LHCb charm physics (including *CPV*)

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Charm Physics at LHCb

- Unique probe to study *CPV* in up-type quark.
- Difficult precise theoretical predictions.
- Expected small *CPV* ($\lesssim$0.1%).
- Large cross section: $\sigma(pp \to c\bar{c}X) \approx 2.4\, mb$ $\sigma(pp \to b\bar{b}X) \approx 144\, \mu b$ @ $\sqrt{s} = 13\, TeV$.
  [JHEP 2016, 159 (2016)] [Phys. Rev. Lett. 118, 052002 (2017)]

LHCb charm program:

- Search for direct *CP* violation.
- Search for *CP* violation in mixing.
- Measurement of rare decays.
- Amplitude analysis in multi-body decays.
- Spectroscopy.

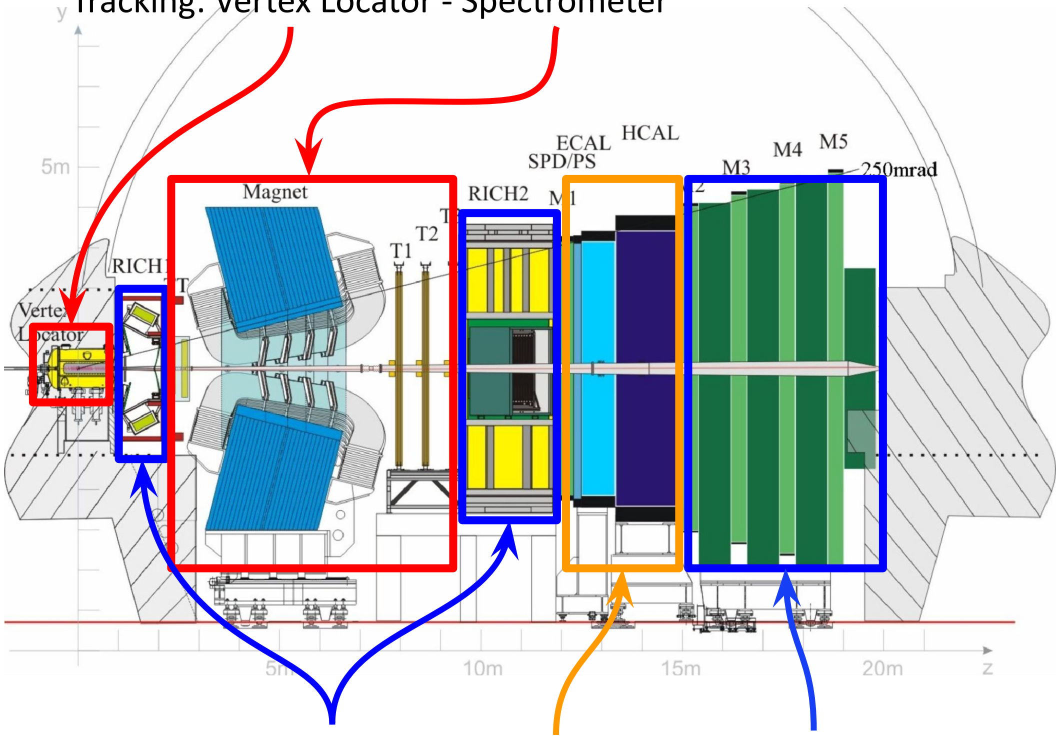
} Arguments of this talk (first three items)

LHCb

[JINST 3 S08005 (2008)]

- Single arm spectrometer
- Vertex Locator (VELO): impact parameter resolution $\sigma(IP) = (15+29/P_T)\mu m$
- Spectrometer: measurement of tracks momentum resolution $\Delta P/P = 0.5\%$ at low momentum
- RICH, calorimeters, muon chambers: particle identification. $\varepsilon_{PID}(K\rightarrow K) \sim 95\%$ and $\varepsilon_{PID}(\pi\rightarrow K) \sim 5\%$.
- Run 1 (2011-2012): 3 fb^{-1} at 7-8 TeV.
- Run 2 (2015-2018): 6 fb^{-1} at 13 TeV.

Tracking: Vertex Locator - Spectrometer



Particle ID: Cherenkov (RICH) - Calorimeters - Muon chambers

Direct CP violation in $D^0 \to K^+K^-$ decays

Direct *CP* violation

- Time-integrated D^0 *CP* asymmetry depends on decay-time acceptance *ε(t)* and is affected by mixing:

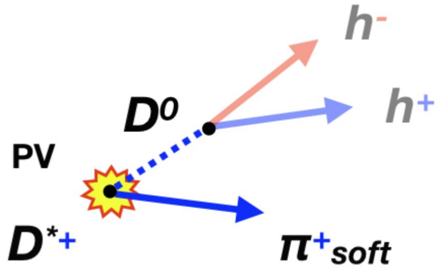
$$A_{CP}(f) = \frac{\int \varepsilon(t)\Gamma(D^0 \to f)dt - \int \varepsilon(t)\Gamma(\bar{D}^0 \to \bar{f})dt}{\int \varepsilon(t)\Gamma(D^0 \to f)dt + \int \varepsilon(t)\Gamma(\bar{D}^0 \to \bar{f})dt} \approx a_f^d + \frac{\langle t \rangle_f}{\tau_{d^0}} \Delta Y_f$$

