Measurements of CP violation and mixing in charm decays at LHCb

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Outline

Introduction

Multi-body D decays

CP violation in $\mathrm{D}^{\pm}_{(s)} \to \mathrm{K}^0_\mathrm{S} h^{\pm}$

CP violation in $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^{(\prime)-}$

Conclusions

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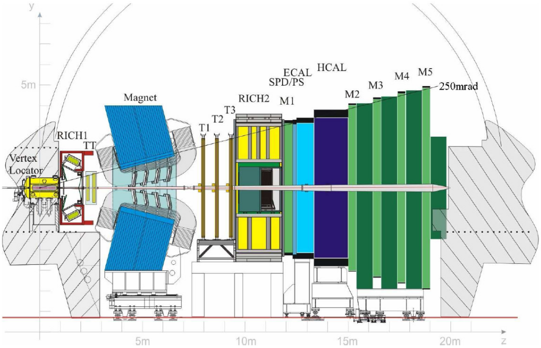
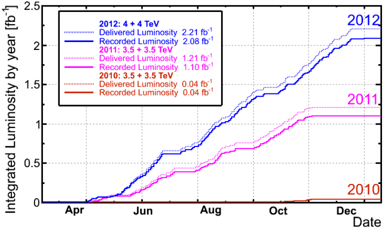
[1] JINST 3 (2008) S08005
[2] arXiv:1405.7808
[3] Eur. Phys. J. C73 (2013) 2431

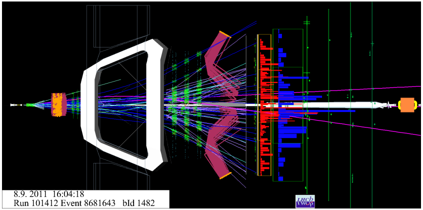
The LHCb Detector



- Single-arm forward spectrometer with acceptance $2 < \eta < 5$, designed for precision measurement of decays involving b and c quarks[1].
- Vertex Locator (VELO) provides fine tracking about the interaction point, achieving impact parameter (IP) resolutions of $\sim$20 $\mu\mathrm{m}$ for tracks with $p_T > 1\,\mathrm{GeV}$[2].
- Two Ring Imaging Cherenkov (RICH) detectors provide particle identification, with excellent separation of π and K over a wide momentum range[3].

Data





- Recorded 1.1 fb^{-1} at $\sqrt{s} = 7$ TeV in 2011 and 2.1 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012.
- Huge $c\bar{c}$ production cross-section ($1419 \pm 133\,\mu$b at $\sqrt{s} = 7$ TeV [4]) yields largest data sets of charm meson decays in the world.

Mixing and *CP* violation formalism

- For a decay $\mathrm{D} \to f$ and its *CP* conjugate $\bar{\mathrm{D}} \to \bar{f}$, with amplitudes A_f and $\bar{A}_{\bar{f}}$ respectively, direct *CP* violation is quantified by:

$$A_d = \frac{\left|A_f\right|^2 - \left|\bar{A}_{\bar{f}}\right|^2}{\left|A_f\right|^2 + \left|\bar{A}_{\bar{f}}\right|^2}.$$

- For D^0, the mass eigenstates $|\mathrm{D}_{1,2}\rangle$, with masses $m_{1,2}$ and widths $\Gamma_{1,2}$, are given by:

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

  with p and q complex, satisfying $|p|^2 + |q|^2 = 1$.

- The rate of mixing is quantified by

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

- *CP* violation in mixing is quantified by

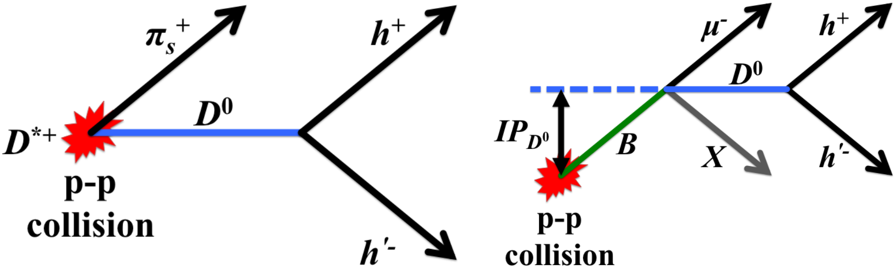
$$A_m \equiv (|q/p|^2 - |p/q|^2)/(|q/p|^2 + |p/q|^2),$$

  and in interference between mixing and decay (when $f = \bar{f}$) by

$$\lambda_f \equiv q\bar{A}_f/pA_f = \left|q\bar{A}_f/pA_f\right| e^{i\phi}.$$

- *CP* violation in charm is predicted to be very small in the Standard Model - observation of significant *CP* violation could indicate new physics.

D^0 flavour tagging



- Flavour of D^0 at production can be determined using:
  - "Prompt" $D^{*+} \to D^0\pi_s^+$, with D^{*+} produced directly from the p-p collision - D^0 IP w.r.t. primary vertex (PV) consistent with zero.
  - "Secondary" $B \to D^0\mu^- X$ - D^0 IP w.r.t. PV significantly non-zero.

