MIXING AND CPV IN CHARM DECAYS AT LHCb

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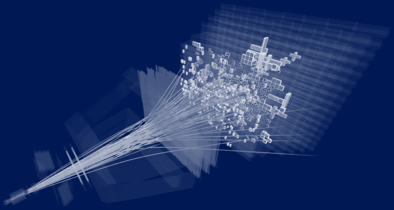
HADRON 2021, MEXICO (VIRTUAL)



- Because of the severe GIM suppression, mixing is slow and CPV small (according to SM)
- m_c is (quite) close to the hadronic scale $\Lambda_{\text{QCD}} \rightarrow \Lambda_{\text{QCD}}/m_c$ perturbative expansion tricky
- Strong coupling $\alpha_s(m_c)$ is large $\rightarrow$ higher order contributions and/or non-perturbative effects can be significant

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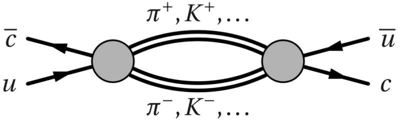
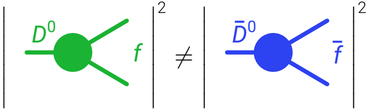
- Long distance contributions are important
- Precise theoretical predictions are difficult

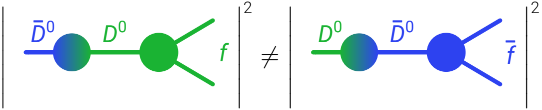


- Experimental input crucial to constrain charm dynamics
- Potential for measurable New Physics is great

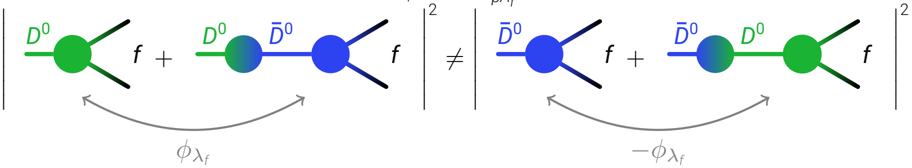
- The only up-type quark decays where CPV can be studied
- Complementary to K and B
- All three types of CPV are realized in charm
  - Direct



  - Pure mixing ($|q/p| \neq 1$)



  - Decay-mixing interference ($\phi_{\lambda_f} = \arg(\frac{q\bar{A}_f}{pA_f}) \neq 0$)



PARAMETERS

- Mixing comes from a mismatch between flavour and mass eigenstates

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

- Usually described by

$$x = \Delta m_D/\Gamma_D \quad \text{and} \quad y = \Delta\Gamma_D/2\Gamma_D$$

- In case of CPV $|q/p|$ and $\phi \approx \phi_{\lambda_f}$ or

$$\Delta x = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

$$\Delta y = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

Search for time-dependent CPV in $D^0 \to h^+h^-$ ($h \in \{K, \pi\}$)

arXiv:2105.09889

- Same channels as ΔA_{CP} discovery

$$A_{CP} = \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} = a_f^d + \Delta Y_f \frac{t}{\tau_D} + \mathcal{O}(x^2, y^2, xy)$$

- SM prediction is very small $\sim 10^{-5}$ (Kagan & Silvestrini, 2020, Li & Umeeda, 2020)

- We don't observe A_{CP}

$$A_{\mathrm{raw}} = \frac{N(D^0(t) \to f) - N(\bar{D}^0(t) \to f)}{N(D^0(t) \to f) + N(\bar{D}^0(t) \to f)} \approx a_f^d + \Delta Y_f \frac{t}{\tau_D} + \overbrace{A_{\mathrm{prod}}(f, t) + A_{\mathrm{det}}(f, t)}^{\text{Time-dep. nuisance parameters}}$$

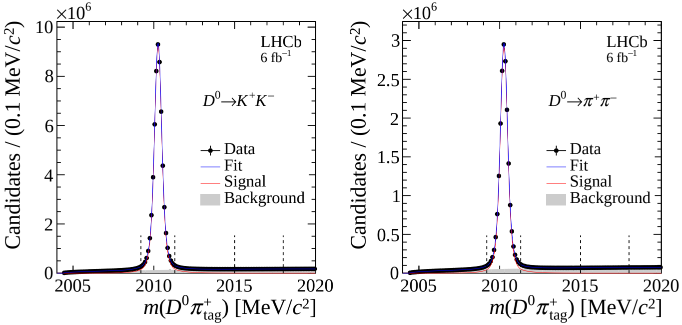
$$\Delta Y_f \approx x\phi_{\lambda_f} - y\left(\left|\frac{q}{p}\right| - 1\right) + y a_f^d$$

