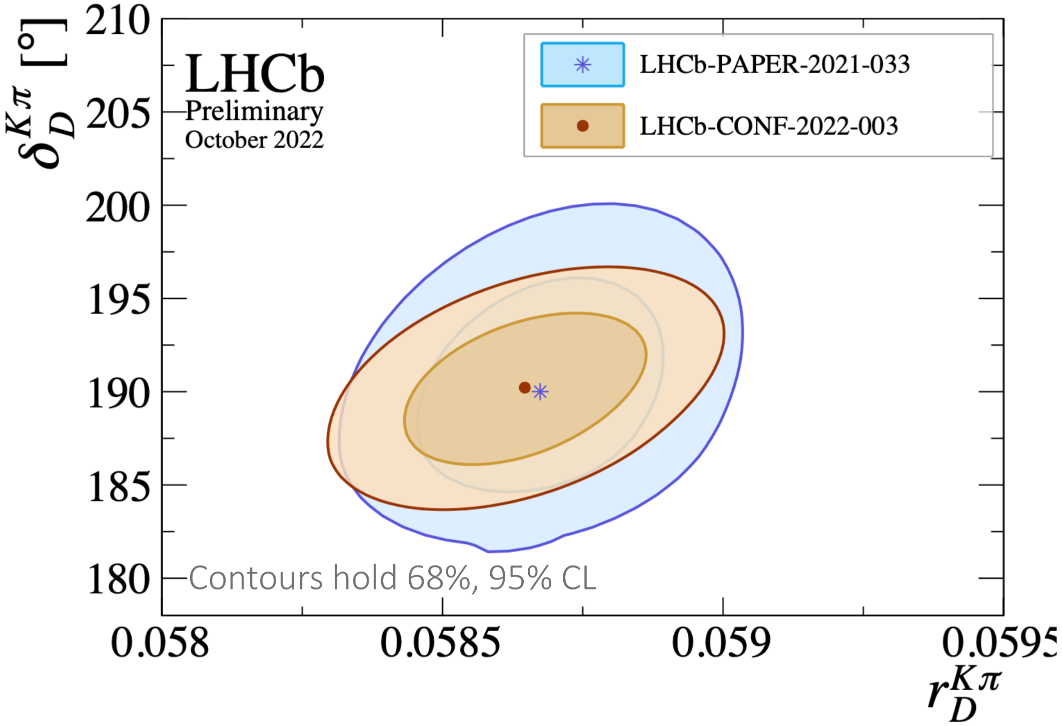
$$x = \left(0.398^{+0.050}_{-0.049}\right)\%$$

$$y = \left(0.636^{+0.020}_{-0.019}\right)\%$$

$$r_D^{K\pi} = \frac{\mathcal{B}(D^0 \to K^+\pi^-, t=0)}{\mathcal{B}(D^0 \to K^-\pi^+, t=0)} = \left(5.865^{+0.014}_{-0.015}\right)\%$$

$$\delta_D^{K\pi} = (190.2 \pm 2.8)°$$



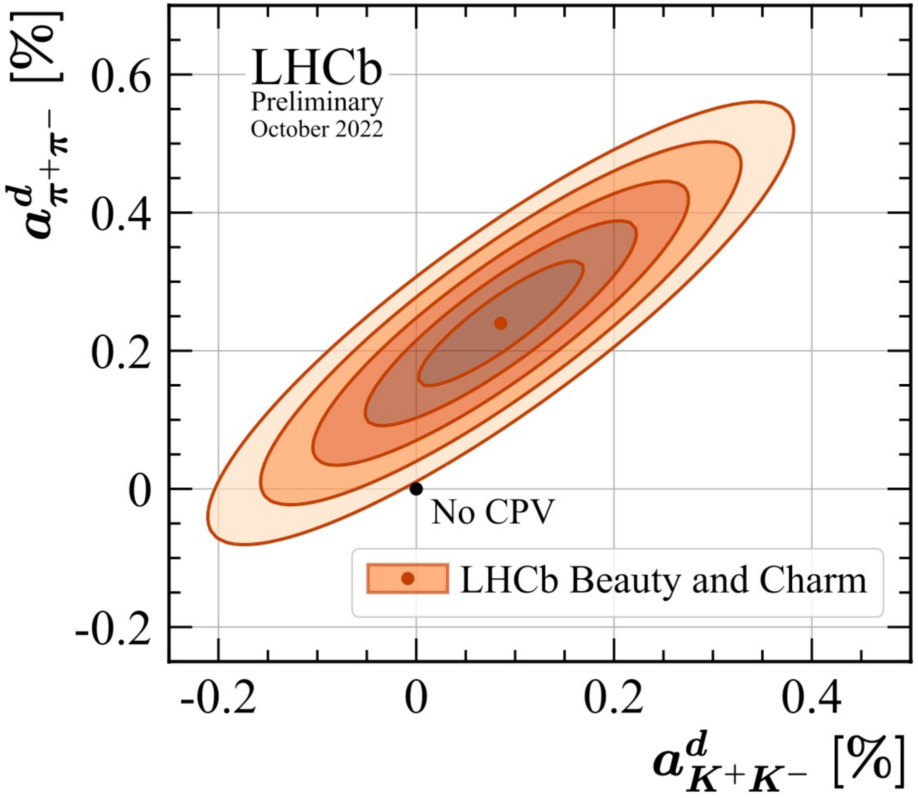



# New charm combinations

[LHCb-CONF-2022-003]