Outline

T-odd correlations in $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-\pi^+\pi^-$

- Multi-body decays give sensitivity to *CP* violation due to interference between resonance structures in different phase space regions.
- In $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-\pi^+\pi^-$, triple products of final state particle momenta in D^0 rest frame are odd under T:

$$C_T \equiv \vec{p}_{\mathrm{K}^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}), \text{ for } \mathrm{D}^0,$$
$$\bar{C}_T \equiv \vec{p}_{\mathrm{K}^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}), \text{ for } \overline{\mathrm{D}}^0.$$

- T-odd observables are then sensitive to *CP* violation:

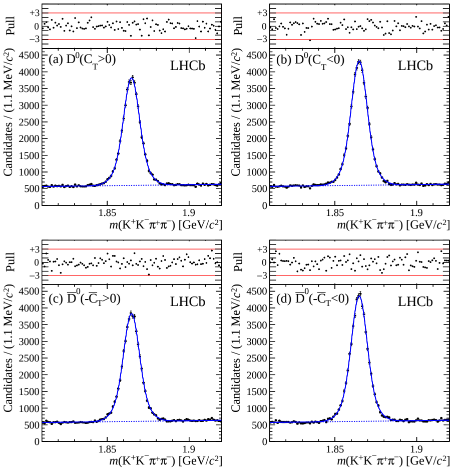
$$A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}, \quad \bar{A}_T \equiv \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}$$

- Final state interactions introduce significant asymmetries, so are cancelled in the difference to access the D^0 *CP* asymmetry

$$a_{CP}^{T\text{-odd}} \equiv \frac{1}{2}(A_T - \bar{A}_T).$$

- By definition insensitive to production and detection asymmetries.

T-odd correlations in $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-\pi^+\pi^-$ (II)



- 171k $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-\pi^+\pi^-$ candidates, tagged using $\mathrm{B} \to \mathrm{D}^0\mu^- X$, selected from 3 fb^{-1} of data.
- Fits to $m(\mathrm{K}^+\mathrm{K}^-\pi^+\pi^-)$ distributions directly yield asymmetries using:

$$N_{\mathrm{D}^0, C_T>0} = \frac{1}{2} N_{\mathrm{D}^0}(1 + A_T),$$

$$N_{\mathrm{D}^0, C_T<0} = \frac{1}{2} N_{\mathrm{D}^0}(1 - A_T),$$

$$N_{\bar{\mathrm{D}}^0, -\bar{C}_T>0} = \frac{1}{2} N_{\bar{\mathrm{D}}^0}(1 + \bar{A}_T),$$

$$N_{\bar{\mathrm{D}}^0, -\bar{C}_T<0} = \frac{1}{2} N_{\bar{\mathrm{D}}^0}(1 - \bar{A}_T).$$

[5] LHCb-PAPER-2014-046
[6] HFAG

T-odd correlations in $D^0 \rightarrow K^+K^-\pi^+\pi^-$ (III)

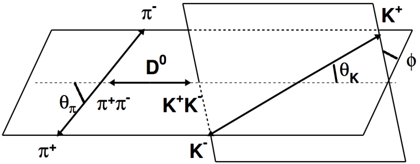
- Phase space integrated fits yield

$$A_T = (-7.18 \pm 0.41(\text{stat}) \pm 0.13(\text{syst}))\%,$$
$$\bar{A}_T = (-7.55 \pm 0.41(\text{stat}) \pm 0.12(\text{syst}))\%,$$
$$a_{CP}^{T\text{-odd}} = (0.18 \pm 0.29(\text{stat}) \pm 0.04(\text{syst}))\%.$$

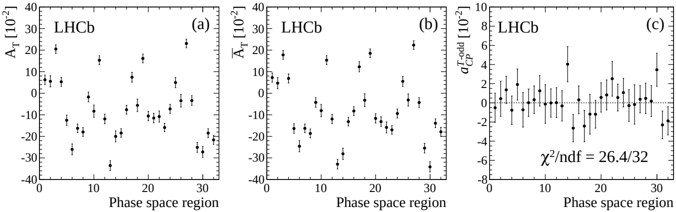
- *cf.* current world average: $a_{CP}^{T\text{-odd}} = (0.11 \pm 0.67)\%$[6].

T-odd correlations in $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-\pi^+\pi^-$ (IV)

- Asymmetries also measured in 32 bins of Cabibbo-Maksimowicz phase space variables: $m^2_{\pi^+\pi^-}$, $m^2_{\mathrm{K}^+\mathrm{K}^-}$, cos($\theta_\pi$), cos($\theta_\mathrm{K}$) and ϕ.



- χ^2 test for consistency with no *CP* violation across phase space yields *p*-value of 74 %.
- Similarly, binning in D^0 decay time yields a *p*-value for consistency with no indirect *CP* violation of 72 %.
- Thus, no evidence for *CP* violation is seen.



Search for *CP* asymmetries across multi-body phase spaces

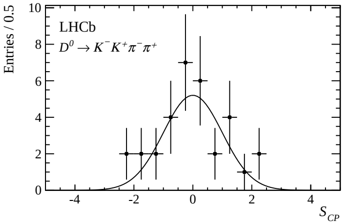
- "Miranda" method examines the significance of *CP* asymmetries across bins of phase space using:

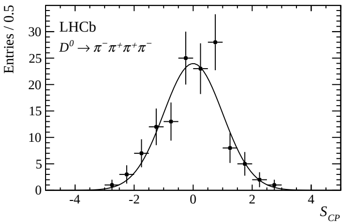
$$S_{CP}^{i} \equiv \frac{N_i(\mathrm{D}^0) - \alpha N_i(\bar{\mathrm{D}}^0)}{\sqrt{\alpha(N_i(\mathrm{D}^0) + N_i(\bar{\mathrm{D}}^0))}}, \ \alpha \equiv \frac{N(\mathrm{D}^0)}{N(\bar{\mathrm{D}}^0)}.$$

- N_i is the number of $\overset{(-)}{\mathrm{D}}{}^0$ in bin i, and α cancels any global production and detection asymmetries.
- A χ^2 test for consistency with zero *CP* violation is then performed, with $\chi^2 = \Sigma_i {S_{CP}^{i}}^2$ and $N_{bins} - 1$ degrees of freedom.
- Complementary to T-odd method as $a_{CP}^{T\text{-odd}} \propto \sin(\phi)\cos(\delta)$ while $S_{CP} \propto \sin(\phi)\sin(\delta)$, with ϕ the weak phase and δ the strong phase of the interfering amplitudes.