↑ Decay-mix. interference ↑ Mixing ↑ Direct ($\leq 10^{-5}$)

SEARCH FOR TIME-DEPENDENT CPV IN $D^0 \to h^+h^-$

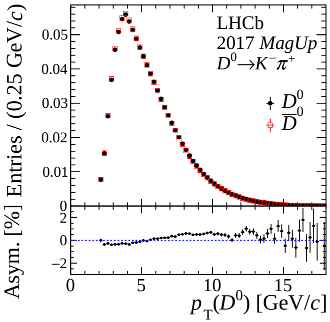
arXiv:2105.09889

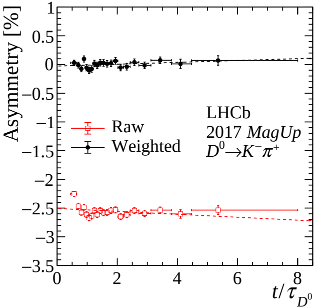
- D^0 from $D^{*+} \to D^0\pi^+_{\text{tag}}$
- At $\sqrt{s} = 13\,\text{TeV}$ with $\mathcal{L} = 5.7\,\text{fb}^{-1}$
- 58M $D^0 \to K^+K^-$, 18M $D^0 \to \pi^+\pi^-$, purity $\sim 95\%$



- Residual combinatorial background subtracted using a sideband

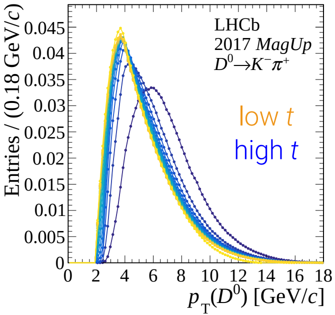
- Momentum-dependent detection asymmetries A_{det} based on magnet field polarity and charge of $\pi^{\pm}_{\text{tag}}$
- $A_{\text{det}} + A_{\text{prod}} \longrightarrow D^0/\bar{D}^0$ momentum asym.
- Trigger correlates D^0 decay time with kinematics $\longrightarrow A_{\text{det}}(t), A_{\text{prod}}(t)$ become time-dependent
- Solution: equalize D^0 and $\bar{D}^0$ kinematics by reweighting





After reweighting $\Delta Y_{K^-\pi^+} = 0$ (control channel) ←

Before reweighting $\Delta Y_{K^-\pi^+} \neq 0$ ←

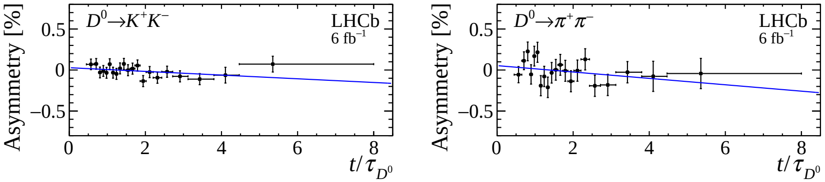


Search for time-dependent CPV in $D^0 \to h^+h^-$

arXiv:2105.09889

stat. syst.

$$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4} \qquad \Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}$$



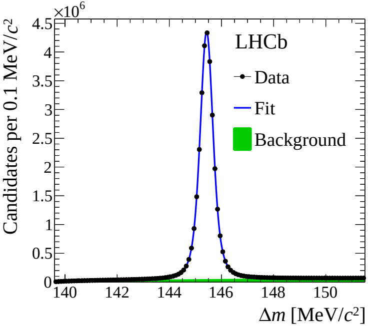
- $\Delta Y_{K^+K^-}$ and $\Delta Y_{\pi^+\pi^-}$ agree withing 0.5σ
- Compatible with no CPV within 2σ
- Precision improved by a factor of two
- Small systematic uncertainty $\longrightarrow$ great prospects for future LHCb measurements (σ approaching SM prediction $\mathcal{O}(10^{-5})$, LHCB-TDR-023-001)