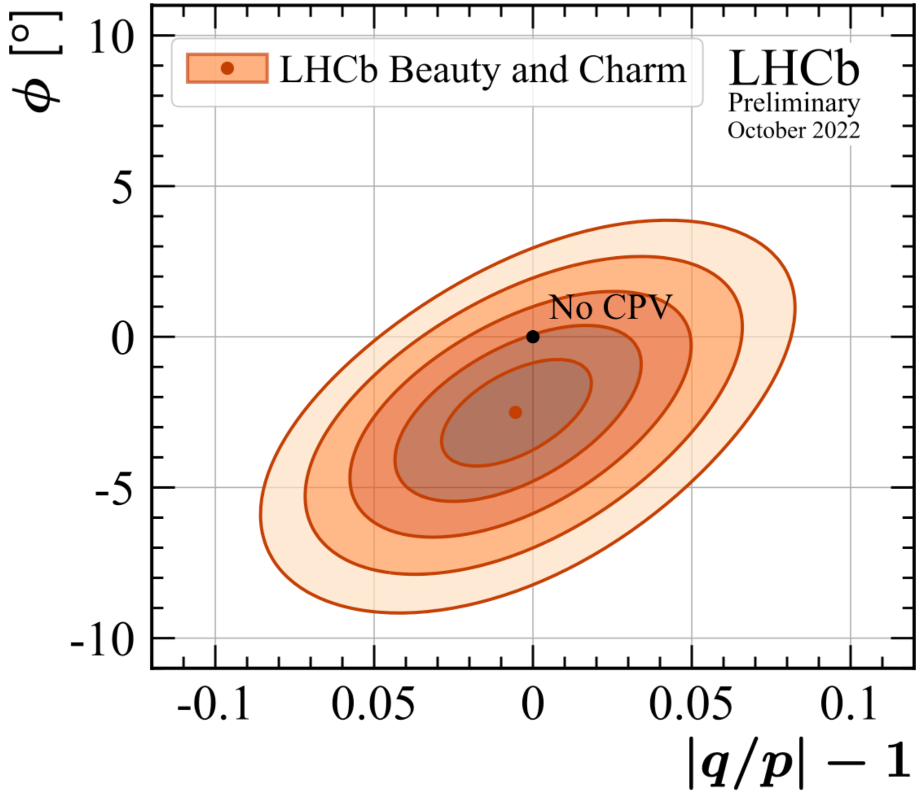
## Direct CPV

$$a^d_{K^+K^-} = (9.0 \pm 5.7)\times10^{-4}$$
$$a^d_{\pi^+\pi^-} = (24.0^{+6.1}_{-6.2})\times10^{-4}$$