- 2019 first observation of *CPV* in charm decays [Phys. Rev. Lett. 122, 211803 (2019)]:

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = a_{KK}^d - a_{\pi\pi}^d + \frac{\langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}}{\tau_{D^0}} \Delta Y = (-15.4 \pm 2.9) \times 10^{-4}$$

- a_{KK}^d and $a_{\pi\pi}^d$ measurable combining ΔA_{CP} and $A_{CP}(D^0 \to K^+K^-)$.
- LHCb measured $A_{CP}(D^0 \to K^+K^-) = (4 \pm 12 \pm 10) \times 10^{-4}$ with Run 1 data [Phys.Lett. B 767 (2017)]
- Updated measurement of $A_{CP}(D^0 \to K^+K^-)$ with Run 2 dataset [LHCB-PAPER-2022-024 (2022)] in preparation

CP asymmetry in $D^0 \to K^+K^-$



- D^0 flavor tagged from prompt $D^{*\pm} \to \overset{(-)}{D^0} \pi^{\pm}_{soft}$ decays (π-tagging).
- Measure raw asymmetry:

$$A(D^0 \to K^+K^-) = \frac{N(D^0 \to K^+K^-) - N(\bar{D}^0 \to K^+K^-)}{N(D^0 \to K^+K^-) + N(\bar{D}^0 \to K^+K^-)}$$

- Subtract production and detection asymmetries:

$$A(D^0 \to K^+K^-) = A_{CP}(D^0 \to K^+K^-) + A_{prod}(D^0) + A_{det}(\pi^{\pm}_{soft})$$

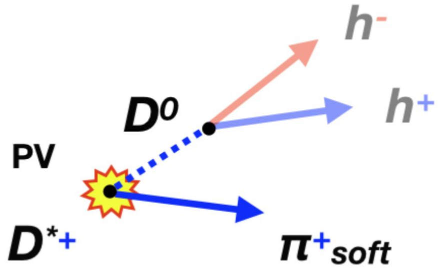
exploiting high-statistics $D^{\pm}$ and $D^{\pm}_s$ decays

C_{D+}:

$$A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+_{soft})$$
$$+A(D^+ \to K^-\pi^+\pi^+) - \left[A(D^+ \to \overline{K}^0\,\pi^+) - A(\overline{K}^0)\right]$$

- Particles kinematics are equalised with a reweighting procedure.

CP asymmetry in $D^0 \rightarrow K^+K^-$



- D^0 flavor tagged from prompt $D^{*\pm} \rightarrow \overset{(-)}{D}{}^0 \pi^{\pm}_{soft}$ decays (π-tagging).
- Measure raw asymmetry:

$$A(D^0 \rightarrow K^+K^-) = \frac{N(D^0 \rightarrow K^+K^-) - N(\bar{D}^0 \rightarrow K^+K^-)}{N(D^0 \rightarrow K^+K^-) + N(\bar{D}^0 \rightarrow K^+K^-)}$$

- Subtract production and detection asymmetries:

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exploiting high-statistics $D^{\pm}$ and $D^{\pm}_s$ decays

C_{Ds+}: $$A_{CP}(D^0 \rightarrow K^-K^+) = +A(D^{*+} \rightarrow (D^0 \rightarrow K^-K^+)\,\pi^+_{soft}) - A(D^{*+} \rightarrow (D^0 \rightarrow K^-\pi^+)\,\pi^+_{soft}) + A(D_s^+ \rightarrow \phi\pi^+) - \left[A(D_s^+ \rightarrow \overline{K}^0\, K^+) - A(\overline{K}^0)\right]$$

- Particles kinematics are equalised with a reweighting procedure.

CP asymmetry in $D^0 \rightarrow K^+K^-$

[LHCB-PAPER-2022-024 (2022)]

- Combining the result obtained with the two control modes:

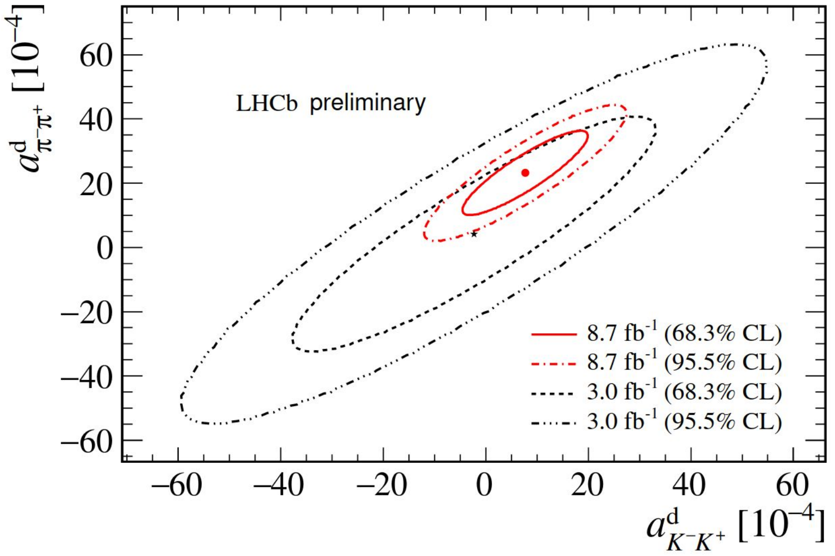
$$A_{CP}(D^0 \rightarrow K^+K^-) = (6.8 \pm 5.4 \pm 1.6) \times 10^{-4}$$

more than twice times more precise than Run 1 measurement.

- From combination with Run 1, ΔA_{CP}, and ΔY measurements:

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

first evidence of direct CP violation in $D^0 \rightarrow \pi^+\pi^-$ decays (3.8 σ).



CP violation in mixing

CP violation in mixing

- Oscillation between $D^0 - \bar{D}^0$ mesons can be described by:

$$x = (m_1 - m_2)c^2/\Gamma \quad y = (\Gamma_1 - \Gamma_2)/\Gamma$$

- With mass eigenstates $|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\bar{D}^0\rangle$.
- *CP* is violated if: $\left|\frac{q}{p}\right| \neq 1$ or $\phi \equiv arg\left(\frac{q\bar{A}}{pA}\right) \neq 0$

- LHCb observed *x > 0* in π-tagged $D^0 \to K^0_S\pi^+\pi^-$ decays [Phys. Rev. Lett. 127, 111801 (2021)]:

$$x = \left(3.98^{+0.56}_{-0.54}\right) \times 10^{-3}$$

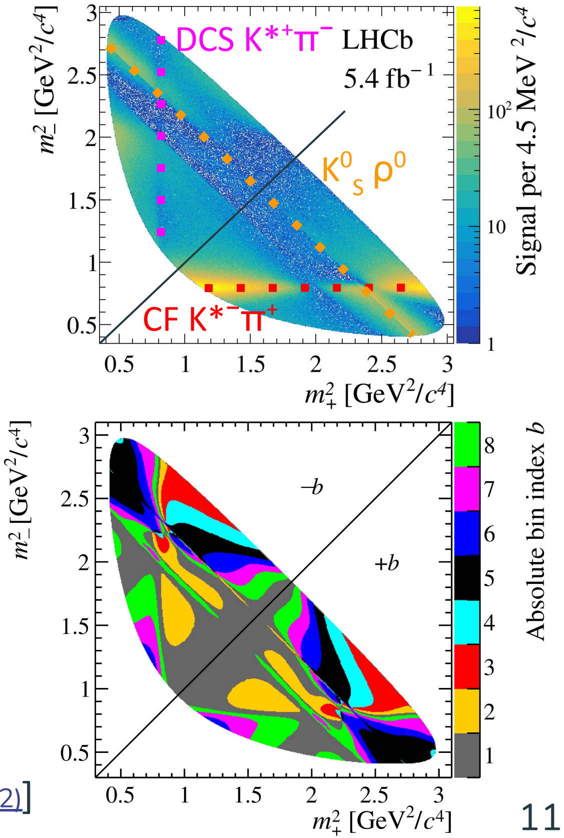
- New measurement with $\bar{B} \to D^0\left(\to K^0_S\pi^+\pi^-\right)\mu^-\bar{\nu}_\mu X$ decays [LHCb-PAPER-2022-020 (2022)].
  - Paper includes also results combination.

- Both analyses use bin-flip method.

Mixing parameters in $D^0 \to K^0_S \pi^+\pi^-$ decays

Bin-flip method [Phys. Rev. D 99, 012007 (2019)]:

- Model independent.
- Sensitive manly to *x* parameter but also to *y*.
- Access to mixing parameters through time-dependent ratio between -b and +b Dalitz bins (10 equipopulated time bins).
- Dalitz bins chosen to have constant strong-phase difference between D^0 and $\bar{D}^0$ (measured by CLEO [Phys. Rev. D 82, 112006 (2010)]).
- Suppresses biases due to non-uniform efficiencies.