Miranda analysis in $D^0 \to K^+K^-\pi^+\pi^-$ and $D^0 \to \pi^+\pi^-\pi^+\pi^-$

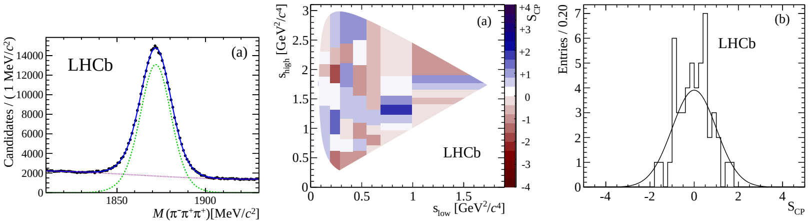
- 57k $D^0 \to K^+K^-\pi^+\pi^-$ and 330k $D^0 \to \pi^+\pi^-\pi^+\pi^-$ candidates, tagged using $D^{*+} \to D^0\pi_s^+$, selected from 1 fb^{-1} 2011 data.
- Distributions of $m(hhhh)$ and $\Delta m \equiv m(D^{*+}) - m(D^0)$ fitted to determine yields.
- Nominal binning schema yields *p*-value of consistency with zero *CP* violation of 9.1 % (41 %) for $D^0 \to K^+K^-\pi^+\pi^-$ ($D^0 \to \pi^+\pi^-\pi^+\pi^-$).
- Cross checked using $D^0 \to K^-\pi^+\pi^+\pi^-$ and various different binning schema.





Miranda analysis in $D^+ \to \pi^-\pi^+\pi^+$

- 3.1M prompt $D^+ \to \pi^-\pi^+\pi^+$ candidates selected from 1 fb^{-1} 2011 data.
- Distribution of $m(\pi^-\pi^+\pi^+)$ fitted to determine signal yield.
- Various binning schema used, as well as an unbinned technique to measure *CP* asymmetries, all yielding *p*-values for consistency with zero *CP* violation $>$ 20%.
- Cross checked with CF $D_s^+ \to \pi^-\pi^+\pi^+$.



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- CP asymmetry and measured asymmetry defined as:

$$\mathcal{A}_{CP}^{\mathrm{D}^{\pm}_{(s)} \to \mathrm{K}^0_\mathrm{S} h^{\pm}} \equiv \frac{\Gamma(\mathrm{D}^{+}_{(s)} \to \mathrm{K}^0_\mathrm{S} h^{+}) - \Gamma(\mathrm{D}^{-}_{(s)} \to \mathrm{K}^0_\mathrm{S} h^{-})}{\Gamma(\mathrm{D}^{+}_{(s)} \to \mathrm{K}^0_\mathrm{S} h^{+}) + \Gamma(\mathrm{D}^{-}_{(s)} \to \mathrm{K}^0_\mathrm{S} h^{-})},$$

$$\mathcal{A}_{\mathrm{meas}}^{\mathrm{D}^{\pm}_{(s)} \to \mathrm{K}^0_\mathrm{S} h^{\pm}} \equiv \frac{N_{\mathrm{sig}}^{\mathrm{D}^{+}_{(s)} \to \mathrm{K}^0_\mathrm{S} h^{+}} - N_{\mathrm{sig}}^{\mathrm{D}^{-}_{(s)} \to \mathrm{K}^0_\mathrm{S} h^{-}}}{N_{\mathrm{sig}}^{\mathrm{D}^{+}_{(s)} \to \mathrm{K}^0_\mathrm{S} h^{+}} + N_{\mathrm{sig}}^{\mathrm{D}^{-}_{(s)} \to \mathrm{K}^0_\mathrm{S} h^{-}}}$$

$$\simeq \mathcal{A}_{CP}^{\mathrm{D}^{\pm}_{(s)} \to \mathrm{K}^0_\mathrm{S} h^{\pm}} + \mathcal{A}_{\mathrm{prod}}^{\mathrm{D}^{\pm}_{(s)}} + \mathcal{A}_{\mathrm{det}}^{h^{\pm}} + \mathcal{A}_{\mathrm{K}^0_\mathrm{S}}.$$

- $\mathcal{A}_{\mathrm{prod}}^{\mathrm{D}^{\pm}_{(s)}}$ is the production asymmetry of the $\mathrm{D}^{\pm}_{(s)}$, $\mathcal{A}_{\mathrm{det}}^{h^{\pm}}$ the detection asymmetry of the $h^{\pm}$, and $\mathcal{A}_{\mathrm{K}^0_\mathrm{S}}$ is the combined detection and CP asymmetry of the K^0_S.

CP violation in $\mathrm{D}^{\pm} \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^{\pm}$ and $\mathrm{D}^{\pm}_s \to \mathrm{K}^0_\mathrm{S}\pi^{\pm}$ (II)

- Assuming negligible CP violation in Cabibbo-favoured decays $\mathrm{D}^{\pm}_s \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^{\pm}$, $\mathrm{D}^{\pm} \to \mathrm{K}^0_\mathrm{S}\pi^{\pm}$ and $\mathrm{D}^{\pm}_s \to \phi\pi^{\pm}$, can define double difference:

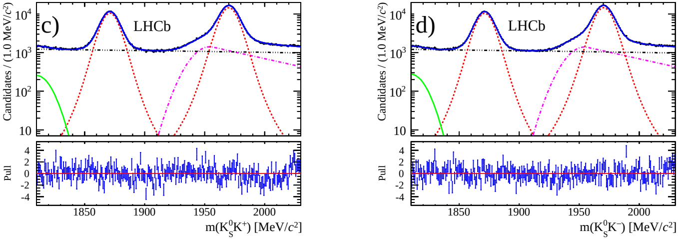
$$\begin{aligned}\mathcal{A}_{CP}^{DD} &\equiv \left[\mathcal{A}_{\text{meas}}^{\mathrm{D}^{\pm}_s \to \mathrm{K}^0_\mathrm{S}\pi^{\pm}} - \mathcal{A}_{\text{meas}}^{\mathrm{D}^{\pm}_s \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^{\pm}}\right] - \left[\mathcal{A}_{\text{meas}}^{\mathrm{D}^{\pm} \to \mathrm{K}^0_\mathrm{S}\pi^{\pm}} - \mathcal{A}_{\text{meas}}^{\mathrm{D}^{\pm} \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^{\pm}}\right] - 2\mathcal{A}_{\mathrm{K}^0_\mathrm{S}}, \\ &= \mathcal{A}_{CP}^{\mathrm{D}^{\pm} \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^{\pm}} + \mathcal{A}_{CP}^{\mathrm{D}^{\pm}_s \to \mathrm{K}^0_\mathrm{S}\pi^{\pm}}.\end{aligned}$$

- Production and detection asymmetries cancel, and $\mathcal{A}_{\mathrm{K}^0_\mathrm{S}}$ is known.
- Similarly, individual asymmetries can be accessed:

$$\mathcal{A}_{CP}^{\mathrm{D}^{\pm} \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^{\pm}} = \left[\mathcal{A}_{\text{meas}}^{\mathrm{D}^{\pm} \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^{\pm}} - \mathcal{A}_{\text{meas}}^{\mathrm{D}^{\pm}_s \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^{\pm}}\right] - \left[\mathcal{A}_{\text{meas}}^{\mathrm{D}^{\pm} \to \mathrm{K}^0_\mathrm{S}\pi^{\pm}} - \mathcal{A}_{\text{meas}}^{\mathrm{D}^{\pm}_s \to \phi\pi^{\pm}}\right] - \mathcal{A}_{\mathrm{K}^0_\mathrm{S}},$$

$$\mathcal{A}_{CP}^{\mathrm{D}^{\pm}_s \to \mathrm{K}^0_\mathrm{S}\pi^{\pm}} = \mathcal{A}_{\text{meas}}^{\mathrm{D}^{\pm}_s \to \mathrm{K}^0_\mathrm{S}\pi^{\pm}} - \mathcal{A}_{\text{meas}}^{\mathrm{D}^{\pm}_s \to \phi\pi^{\pm}} - \mathcal{A}_{\mathrm{K}^0_\mathrm{S}}.$$

CP violation in $\mathrm{D}^{\pm} \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^{\pm}$ and $\mathrm{D}^{\pm}_s \to \mathrm{K}^0_\mathrm{S}\pi^{\pm}$ (III)



- 1.0M prompt $\mathrm{D}^{\pm} \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^{\pm}$ and 121k prompt $\mathrm{D}^{\pm}_s \to \mathrm{K}^0_\mathrm{S}\pi^{\pm}$ candidates selected from 3 fb^{-1} data.
- Fit $m(\mathrm{D}^{\pm}_{(s)})$ distributions to obtain signal yields, giving:

$$\mathcal{A}_{CP}^{\mathrm{D}^{\pm}\to\mathrm{K}^0_\mathrm{S}\mathrm{K}^{\pm}} + \mathcal{A}_{CP}^{\mathrm{D}^{\pm}_s\to\mathrm{K}^0_\mathrm{S}\pi^{\pm}} = (+0.41 \pm 0.49(\mathrm{stat}) \pm 0.26(\mathrm{syst}))\%,$$

$$\mathcal{A}_{CP}^{\mathrm{D}^{\pm}\to\mathrm{K}^0_\mathrm{S}\mathrm{K}^{\pm}} = (+0.03 \pm 0.17(\mathrm{stat}) \pm 0.14(\mathrm{syst}))\%,$$

$$\mathcal{A}_{CP}^{\mathrm{D}^{\pm}_s\to\mathrm{K}^0_\mathrm{S}\pi^{\pm}} = (+0.38 \pm 0.46(\mathrm{stat}) \pm 0.17(\mathrm{syst}))\%.$$

- Most precise measurements to date, but no indication of *CP* violation.

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Direct *CP* violation in $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$

- Using $\mathrm{B} \to \mathrm{D}^0\mu^- X$ tagged $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$, the measured *CP* asymmetry is:

$$\mathcal{A}_{\text{meas}}^{\mathrm{D}^0\to\mathrm{h}^+\mathrm{h}^-} = \mathcal{A}_{CP}^{\mathrm{D}^0\to\mathrm{h}^+\mathrm{h}^-} + \mathcal{A}_{\text{det}}^{\mu^\pm} + \mathcal{A}_{\text{prod}}^{\mathrm{B}}.$$

- No detection asymmetry for $\mathrm{K}^+\mathrm{K}^-$ and $\pi^+\pi^-$ final states.
- Taking difference of measured asymmetries, B production and μ detection asymmetries cancel:

$$\Delta\mathcal{A}_{CP} \equiv \mathcal{A}_{\text{meas}}^{\mathrm{D}^0\to\mathrm{K}^+\mathrm{K}^-} - \mathcal{A}_{\text{meas}}^{\mathrm{D}^0\to\pi^+\pi^-} = \mathcal{A}_{CP}^{\mathrm{D}^0\to\mathrm{K}^+\mathrm{K}^-} - \mathcal{A}_{CP}^{\mathrm{D}^0\to\pi^+\pi^-}.$$

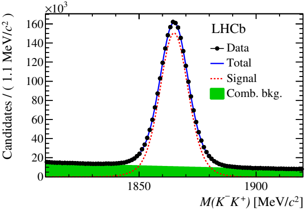
- Assuming *CP* violation is negligible in $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ it can be used to cancel nuisance asymmetries and access individual *CP* asymmetries:

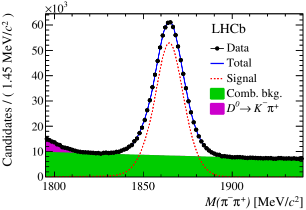
$$\mathcal{A}_{CP}^{\mathrm{D}^0\to\mathrm{K}^+\mathrm{K}^-} = \mathcal{A}_{\text{meas}}^{\mathrm{D}^0\to\mathrm{K}^+\mathrm{K}^-} - \mathcal{A}_{\text{meas}}^{\mathrm{D}^0\to\mathrm{K}^-\pi^+} + \mathcal{A}_{\text{det}}^{\mathrm{K}^\mp\pi^\pm},$$

$$\mathcal{A}_{CP}^{\mathrm{D}^0\to\pi^+\pi^-} = \mathcal{A}_{CP}^{\mathrm{D}^0\to\mathrm{K}^+\mathrm{K}^-} - \Delta\mathcal{A}_{CP}.$$

- $\mathcal{A}_{\text{det}}^{\mathrm{K}^\mp\pi^\pm}$ is determined from prompt $\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+$ and $\mathrm{D}^+ \to \mathrm{K}^0_\mathrm{S}\pi^+$ decays, and the known $\mathcal{A}_{\mathrm{K}^0_\mathrm{S}}$.

Direct *CP* violation in $D^0 \to h^+h^-$ (II)



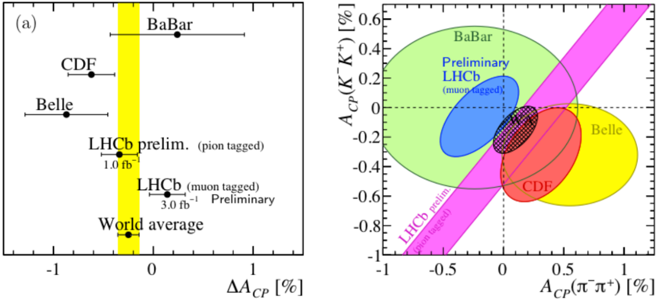


- From 3 fb^{-1} data select 2.2M $D^0 \to K^+K^-$ and 770k $D^0 \to \pi^+\pi^-$ candidates, yielding:

$$\Delta\mathcal{A}_{CP} = (+0.14 \pm 0.16(\text{stat}) \pm 0.08(\text{syst}))\%,$$
$$\mathcal{A}_{CP}^{D^0 \to K^+K^-} = (-0.06 \pm 0.15(\text{stat}) \pm 0.10(\text{syst}))\%,$$
$$\mathcal{A}_{CP}^{D^0 \to \pi^+\pi^-} = (-0.20 \pm 0.19(\text{stat}) \pm 0.10(\text{syst}))\%.$$

- Most accurate measurements to date, no indication of *CP* violation.
- $\Delta\mathcal{A}_{CP}$ and $\mathcal{A}_{CP}^{D^0 \to K^+K^-}$ are 28 % correlated.

World average direct *CP* violation in $D^0 \to h^+h^-$



- New world averages dominated by LHCb measurements:

$$\mathcal{A}_{CP}^{D^0\to K^+K^-} = (-0.15 \pm 0.11)\%, \quad \mathcal{A}_{CP}^{D^0\to \pi^+\pi^-} = (+0.10 \pm 0.12)\%,$$

$$\Delta\mathcal{A}_{CP} = (-0.25 \pm 0.11)\%.$$

Indirect CP violation in $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$

- Using $\mathrm{D}^{*+} \to \mathrm{D}^0\pi_s^+$ tagged $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$ and $\mathrm{D}^0 \to \pi^+\pi^-$ measure asymmetry in effective lifetime:

$$A_\Gamma \equiv \frac{\hat{\Gamma}(\mathrm{D}^0 \to f) - \hat{\Gamma}(\overline{\mathrm{D}}^0 \to f)}{\hat{\Gamma}(\mathrm{D}^0 \to f) + \hat{\Gamma}(\overline{\mathrm{D}}^0 \to f)} \approx \eta_{CP}\left[\frac{1}{2}(A_m + A_d) y \cos\phi - x \sin\phi\right].$$

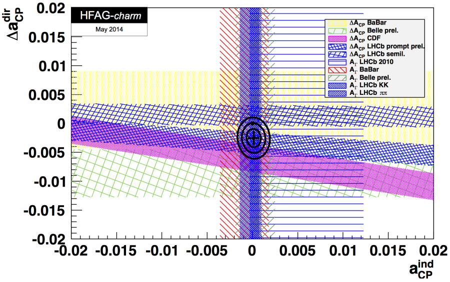
- $\hat{\Gamma}$ is the inverse of the effective lifetime of the decay, and η_{CP} is the CP eigenvalue of f.
- $\hat{\Gamma}$ measured directly using data-driven, per-candidate correction for selection efficiency.

[12] Phys. Rev. Lett. 112 (2014) 041801
[6] HFAG

Indirect *CP* violation in $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$ (II)

- Using 1 fb^{-1} 2011 data 1.5M $\pi\pi$ and 4.8M KK candidates are selected, yielding:

$$A_\Gamma(\pi\pi) = \quad (0.033 \pm 0.106(\text{stat}) \pm 0.014(\text{syst}))\%,$$
$$A_\Gamma(\mathrm{KK}) = (-0.035 \pm 0.062(\text{stat}) \pm 0.012(\text{syst}))\%.$$



- World average:

$$-A_\Gamma \simeq a_{CP}^{\text{ind}} = (0.013 \pm 0.052)\%.$$

- Combined fit with direct *CP* violation measurements yields *p*-value for zero *CP* violation of 5.1 %.