## Indirect CPV

$$\phi = (-2.5 \pm 1.2)^\circ$$
$$|q/p| = 0.995^{+0.015}_{-0.016}$$

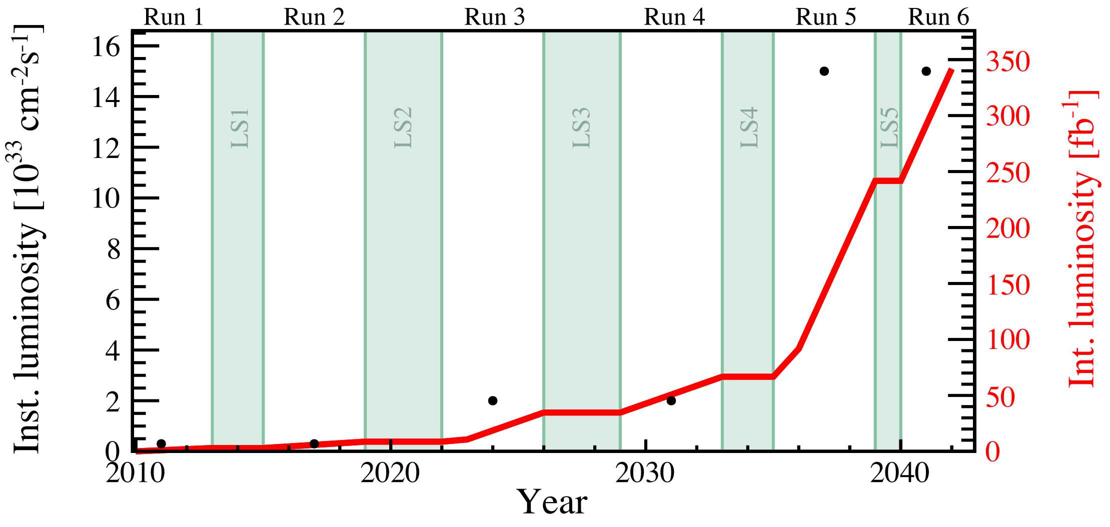





*Charm only results almost indistinguishable

# Prospects

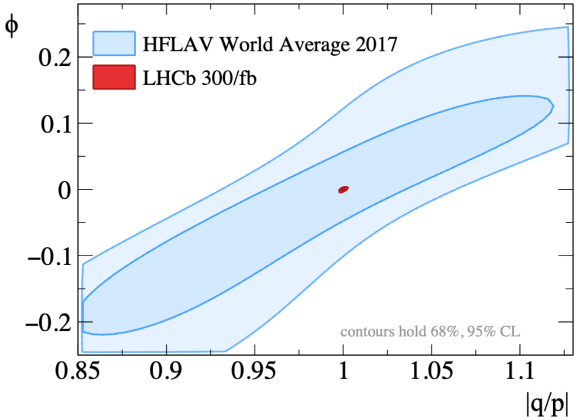
- What's in the oven (among many other things) with Run 1/2?
  - Many searches of CPV in multi-body modes.
  - Charm mixing parameters from RS/WS $D^0 \to K\pi$ ratio with Run 2 data.




$A_\Gamma$ ($\Delta Y$): will be able to test SM prediction at $\mathcal{O}(2 \times 10^{-5})$

Kagan & Silvestrini 2020
Li, Umeeda, Xu, Yu 2020

| Sample ($\mathcal{L}$) | Tag | Yield $K^+K^-$ | $\sigma(A_\Gamma)$ | Yield $\pi^+\pi^-$ | $\sigma(A_\Gamma)$ |
|---|---|---|---|---|---|
| Run 1–2 (9 fb$^{-1}$) | Prompt | 60M | 0.013% | 18M | 0.024% |
| Run 1–3 (23 fb$^{-1}$) | Prompt | 310M | 0.0056% | 92M | 0.0104 % |
| Run 1–4 (50 fb$^{-1}$) | Prompt | 793M | 0.0035% | 236M | 0.0065 % |
| Run 1–5 (300 fb$^{-1}$) | Prompt | 5.3G | 0.0014% | 1.6G | 0.0025 % |




Expectated sensitivities for Run 5 (300fb$^{-1}$):
$\sigma(\phi) \sim 0.1°$ (now 1.2°)
$\sigma(|q/p|) \sim 0.001$ (now 0.015)

[arXiv:1808.08865]

# Framework for charm $A_{CP}$ results

- All the LHCb $A_{CP}$ measurements use the same detector → many instrumental uncertainties are correlated (for instance uncertainty on $A_{det}(K\pi)$).
- Often hard for theorists to assess the correlations between the LHCb measurements.
- NEW PROJECT, create a public LHCb webpage with:
    1. Global covariance matrices.
    2. evaluate "experimentally clean", yet motivated, observables.
- Will be constantly updated!
- Open to hear wishes from theorists concerning what to include in the framework.

*Forging the combination*

*to rule them all*

# Conclusion

- Charm physics: huge datasets with often low background pollution → ideal laboratory to test and implement novel data analysis methods!
  → We improve significantly previous analyses and perform measurements we thought were not possible!

- Challenging measurement of $A_{CP}(KK)$ has been performed with Run 2
  → First evidence of CP violation in $D^0 \to \pi^-\pi^+$ decays at $3.8\sigma$!

- We are working hard to finalise other charm measurements with the full Run 2 dataset.

- All results are limited by statistics: room for improvement in the next data-taking periods.

**Stay Tuned!**

# BACKUP

# Systematic uncertainties

Measurement of the time-integrated CP asymmetry in $D^0 \to K^- K^+$ decays [LHCb-PAPER-2022-024]

| Source | $C_D^+$ $[10^{-4}]$ | $C_{Ds}^+$ $[10^{-4}]$ | Corr. |
|---|---|---|---|
| Fit model | 1.1 | 1.0 | 0.05 |
| Peaking backgrounds | 0.3 | 0.4 | 0.74 |
| Secondary decays | 0.6 | 0.3 | – |
| Kinematic weighting | 0.8 | 0.4 | – |
| Neutral kaon asymmetry | 0.6 | 1.3 | 1.00 |
| Charged kaon asymmetry | – | 1.0 | – |
| Total | 1.6 | 2.0 | 0.28 |

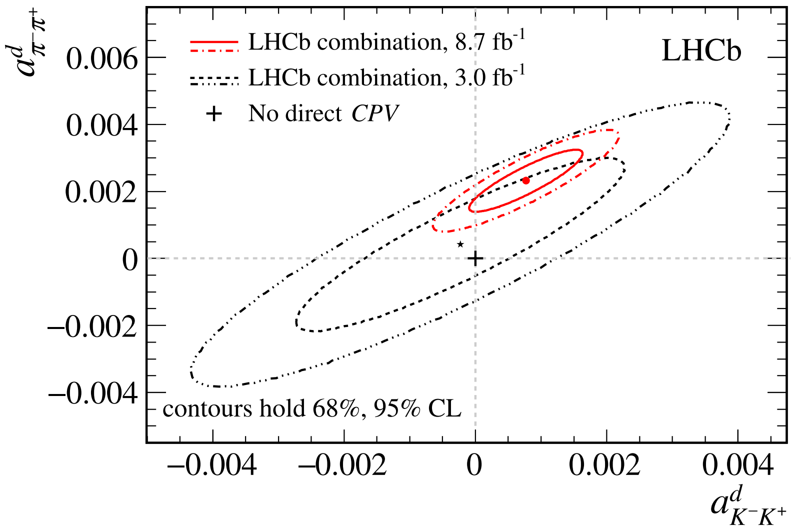
Model-independent measurement of charm mixing parameters in $\bar{B} \to D^0(\to K_S^0 \pi^+ \pi^-)\mu^- \bar{\nu}_\mu X$ decays [LHCb-PAPER-2022-020]
accepted for publication by PRD