Mass difference between neutral D eigenstates

arXiv:2106.03744

- The Γ difference ($y \neq 0$) between neutral charm-meson eigenstates has been established in the past years (PRL 122, 011802 (2019), PLB 753 (2016), PRD 87, 012004 (2013))
- The mass difference ($x \neq 0$) has so far been elusive; the most precise measurement by LHCb reported $x_{CP} = (2.7 \pm 1.6) \times 10^{-3}$ (PRL 122, 231802 (2019))

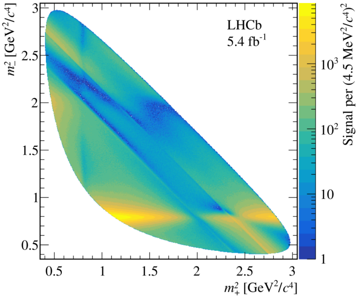
- $D^{*+} \to D^0 \pi^+_{\text{tag}}$
- $D^0 \to K^0_S \pi^+ \pi^-$
- $\mathcal{L} = 5.4\,\text{fb}^{-1}$
- 30.6M signal events
- Exploits multi-body final state; sensitive to local CPV

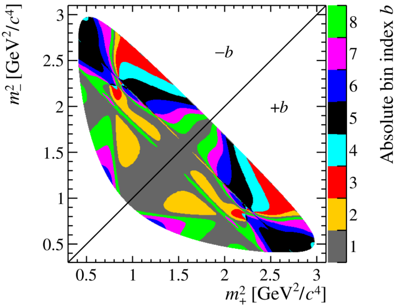


MASS DIFFERENCE BETWEEN NEUTRAL D EIGENSTATES

arXiv:2106.03744

- Rich resonant structure
- Many interfering amplitudes
  - $D^0 \xrightarrow{\text{DCS}} K^{*+}\pi^- \rightarrow K_S^0\pi^+\pi^-$
  - $D^0 \xrightarrow{\text{mix}} \bar{D}^0 \xrightarrow{\text{CF}} K^{*+}\pi^- \rightarrow K_S^0\pi^+\pi^-$
  - $D^0 \xrightarrow{\text{CF}} K^{*-}\pi^+ \rightarrow K_S^0\pi^+\pi^-$
  - $D^0 \xrightarrow{\text{CP}} K_S^0\rho^0 \rightarrow K_S^0\pi^+\pi^-$
- Dalitz plot divided into $\pm$ bins; strong-phase difference is $\sim$ constant in each bin
- Strong-phases constrained using CLEO and BES-III inputs
- Measure a time-dep. ratio for each $\pm$ bin; "bin-flip" (PRD 99, 012007 (2019))
- Most detector effects cancel





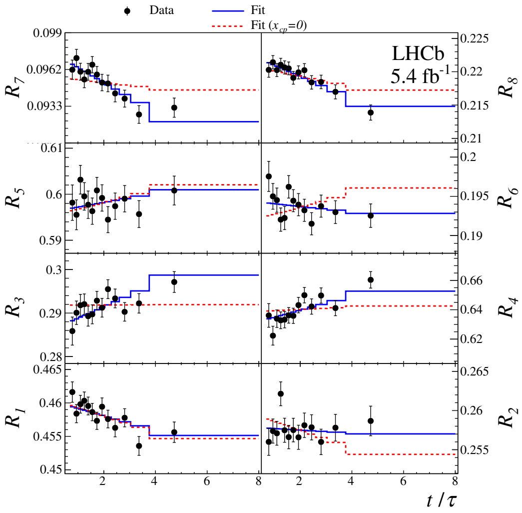
Mass difference between neutral D eigenstates

arXiv:2106.03744

- Ratios of $\pm$ bins
- Deviations from constant values due to mixing
- Red lines are fit projections where $x_{CP} \equiv 0 \longrightarrow y_{CP}$ alone can't reproduce observation

$$x_{CP} = (3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$$
$$y_{CP} = (4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$$

- First measurement of non-zero x ($> 7\sigma$)