Mixing and CP violation in $D^0 \to K^+\pi^-$

- Ratio of DCS "wrong sign" (WS) $D^0 \to K^+\pi^-$ to CF "right sign" (RS) $D^0 \to K^-\pi^+$ decay rates vs decay time give access to mixing parameters (assuming no CPV):

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D} y' t + \frac{x'^2 + y'^2}{4} t^2.$$

where:

$$R_D = \left|\frac{A_{DCS}}{A_{CF}}\right|^2, \; x' = x\cos(\delta) + y\sin(\delta),$$
$$y' = -x\sin(\delta) + y\cos(\delta), \; \delta = \arg\left(\frac{A_{DCS}}{A_{CF}}\right).$$

- Analysing D^0 and $\overline{D}^0$ separately gives sensitivity to CPV.
- Using $D^{*+} \to D^0\pi_s^+$ tagged candidates, fits to the distributions of $m(D^{*+})$ in bins of D^0 decay time determine $R(t)$.

[13] Phys. Rev. Lett. 111 (2013) 251801
[6] HFAG

Mixing and CP violation in $\mathrm{D}^0 \to \mathrm{K}^+\pi^-$ (II)

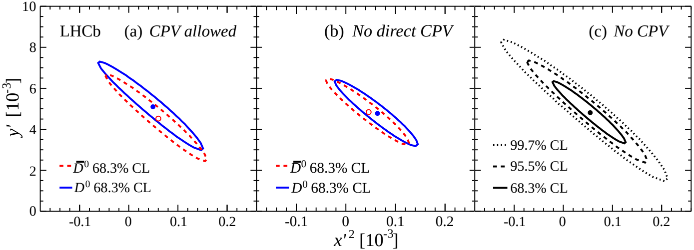
- Using 3 fb^{-1} data, a yield of 229K signal WS candidates is determined. Assuming zero CP violation gives:

$$x'^2 = (5.5 \pm 4.9) \times 10^{-5}, y' = (4.8 \pm 1.0) \times 10^{-3},$$
$$R_D = (3.568 \pm 0.066) \times 10^{-3}.$$

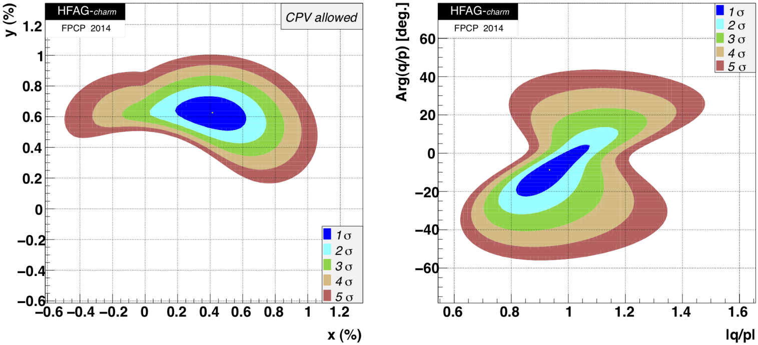
- Allowing for CP violation yields:

$$A_D \equiv (R_D(\mathrm{D}^0) - R_D(\overline{\mathrm{D}}^0))/(R_D(\mathrm{D}^0) - R_D(\overline{\mathrm{D}}^0)) = (-0.7 \pm 1.9)\%,$$
$$0.75 < |q/p| < 1.24, (68.3\ \%\ \mathrm{CL}).$$

- Assuming no CP violation in DCS decays ($A_D = 0$) yields much tighter constraints on $|q/p|$ in combined fits[6].



World average mixing and indirect *CP* violation



- WS $D^0 \to K^+\pi^-$ measurements contribute to constraints on y and $|q/p|$, and to a lesser extent x and $\text{Arg}(q/p)$.
- $|q/p|$ and $\text{Arg}(q/p)$ also constrained by A_Γ measurements.
- No evidence for indirect *CP* violation.

Outline

Conclusions

- Rich charm physics programme at LHCb, yielding world best measurements of *CP* violation and mixing in many decay modes.
  - Complementary searches using *T*-odd observables and Miranda method in $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-\pi^+\pi^-$, $\mathrm{D}^0 \to \pi^+\pi^-\pi^+\pi^-$ and $\mathrm{D}^+ \to \pi^-\pi^+\pi^+$.
  - Direct *CP* violation in $\mathrm{D}^{\pm}_{(s)} \to \mathrm{K}^0_\mathrm{S} h^{\pm}$ and $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$.
  - Indirect *CP* violation using $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$.
  - Mixing and *CP* violation using WS $\mathrm{D}^0 \to \mathrm{K}^+\pi^-$.
- Precision on D^0 mixing parameters significantly improved.
- No evidence for direct or indirect *CP* violation, but constraints of $\mathcal{O}(10^{-3})$ made in several modes.
- With some analyses still to add 2 fb^{-1} recorded in 2012, run II approaching, and the LHCb upgrade on the horizon, LHCb will continue to dominate the landscape of charm physics for several years to come.
- Potential to probe down to $\mathcal{O}(10^{-4})$ and further constrain (or discover!) new physics.