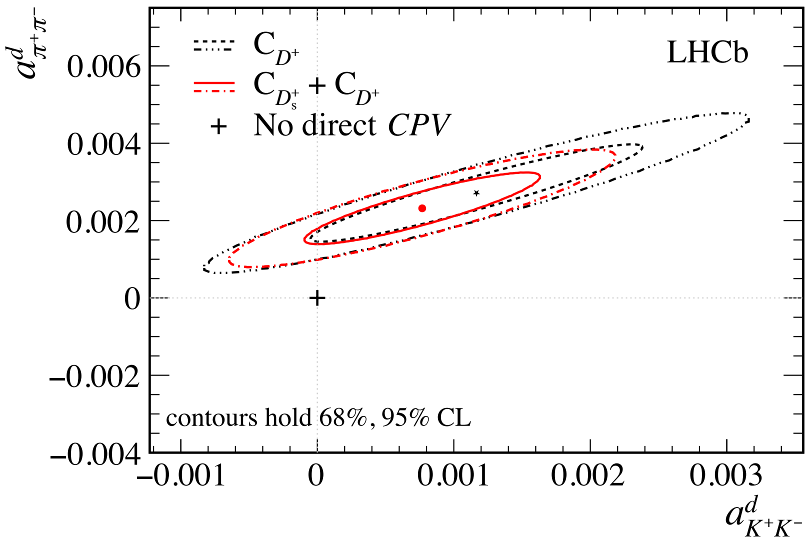
| Source | $x_{CP}$ $[10^{-3}]$ | $y_{CP}$ $[10^{-3}]$ | $\Delta x$ $[10^{-3}]$ | $\Delta y$ $[10^{-3}]$ |
|---|---|---|---|---|
| Reconstruction and selection | 0.06 | 0.79 | 0.28 | 0.24 |
| Detection asymmetry | 0.06 | 0.03 | 0.01 | 0.09 |
| Mass-fit model | 0.03 | 0.09 | 0.01 | 0.01 |
| Unrelated $D^0\mu$ combinations | 0.24 | 0.22 | 0.01 | 0.05 |
| Total systematic | 0.26 | 0.83 | 0.28 | 0.26 |
| Strong phase inputs | 0.32 | 0.68 | 0.16 | 0.21 |
| Statistical (w/o phase inputs) | 1.45 | 3.04 | 0.92 | 1.91 |
| Statistical | 1.48 | 3.12 | 0.93 | 1.92 |

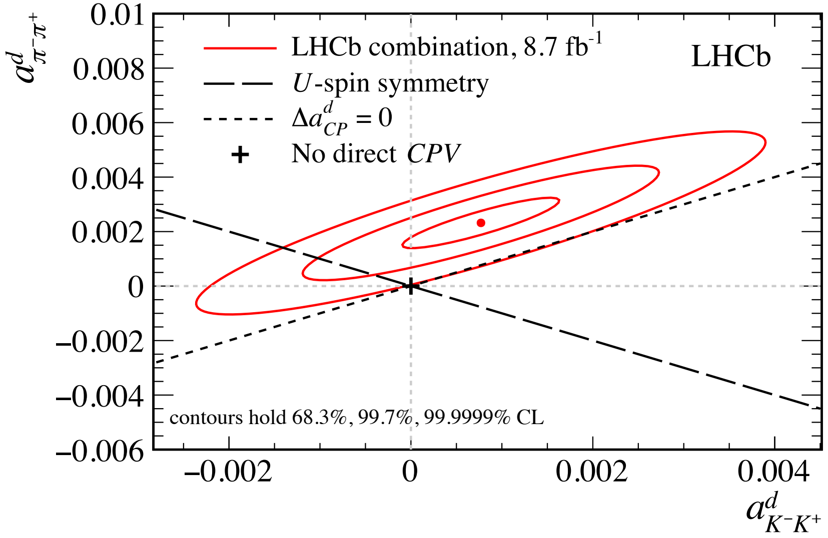
Measurement of the charm mixing parameter $y_{CP} - y_{CP}^{K\pi}$ using two-body $D^0$ decays [Phys. Rev. D 105, 092013]

| | $\sigma(y_{CP}^{\pi\pi} - y_{CP}^{K\pi})$ $[10^{-3}]$ | $\sigma(y_{CP}^{KK} - y_{CP}^{K\pi})$ $[10^{-3}]$ |
|---|---|---|
| Combinatorial background | 0.12 | 0.07 |
| Peaking background | 0.02 | 0.11 |
| Treatment of secondary decays | 0.03 | 0.03 |
| Kinematic weighting procedure | 0.08 | 0.02 |
| Input $D^0$ lifetime | 0.03 | 0.03 |
| Residual nuisance asymmetries | 0.03 | $< 0.01$ |
| Fit bias | 0.03 | 0.03 |
| Total | 0.16 | 0.14 |