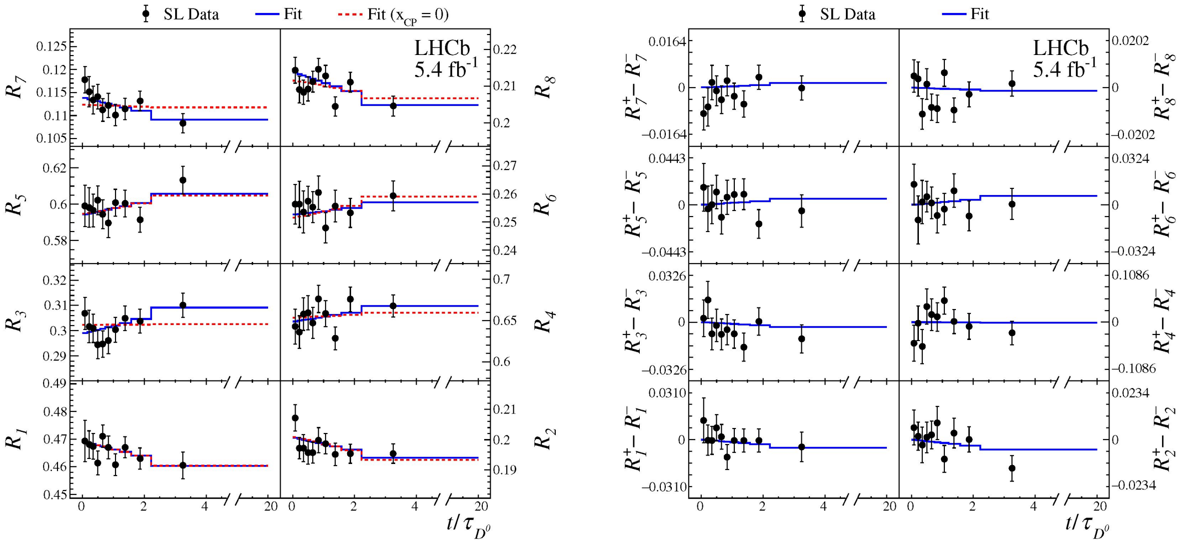
[LHCb-PAPER-2022-020 (2022)]

Mixing parameters in $D^0 \to K^0_S \pi^+\pi^-$ decays

- Fit the ratio of Dalitz bin *b* and time bin *j* with:

$$R^{\pm}_{bj} \approx r_b - \langle t \rangle_j \sqrt{r_b}\left[(1 - r_b)c_b\, y - (1 + r_b)s_b\, x\right]$$

where "+" for D^0 and "−" for $\bar{D}^0$, r_b the ratio of bins, $\langle t \rangle_j$ average decay-time in bin *j*, and c_b and s_b are the strong phase parameters.



[LHCb-PAPER-2022-020 (2022)]

Mixing parameters in $D^0 \to K^0_S \pi^+\pi^-$ decays

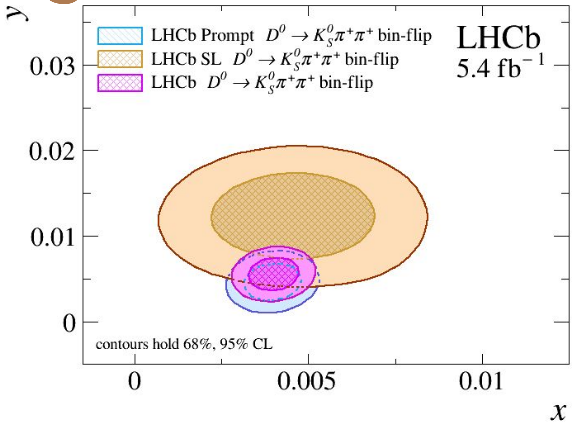
- Results:

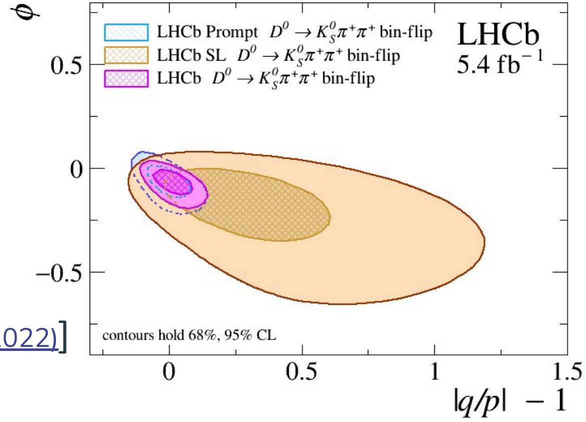
$$x_{CP} = (+\ 4.29 \pm 1.48 \pm 0.26) \times 10^{-3}$$
$$y_{CP} = (+12.61 \pm 3.12 \pm 0.83) \times 10^{-3}$$
$$\Delta x = (-\ 0.77 \pm 0.93 \pm 0.28) \times 10^{-3}$$
$$\Delta y = (+\ 3.01 \pm 1.92 \pm 0.26) \times 10^{-3}$$

Compatible with π-tagged analysis.