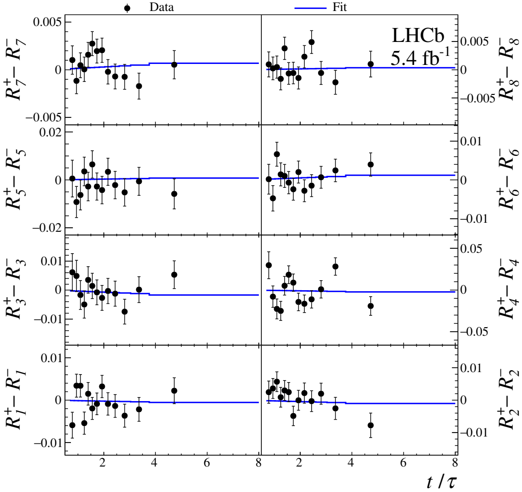
MASS DIFFERENCE BETWEEN NEUTRAL D EIGENSTATES

arXiv:2106.03744

- Difference of ratios for D^0 and $\bar{D}^0$
- No CPV observed (slope)

$\Delta x = (0.27 \pm 0.18 \pm 0.01) \times 10^{-3}$
$\Delta y = (0.20 \pm 0.36 \pm 0.13) \times 10^{-3}$

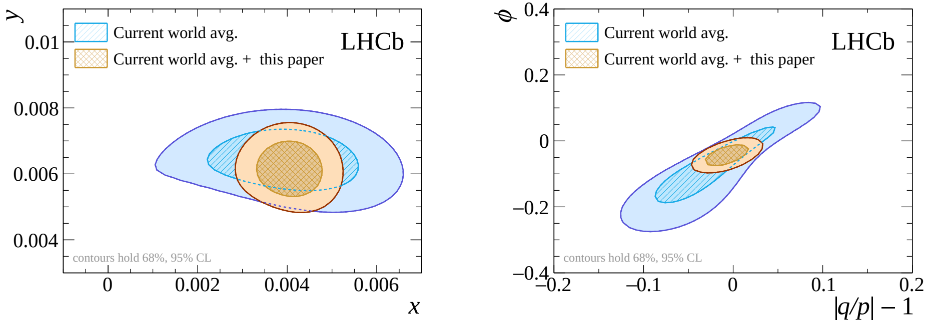
- Limits significantly improved



Mass difference between neutral D eigenstates

arXiv:2106.03744

- WA significantly improved for both mixing and CPV
- Blue contours include the presented $D^0 \to h^+h^-$ result

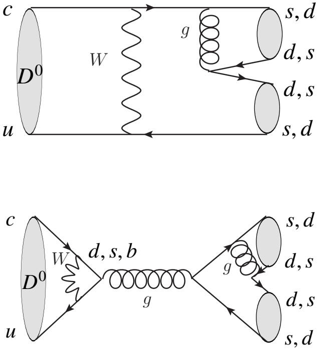


- Especially Δx and Δy statistically dominated → future improvement

Measurement of CP asymmetry in $D^0 \to K^0_S K^0_S$ decays

arXiv:2105.01565

- Two similarly sized contributions $\longrightarrow$ great for CPV observation
- A_{CP} can be large; up to 1% (Nierste & Schacht, 2015)
- Improved methods over previous analysis on a smaller dataset (JHEP 11 (2018) 048) $\longrightarrow$ 30% sensitivity improvement
  - Nuisance production and detection asymmetries removed by a weighting technique exploiting $D^0 \to K^+K^-$ calib. sample
  - Sample split into consistent sub-samples (K^0_S daughters tracking, primary interaction origin, etc.)
- $\mathcal{L} = 2\,\text{fb}^{-1}$(previous analysis) $\longrightarrow 6\,\text{fb}^{-1}$
- 8k signal events

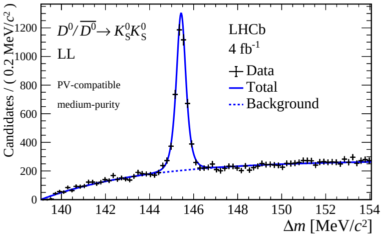


Cheng & Chiang, 2012

Measurement of CP asymmetry in $D^0 \to K^0_S K^0_S$ decays

arXiv:2105.01565

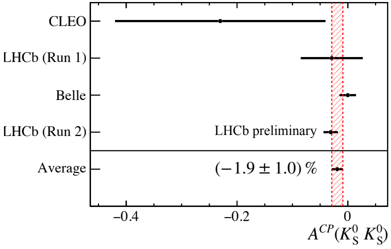
- Time-integrated A_{CP} from a 3D fit to $\Delta m = m(K^0_S K^0_S \pi^+) - m(K^0_S K^0_S)$ and $m(K^0_S)$ of both K^0_S