# Measurement of the time-integrated CP asymmetry in $D^0 \to K^- K^+$ decays [LHCb-PAPER-2022-024]



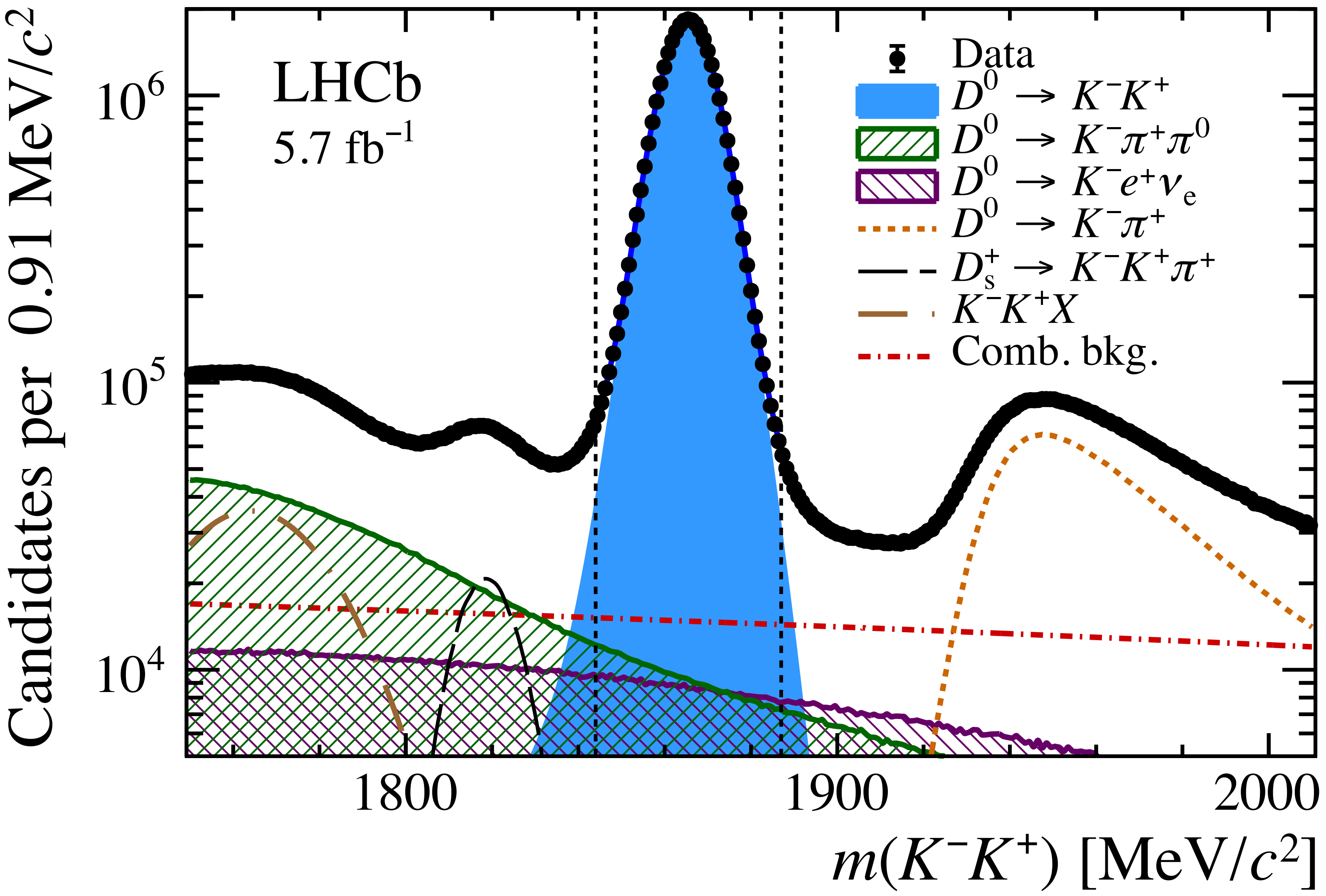



# $A_{CP}(KK)$: Signal yields

Table 1: Signal yields and statistical reduction factors arising from the kinematic weighting of the sample for the various decay modes and both calibration procedures.

| Decay mode | Signal yield $[10^6]$ | | Red. factor | |
|---|---|---|---|---|
| | $C_{D^+}$ | $C_{D_s^+}$ | $C_{D^+}$ | $C_{D_s^+}$ |
| $D^0 \to K^- K^+$ | 37 | 37 | 0.75 | 0.75 |
| $D^0 \to K^- \pi^+$ | 58 | 56 | 0.35 | 0.75 |
| $D^+ \to K^- \pi^+ \pi^+$ | 188 | – | 0.25 | – |
| $D^+ \to \overline{K}^0 \pi^+$ | 6 | – | 0.25 | – |
| $D_s^+ \to \phi \pi^+$ | – | 43 | – | 0.55 |
| $D_s^+ \to \overline{K}^0 K^+$ | – | 5 | – | 0.70 |

# $A_{CP}(KK)$: background contributions



# $A_{CP}(KK)$: neutral kaon detection asymmetry

[JHEP 07 (2014) 041]