- Combining the results:

$$x = (+0.40 \pm 0.05) \times 10^{-2} (8\sigma)$$
$$y = (+0.55 \pm 0.13) \times 10^{-2}$$
$$|q/p| = 1.012^{+0.050}_{-0.048}$$
$$\phi = -0.061^{+0.037}_{-0.044}$$





[LHCb-PAPER-2022-020 (2022)]

Measurement of $y_{CP} - y_{CP}^{K\pi}$

Measurement of $y_{CP} - y_{CP}^{K\pi}$

- Due to mixing, effective decay widths $\hat{\Gamma}$ of Cabibbo suppressed decays is not equal to Γ.
- From the decays rates, we define the observable [JHEP 2022, 162 (2022)]:

$$y_{CP}^{hh} - y_{CP}^{K\pi} \approx \frac{\hat{\Gamma}(D^0 \to h^+h^-) + \hat{\Gamma}(\bar{D}^0 \to h^+h^-)}{\hat{\Gamma}(D^0 \to K^-\pi^+) + \hat{\Gamma}(\bar{D}^0 \to K^+\pi^-)} - 1$$

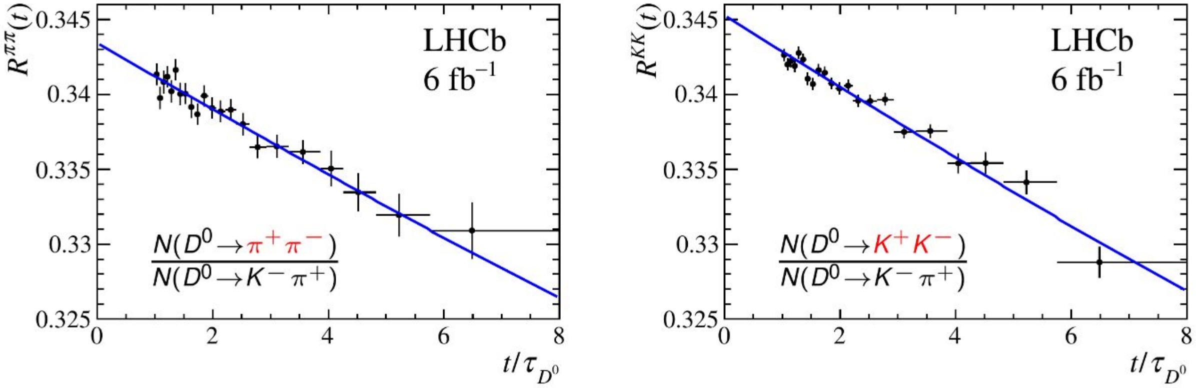
- $y_{CP}^{hh} = y_{12} \approx y$ in absence of *CPV*.
- New measure of $y_{CP} - y_{CP}^{K\pi}$ with π-tagged decays [Phys. Rev. D 105, 092013 (2022)].
- Measure of

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

Combine $y_{CP}^{KK} - y_{CP}^{K\pi}$ and $y_{CP}^{\pi\pi} - y_{CP}^{K\pi}$ in $y_{CP} - y_{CP}^{K\pi}$.

Measurement of $y_{CP} - y_{CP}^{K\pi}$

[Phys. Rev. D 105, 092013 (2022)]



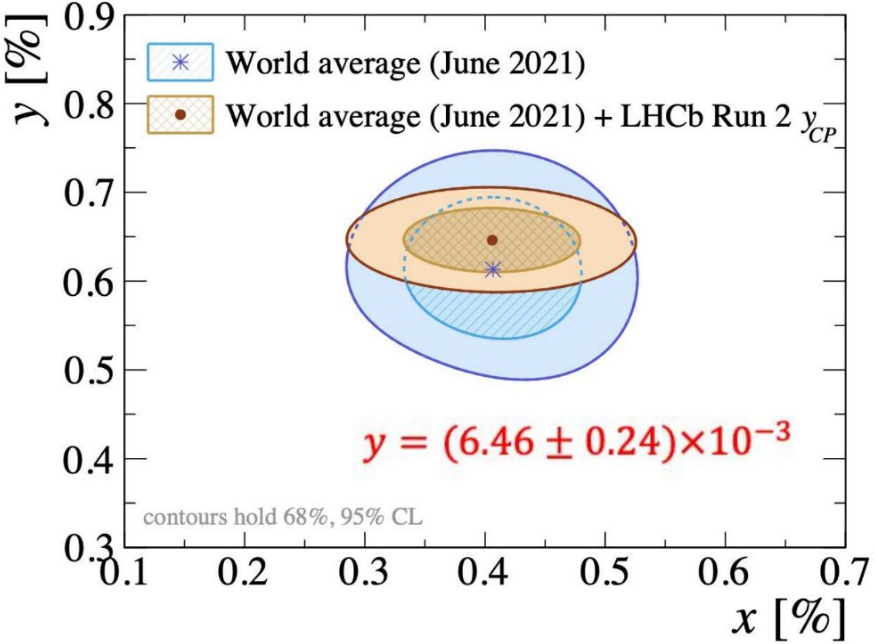
$$\left.\begin{aligned} y_{CP}^{\pi\pi} - y_{CP}^{K\pi} &= (6.57 \pm 0.53 \pm 0.16) \times 10^{-3} \\ y_{CP}^{KK} - y_{CP}^{K\pi} &= (7.08 \pm 0.30 \pm 0.14) \times 10^{-3} \end{aligned}\right\} \Longrightarrow y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$$