Backup

T-odd correlations, systematics

Contribution	$\Delta A_T(\%)$	$\Delta\overline{A}_T(\%)$	$\Delta a_{CP}^{T\text{-odd}}(\%)$
Prompt background	± 0.09	± 0.08	± 0.00
Detector bias	± 0.04	± 0.04	± 0.04
C_T resolution	± 0.02	± 0.03	± 0.01
Fit model	± 0.01	± 0.01	± 0.01
Flavour misidentification	± 0.08	± 0.07	± 0.00
Total	± 0.13	± 0.12	± 0.04

CP violation in $\mathrm{D}^{\pm} \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^{\pm}$ and $\mathrm{D}^{\pm}_s \to \mathrm{K}^0_\mathrm{S}\pi^{\pm}$, systematics

Source	$\sqrt{s} = 7$ TeV			$\sqrt{s} = 8$ TeV		
	$\mathcal{A}_{CP}^{\mathcal{DD}}$	$\mathcal{A}_{CP}^{D^{\pm}\to K^0_S K^{\pm}}$	$\mathcal{A}_{CP}^{D_s^{\pm}\to K^0_S \pi^{\pm}}$	$\mathcal{A}_{CP}^{\mathcal{DD}}$	$\mathcal{A}_{CP}^{D^{\pm}\to K^0_S K^{\pm}}$	$\mathcal{A}_{CP}^{D_s^{\pm}\to K^0_S \pi^{\pm}}$
Fit procedure	0.14	0.09	0.11	0.07	0.05	0.01
Cross-feed bkgd.	0.03	0.01	0.02	0.01	–	0.01
Non-prompt charm	0.01	–	–	0.01	–	–
Kinematic weighting	0.08	0.06	0.13	0.05	0.07	0.12
Kinematic region	0.10	0.06	0.04	0.19	0.02	0.17
Trigger	0.13	0.13	0.07	0.17	0.17	0.09
K^0 asymmetry	0.03	0.02	0.02	0.04	0.02	0.02
Total	0.23	0.18	0.19	0.27	0.19	0.22

Direct *CP* violation in $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$, systematics

Source of uncertainty	ΔA_{CP}	$A_{CP}(K^-K^+)$
Production asymmetry:		
Difference in b-hadron mixture	0.02%	0.02%
Difference in B decay time acceptance	0.02%	0.02%
Production and detection asymmetry:		
Different weighting	0.02%	0.05%
Non-cancellation	-	0.03%
Neutral kaon asymmetry	-	0.01%
Background from real D^0 mesons:		
Mistag asymmetry	0.03%	0.03%
Background from fake D^0 mesons:		
D^0 mass fit model	0.06%	0.06%
Wrong background modelling	0.03%	0.03%
Quadratic sum	0.08%	0.10%

Indirect *CP* violation in $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$, systematics

- Complementary binned fit method yields:

$$A_\Gamma(\pi\pi) = (0.085 \pm 0.122(\text{stat}) \pm 0.113(\text{syst}))\%,$$
$$A_\Gamma(\mathrm{KK}) = (0.050 \pm 0.065(\text{stat}) \pm 0.089(\text{syst}))\%.$$

- Main systematic from difference in magnet polarities, and background modelling.
- Main systematics for unbinned method from modelling of D^0 from B decays, and decay-time acceptance correction.

Source	$A_\Gamma^{\text{unb}}(KK)$	$A_\Gamma^{\text{bin}}(KK)$	$A_\Gamma^{\text{unb}}(\pi\pi)$	$A_\Gamma^{\text{bin}}(\pi\pi)$
Partially reconstructed backgrounds	±0.02	±0.09	±0.00	±0.00
Charm from *b* decays	±0.07	±0.55	±0.07	±0.53
Other backgrounds	±0.02	±0.40	±0.04	±0.57
Acceptance function	±0.09	...	±0.11	...
Magnet polarity	...	±0.58	...	±0.82
Total systematic uncertainty	±0.12	±0.89	±0.14	±1.13

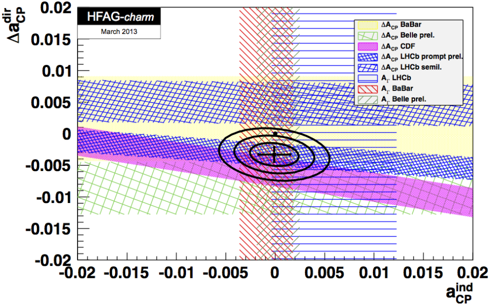
Mixing and *CP* violation in $\mathrm{D}^0 \to \mathrm{K}^+\pi^-$, complete results and systematics

Parameter	Value
Direct and indirect *CP* violation	
R_D^+ (10^{-3})	$3.545 \pm 0.082 \pm 0.048$
y'^+ (10^{-3})	$5.1 \pm 1.2 \pm 0.7$
x'^{2+} (10^{-5})	$4.9 \pm 6.0 \pm 3.6$
R_D^- (10^{-3})	$3.591 \pm 0.081 \pm 0.048$
y'^- (10^{-3})	$4.5 \pm 1.2 \pm 0.7$
x'^{2-} (10^{-5})	$6.0 \pm 5.8 \pm 3.6$
χ^2/ndf	85.9/98
No direct *CP* violation	
R_D (10^{-3})	$3.568 \pm 0.058 \pm 0.033$
y'^+ (10^{-3})	$4.8 \pm 0.9 \pm 0.6$
x'^{2+} (10^{-5})	$6.4 \pm 4.7 \pm 3.0$
y'^- (10^{-3})	$4.8 \pm 0.9 \pm 0.6$
x'^{2-} (10^{-5})	$4.6 \pm 4.6 \pm 3.0$
χ^2/ndf	86.0/99
No *CP* violation	
R_D (10^{-3})	$3.568 \pm 0.058 \pm 0.033$
y' (10^{-3})	$4.8 \pm 0.8 \pm 0.5$
x'^2 (10^{-5})	$5.5 \pm 4.2 \pm 2.6$
χ^2/ndf	86.4/101

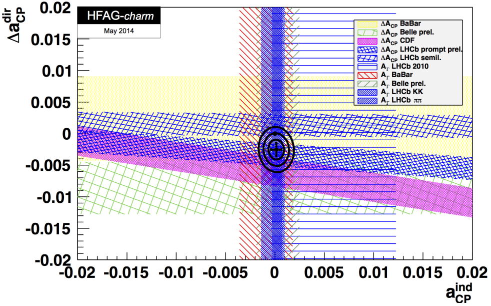
- Systematics include:
  - Uncertainty on the fraction of D^0 produced in $\mathrm{B} \to \mathrm{D}^0\mu^- X$ and the resulting bias on the measured D^0 decay time.
  - Uncertainty on the fraction of peaking background.
  - Uncertainty on the measurement of the instrumental asymmetry.