## Neutral kaon asymmetry

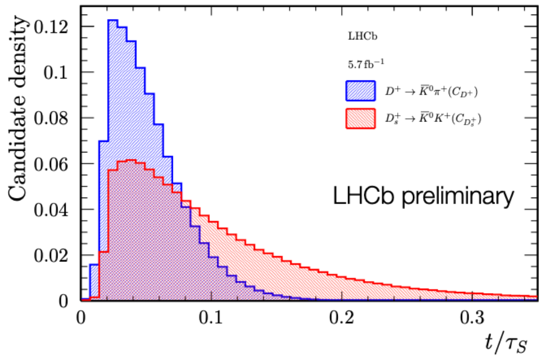
- Different interaction cross-sections of $K^0$ and $\bar{K}^0$ mesons with matter, including effects due to mixing and CPV induce an asymmetry.
- Evaluated for each sample with a $K_S$ in the final state using LHCb material map from simulation (Si,Al,vacuum), neutral-kaon cross-sections, forward scattering phase, mixing and CPV.

$A(\bar{K}^0)$

$D^+ \to K_S \pi^+$ : [ -5.1 ± 0.6 (syst) ] x$10^{-4}$

$D_s^+ \to K_S K^+$ : [ -8.5 ± 1.3 (syst) ] x$10^{-4}$

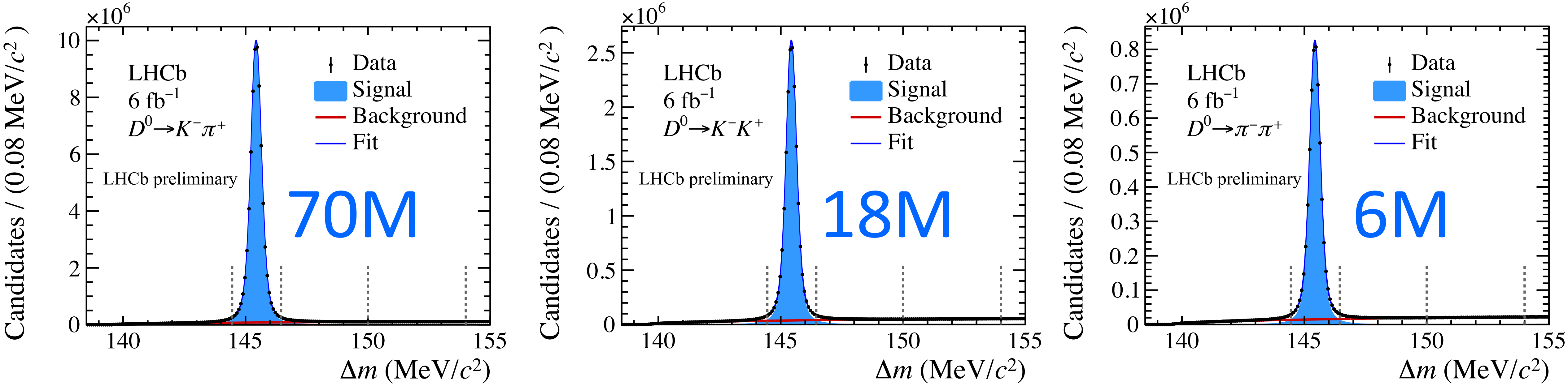
**data driven approach using $K_S$ control sample**




Serena Maccolini — Direct CPV in charm — 7 July 2022 — 22

# $y_{CP} - y_{CP}^{K\pi}$ signal selection: High yields, high purity, unbiased

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

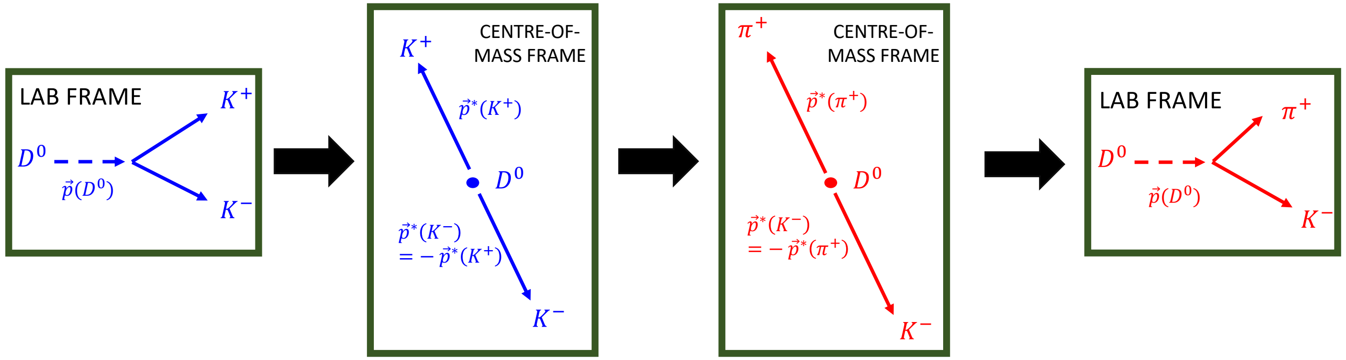


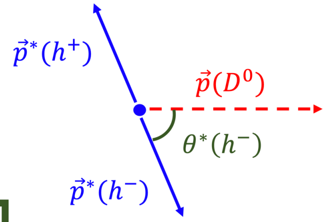
# $y_{CP}^{f} - y_{CP}^{K\pi}$: correction strategy