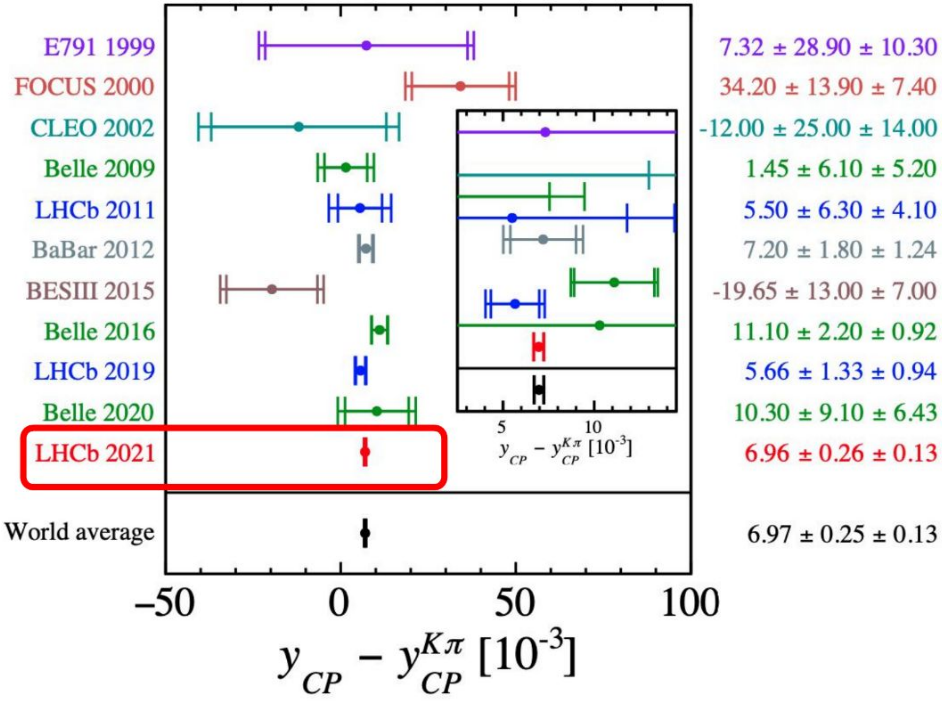
- $y_{CP}^{K\pi} \approx -4 \times 10^{-4}$
- Previous world average: $y_{CP} - y_{CP}^{K\pi} = (7.19 \pm 1.13) \times 10^{-3}$
- 4 times more precise.

Measurement of $y_{CP} - y_{CP}^{K\pi}$

[Phys. Rev. D 105, 092013 (2022)]

- New constrain to world average





Rare decays

$D^0 \to h^+h^-\mu^+\mu^-$ rare decays

- FCNC $c \to ul^+l^-$ transitions sensitive to BSM contribution
  - More suppressed than $b \to sl^+l^-$ due to GIM mechanism.
- 4-body decays have measurable BFs.
  - Measured in 2017 using 2012 data (2 fb^{-1}) [Phys. Rev. Lett. 119, 181805 (2017)].

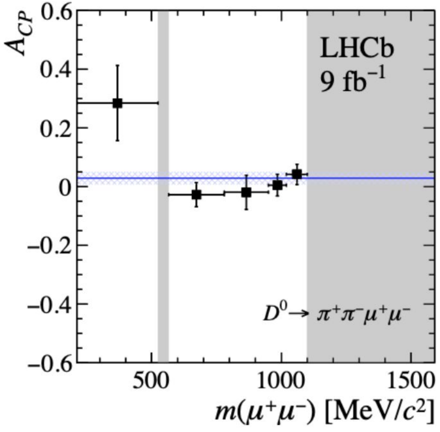
$$\mathcal{B}(D^0 \to \pi^-\pi^+\mu^+\mu^-) \sim 9.6 \times 10^{-7}$$
$$\mathcal{B}(D^0 \to K^-K^+\mu^+\mu^-) \sim 1.5 \times 10^{-7}$$

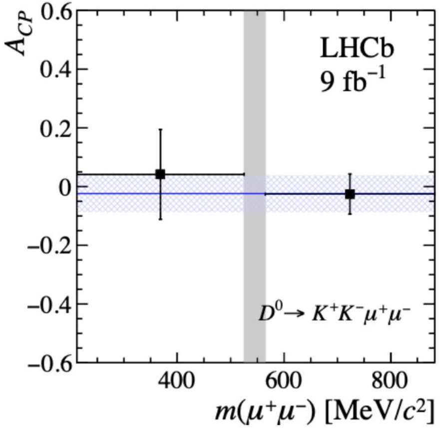
- World's first full angular analysis of a rare decays [Phys. Rev. Lett. 128, 221801 (2022)].
- SM null tests in regions dominated by resonances
  (due to interference between short- and long-distance contributions)