Evolution of *CP* violation measurements

- March 2013:

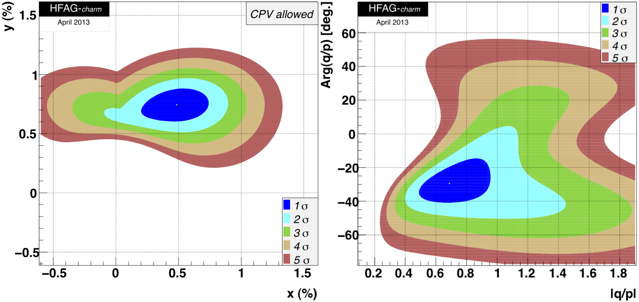


- May 2014:

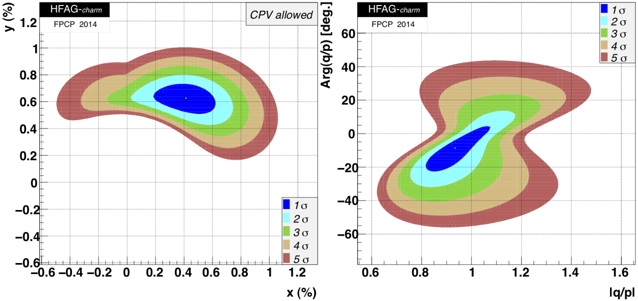


Evolution of mixing and *CP* violation parameters

- April 2013:



- July 2014:



Mixing and *CP* violation averages

Parameter	No CPV	No direct CPV in DCS decays	CPV-allowed	CPV-allowed 95% CL Interval
x (%)	$0.49\,^{+0.14}_{-0.15}$	$0.43\,^{+0.14}_{-0.15}$	$0.41\,^{+0.14}_{-0.15}$	$[0.11, 0.68]$
y (%)	0.62 ± 0.08	0.60 ± 0.07	$0.63\,^{+0.07}_{-0.08}$	$[0.47, 0.76]$
$\delta_{K\pi}$ (°)	$7.8\,^{+9.6}_{-11.1}$	$4.6\,^{+10.3}_{-12.0}$	$7.3\,^{+9.8}_{-11.5}$	$[-18.5, 25.8]$
R_D (%)	0.350 ± 0.004	0.349 ± 0.004	0.349 ± 0.004	$[0.342, 0.356]$
A_D (%)	–	–	$-0.71\,^{+0.92}_{-0.95}$	$[-2.6, 1.1]$
$\lvert q/p\rvert$	–	$1.007\,^{+0.015}_{-0.014}$	$0.93\,^{+0.09}_{-0.08}$	$[0.79, 1.12]$
ϕ (°)	–	$-0.30\,^{+0.58}_{-0.60}$	$-8.7\,^{+8.7}_{-9.1}$	$[-26.9, 8.6]$
$\delta_{K\pi\pi}$ (°)	$18.7\,^{+23.2}_{-23.7}$	$20.8\,^{+23.9}_{-24.3}$	$23.3\,^{+23.9}_{-24.4}$	$[-24.8, 70.2]$
A_π(%)	–	0.11 ± 0.14	0.14 ± 0.15	$[-0.15, 0.42]$
A_K(%)	–	-0.13 ± 0.13	$-0.11\,^{+0.14}_{-0.13}$	$[-0.37, 0.15]$
x_{12} (%)	–	$0.43\,^{+0.14}_{-0.15}$		$[0.13, 0.69]$
y_{12} (%)	–	0.60 ± 0.07		$[0.45, 0.75]$
ϕ_{12}(°)	–	$0.9\,^{+1.9}_{-1.7}$		$[-3.0, 6.1]$

Mixing and *CP* violation averages in 2013

Parameter	No CPV	No direct CPV	CPV-allowed	CPV-allowed 95% C.L.
x (%)	$0.49\,^{+0.17}_{-0.18}$	0.46 ± 0.18	$0.49\,^{+0.17}_{-0.18}$	[0.10, 0.81]
y (%)	0.66 ± 0.09	0.67 ± 0.09	0.74 ± 0.09	[0.56, 0.92]
δ (°)	$10.8\,^{+10.3}_{-12.3}$	$11.4\,^{+10.5}_{-12.7}$	$19.5\,^{+8.6}_{-11.1}$	[−9.6, 35.4]
R_D (%)	0.347 ± 0.006	0.347 ± 0.006	$0.350\,^{+0.007}_{-0.006}$	[0.337, 0.362]
A_D (%)	–	–	-2.6 ± 2.2	[−6.9, 1.7]
$\lvert q/p \rvert$	–	$1.04\,^{+0.07}_{-0.06}$	$0.69\,^{+0.17}_{-0.14}$	[0.44, 1.07]
ϕ (°)	–	$-1.6\,^{+2.4}_{-2.5}$	$-29.6\,^{+8.9}_{-7.5}$	[−44.6, −7.5]
$\delta_{K\pi\pi}$ (°)	$21.3\,^{+23.4}_{-23.8}$	$22.9\,^{+23.7}_{-24.0}$	$25.1\,^{+22.3}_{-23.0}$	[−20.6, 69.2]
A_π	–	–	0.16 ± 0.21	[−0.25, 0.57]
A_K	–	–	-0.16 ± 0.20	[−0.56, 0.23]
x_{12} (%)	–	0.46 ± 0.18	–	[0.10, 0.80]
y_{12} (%)	–	0.67 ± 0.09	–	[0.50, 0.85]
ϕ_{12}(°)	–	$4.8\,^{+9.2}_{-7.4}$	–	[−11.7, 35.9]