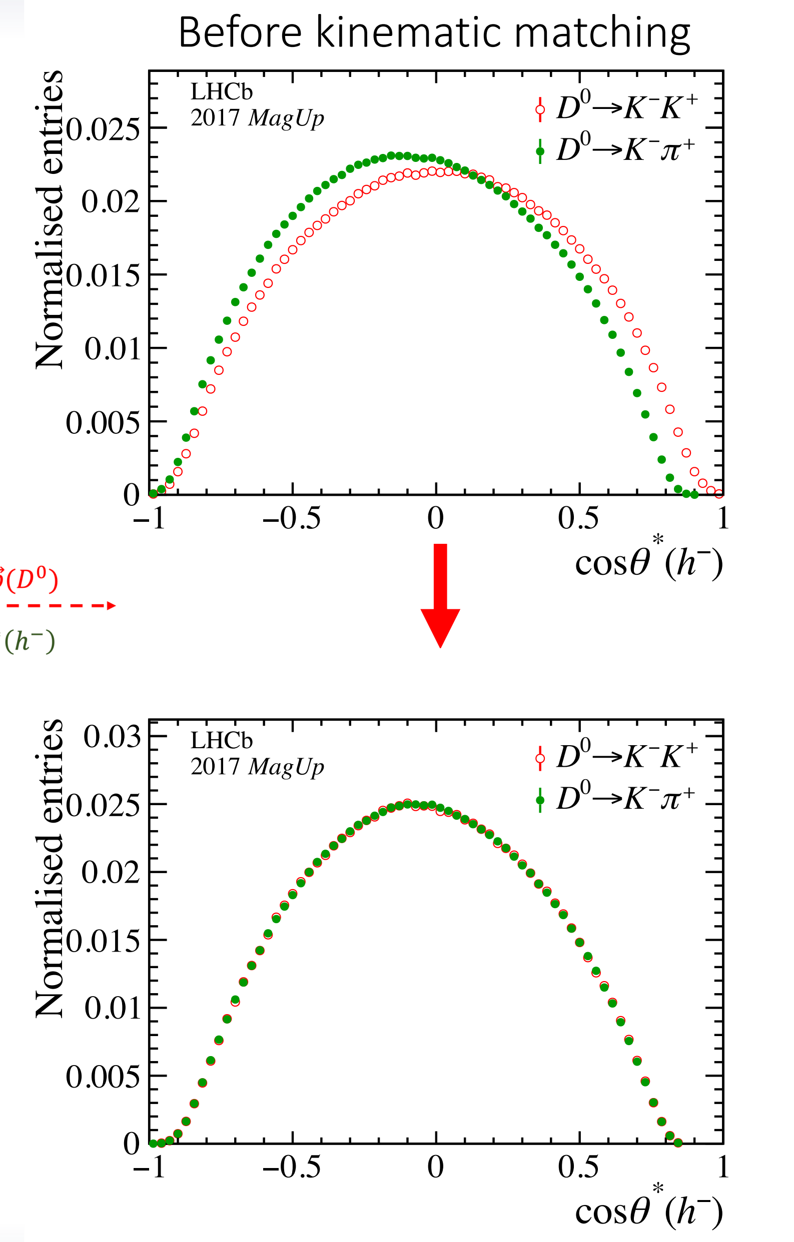
- Trigger requirements (on $p, p_T, \eta$…) are applied to two distinct final states ($K^-\pi^+$ and $K^-K^+$):

  → Unequal time-dependent efficiency profiles (biasing $R^f(t)$)!

- *Kinematic matching*: match the kinematics of each candidate of $D^0 \to K^-K^+$ to the ones of $D^0 \to K^-\pi^+$.




- Both decay modes now have the same efficiency profiles (e.g. equal kinematic distributions)!

# Measurement of CP asymmetries in $D_{(s)}^{+} \to \eta\pi^{+}$ and $D_{(s)}^{+} \to \eta'\pi^{+}$ decays [arXiv:2204.12228]

# Measurement of CP asymmetries in $D^+_{(s)} \to \eta\pi^+$ and $D^+_{(s)} \to \eta'\pi^+$ decays [arXiv:2204.12228]

- Direct access to CP asymmetries prevented by nuisance asymmetries:

$$A\left(D^+_{(s)} \to \eta^{(\prime)}\pi^+\right) = A_{CP}\left(D^+_{(s)} \to \eta^{(\prime)}\pi^+\right) + A_P(D^{*+}) + A_D\left(\eta^{(\prime)}\pi^+\right)$$

- Production and detection asymmetries are subtracted using the $D^+_{(s)} \to \phi\pi^+$ control channels:

$$A\left(D^+ \to \eta^{(\prime)}\pi^+\right) - A(D^+ \to \phi\pi^+) = A^{CP}\left(D^+ \to \eta^{(\prime)}\pi^+\right) - A^{CP}(D^+ \to \phi\pi^+)$$
$$A\left(D^+_s \to \eta^{(\prime)}\pi^+\right) - A(D^+_s \to \phi\pi^+) = A^{CP}\left(D^+_s \to \eta^{(\prime)}\pi^+\right)$$