$D^0 \to h^+h^-\mu^+\mu^-$ rare decays

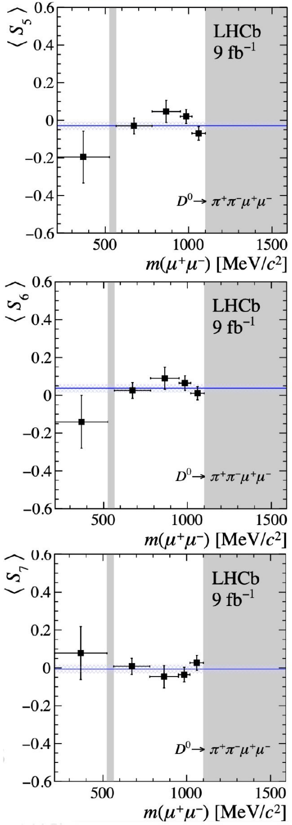
[Phys. Rev. Lett. 128, 221801 (2022)]

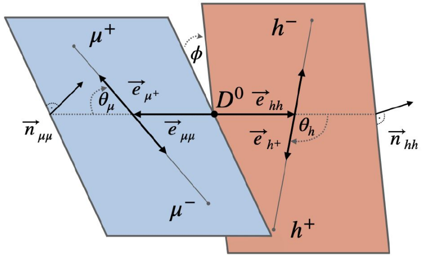
- Measurement of the full set of *CP*-averaged angular observables and *CP* asymmetries as function of $q^2 \equiv m^2(\mu^+\mu^-)$.
- Updated measurement of *CP* asymmetry.
- Results consistent with SM null hypothesis.

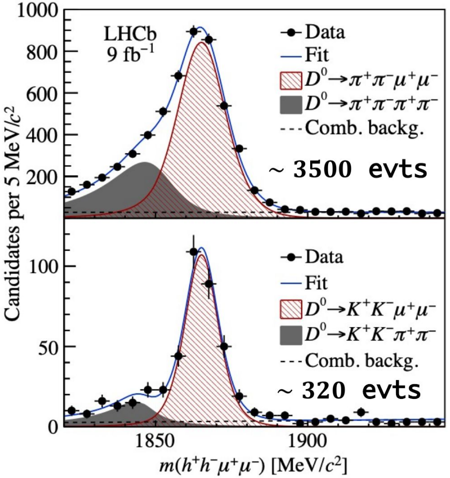




SM null tests







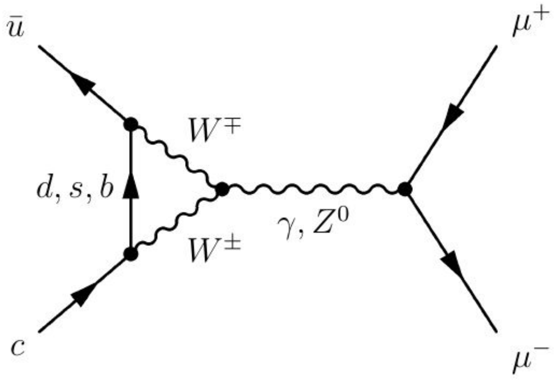
$D^0 \to \mu^+\mu^-$ rare decays

- Very rare decay: FCNC + helicity suppression.
- Lepto-quarks in tree-level.
- SM branching fraction [Phys. Rev. D 93, 074001 (2016)]:
    - Short Distance: $\mathcal{B}(D^0 \to \mu^+\mu^-) \sim 10^{-18}$
    - Long Distance: $\mathcal{B}(D^0 \to \mu^+\mu^-) \sim 10^{-11}$
- Current upper limit (1 fb^{-1}) [Phys. Lett. B 725. 15-24 (2013)]:

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9} \,@\, 90\%\, CL$$

- New upper limit with Run 1 + Run 2 π-tagged data [LHCB-PAPER-2022-029 (2022)].