- Highest precision to date

$$A_{CP}(D^0 \to K^0_S K^0_S) = (3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$$

stat. syst. control sample

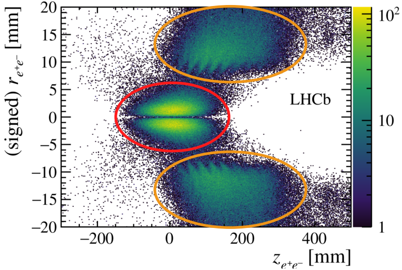


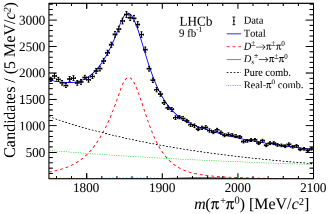
- Compatible with zero within 2.4σ

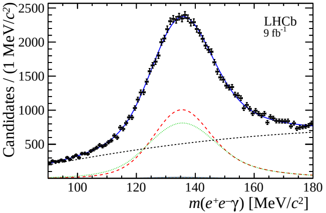
SEARCH FOR CPV IN $D^+_{(s)} \to h^+\pi^0$ AND $D^+_{(s)} \to h^+\eta, h \in \{K, \pi\}$

arXiv:2103.11058

- 7 decays; first $A_{CP}(D^+_{(s)} \to h^+h^0)$ measurement at hadron collider
- $A_{CP}(D^+ \to \pi^+\pi^0) = 0$ in SM because of isospin rules $\to$ good place to look for NP
- Neutral particles in final state challenging at hadron colliders
  - Can't form displaced D decay vertex with only one track
  - Can use converted $\gamma \to e^+e^-$ (low efficiency)
  - Can use $h^0 \to e^+e^-\gamma$ (low branching fraction)
- Asym. extracted from 2D fit





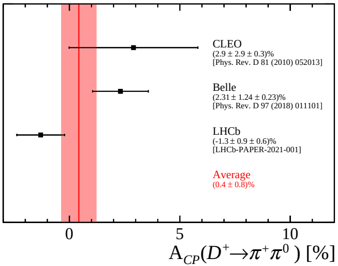


Search for CPV in $D^+_{(s)} \to h^+\pi^0$ and $D^+_{(s)} \to h^+\eta, h \in \{K, \pi\}$

arXiv:2103.11058

- $D^+_{(s)} \to K^0_S h^+$ control samples used to subtract A_{prod} and A_{det}
- $A_{CP}(D^+_{(s)} \to K^0_S h^+)$ known with high precision (PRL 122, 191803 (2019))

$$A_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%$$
$$A_{CP}(D^+ \to K^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%$$
$$A_{CP}(D^+ \to \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\%$$
$$A_{CP}(D^+ \to K^+\eta) = (-6 \pm 10 \pm 4)\%$$
$$A_{CP}(D^+_s \to K^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%$$
$$A_{CP}(D^+_s \to \pi^+\eta) = (0.8 \pm 0.7 \pm 0.5)\%$$
$$A_{CP}(D^+_s \to K^+\eta) = (0.9 \pm 3.7 \pm 1.1)\%$$



- All compatible with CP symmetry
- First 5 are most precise measurements to date

SUMMARY

- LHCb collected the largest sample of charm decays; leading to **new world-best measurements**
  - Time-integrated CP asymmetries (including **channels with neutrals**)
  - Time-dependent CP asymmetries and mixing parameters (including **first observation of a mass difference** between neutral *D* mass eigenstates)
- Precision of the measurements is mostly limited by statistics $\longrightarrow$ **improvement expected**
- More interesting Run 2 analyses in the pipeline
- Run 3 (starting next year) - higher luminosity, upgraded trigger and detector

$\downarrow$

Stay tuned!

Thank you!