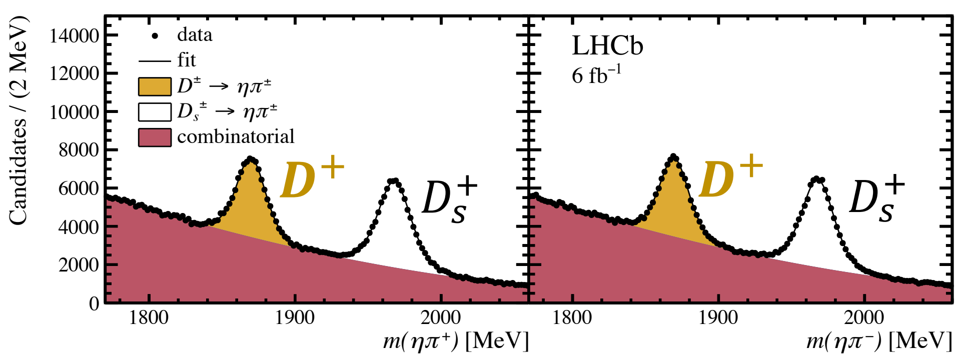
External input $(0.005 \pm 0.051)\%$

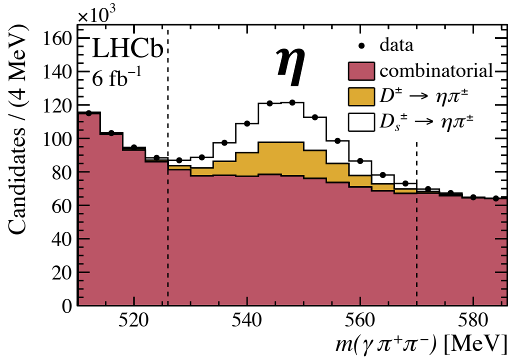
- Kinematic distributions of $D^+_{(s)} \to \phi\pi^+$ weighted to the ones of $D^+_{(s)} \to \eta^{(\prime)}\pi^+$ to cancel out nuisance asymmetries.

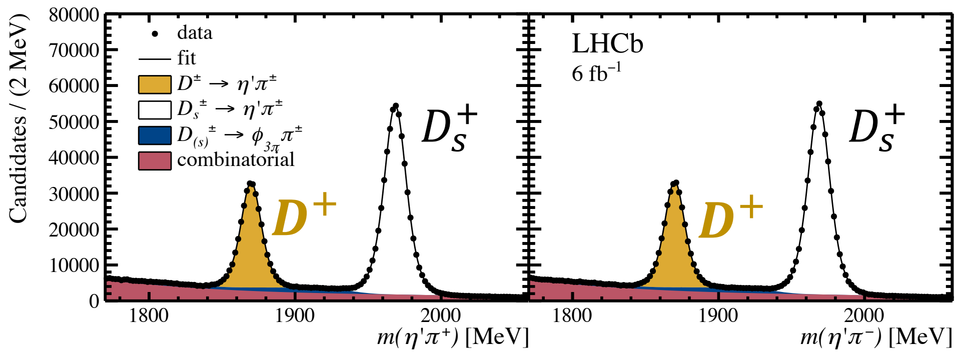
- Dataset: Run 2 (2015-2018, $6\ \mathrm{fb}^{-1}$).

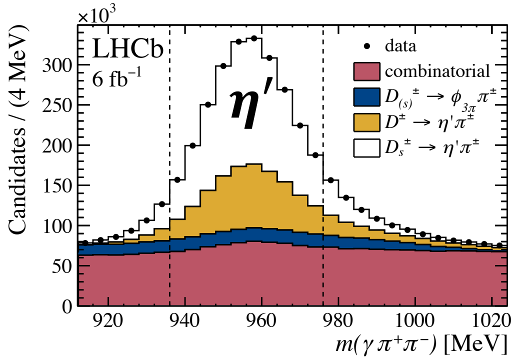
# New important precise asymmetry measurements in these decay channels!

CP asymmetries are obtained from simultaneous fits to $m(\eta^{(\prime)}\pi^{\pm})$ in bins of $m(\gamma\pi^{+}\pi^{-})$.




$A^{CP}(D^{+} \to \eta\pi^{+}) =$
$(0.34 \pm 0.66_{\text{stat}} \pm 0.16_{\text{sys}} \pm 0.05_{\text{ctrl}})\%$ ★

$A^{CP}(D_s^{+} \to \eta\pi^{+}) =$
$(0.32 \pm 0.51_{\text{stat}} \pm 0.11_{\text{sys}})\%$

$A^{CP}(D^{+} \to \eta'\pi^{+}) =$
$(0.49 \pm 0.18_{\text{stat}} \pm 0.06_{\text{sys}} \pm 0.05_{\text{ctrl}})\%$ ★

$A^{CP}(D_s^{+} \to \eta'\pi^{+}) =$
$(0.01 \pm 0.12_{\text{stat}} \pm 0.08_{\text{sys}})\%$ ★

★ These constitute the most precise measurements to date!

No evidence of CP violation.