in preparation



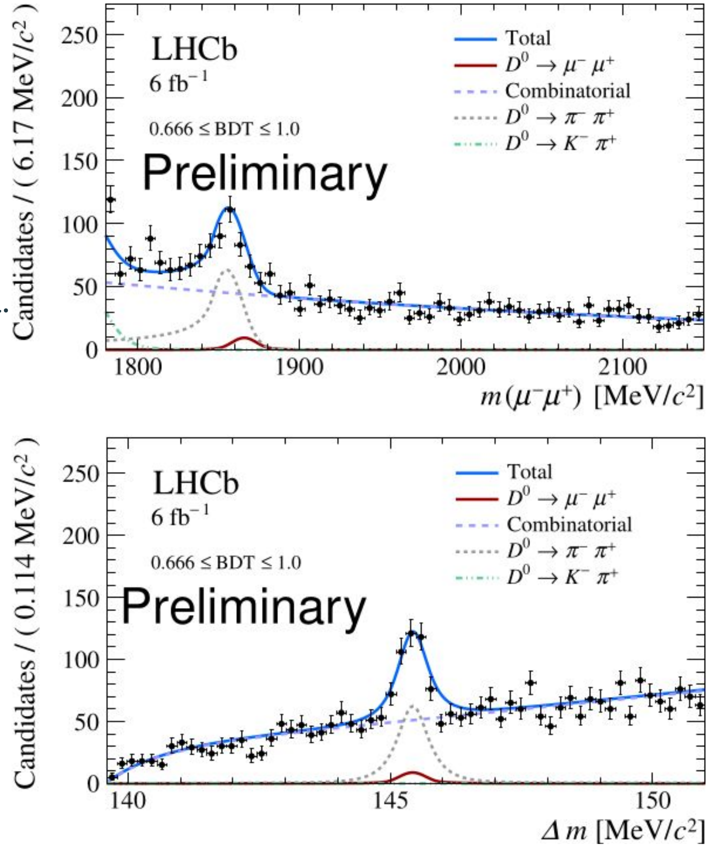
$D^0 \to \mu^+\mu^-$ rare decays

[LHCB-PAPER-2022-029 (2022)]
In preparation

- Analysis strategy:
  - BDT trained against combinatorial background.
  - PID based classifier to suppress misID.
  - $D^0 \to K^-\pi^+$ and $D^0 \to \pi^+\pi^-$ as normalisation channel.
  - Simultaneous fit to $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$.
- No significant signal observed:

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.9 \times 10^{-9} \,@\, 90\%\, CL$$

- Improvement of more than a factor two.
  - Most stringent limit of FCNC in the charm sector.



Conclusion

- LHCb collected the largest dataset of charm hadron decays.
- Major contribution in charm sector:
  - Many LHCb measurements are world's best.
- Measurements are still limited by statistical uncertainties.
  - With Run 3-4 data we expect to improve our results.

Backup

Mixing parameters in $D^0 \to K^0_S\, \pi^+\pi^-$ decays

- Fit the ratio of Dalitz bin *b* and time bin *j* with:

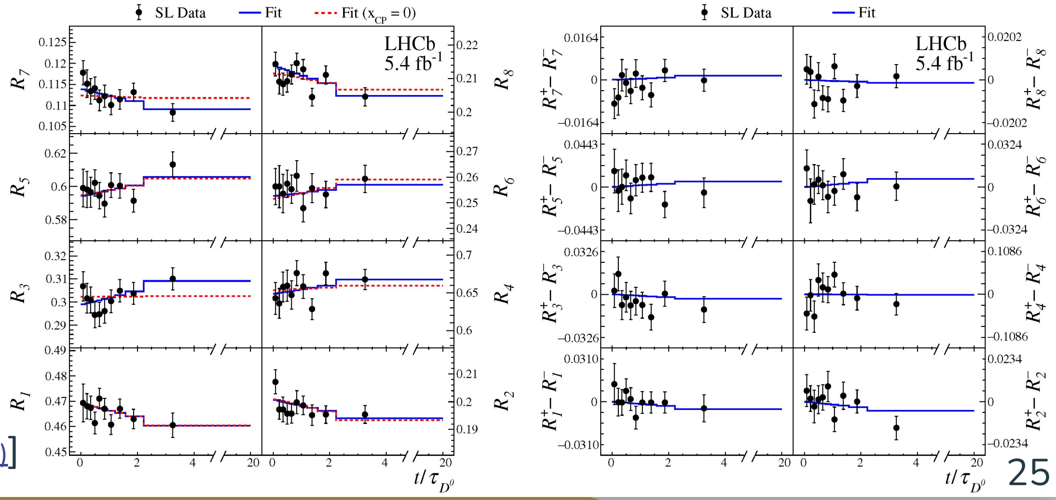
$$R^{\pm}_{bj} \approx \frac{r_b + \frac{1}{4} r_b \left\langle t^2 \right\rangle_j \mathrm{Re}(z_{CP}^2 - \Delta z^2) + \frac{1}{4}\left\langle t^2 \right\rangle_j |z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\,\langle t \rangle_j \,\mathrm{Re}\left[X_B^*(z_{CP} \pm \Delta z)\right]}{1 + \frac{1}{4}\langle t^2 \rangle_j \mathrm{Re}(z_{CP}^2 - \Delta z^2) + r_b \frac{1}{4}\langle t^2 \rangle_j |z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\,\langle t \rangle_j \,\mathrm{Re}\left[X_B(z_{CP} \pm \Delta z)\right]}$$

where "+" for D^0 and "–" for $\bar{D}^0$, r_b the ratio of bins, $\langle t \rangle_j$ average decay-time in bin *j*, and

$$z_{CP} \pm \Delta z = -\left(\frac{q}{p}\right)^{\pm 1}(y + ix)$$

- Therefore

$$x_{CP} = -Im(z_{CP}), \quad \Delta x = Im(\Delta z)$$
$$y_{CP} = -Re(z_{CP}), \quad \Delta y = Re(\Delta z)$$



[LHCb-PAPER-2022-020 (2022)]

Measurement of $y_{CP} - y_{CP}^{K\pi}$

[Phys. Rev. D 105, 092013 (2022)]

- Control channel:

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