

CP violation and mixing in charm from LHCb



Sam Harnew

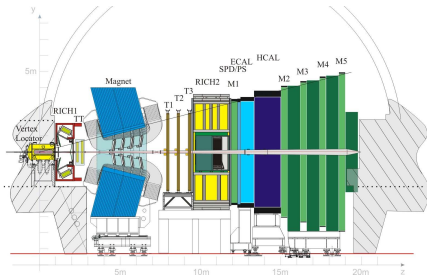
Outline

- ▶ Charm at LHCb.
- ▶ Introduction to charm mixing and CPV.
- ▶ D-mixing in $D \rightarrow K\pi\pi\pi$ decays [preliminary result].
- ▶ ΔA_{CP} in $D \rightarrow hh$ decays [new result].
- ▶ Conclusions.

Going to show just a couple of the most recent LHCb results - many more have already been published!

Charm at LHCb

- ▶ LHCb has the world's largest sample of charm decays.
- ▶ $\mathcal{O}(5 \times 10^{12})$ $c\bar{c}$ pairs produced in LHCb Run1...
- ▶ and plenty more to come in Run2.



Run1 @ 7 TeV* $\sigma(c\bar{c}) = 1419 \pm 12(\text{stat}) \pm 116(\text{syst}) \pm 65$ (frag) μb [1]

Run2 @ 13TeV* $\sigma(c\bar{c}) = 2940 \pm 3$ (stat) $\pm 180(\text{syst}) \pm 160(\text{frag}) \mu\text{b}$ [2]

* $p_T < 8 \text{ GeV}, 2.0 < y < 4.5$

- ▶ High COM collision energy gives D mesons a large flight distance in LHCb.
- ▶ Tracking within 5 mm of the beam
 - ▶ Excellent decay-time resolution of $\sim 0.1\tau$.

[1] Nuclear Physics, Section B 871 (2013), pp. 1-20 [2] arXiv:1510.01707

Mixing in neutral mesons

- Mass eigenstates are a superposition of flavour eigenstates:

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$$

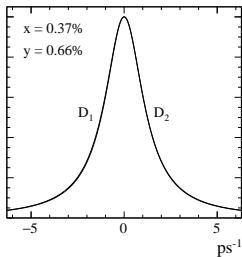
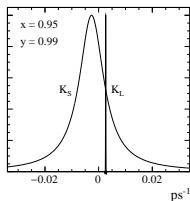
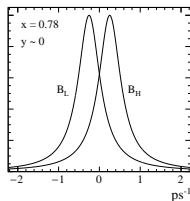
$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$

- Mixing depends on the mass and width difference:

$$x \equiv (m_2 - m_1)/\Gamma$$

$$y \equiv (\Gamma_2 - \Gamma_1)/2\Gamma$$

- Takes ~ 1000 D^0 lifetimes for a full oscillation.
- D mixing now well established with several independent observations.



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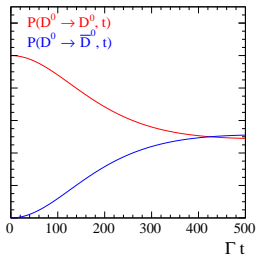
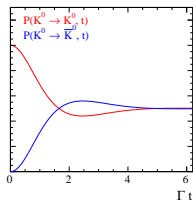
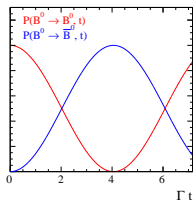
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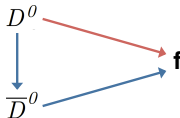
CPV in charm

Direct CPV: $|\mathcal{A}(D^0 \rightarrow f)| \neq |\mathcal{A}(\bar{D}^0 \rightarrow \bar{f})|$

- ▶ Search in time-integrated measurements of D^0 or D^\pm decays.
- ▶ Most likely in Singly Cabibbo suppressed decays such as $D^0 \rightarrow hh$ [see later]

Indirect CPV:

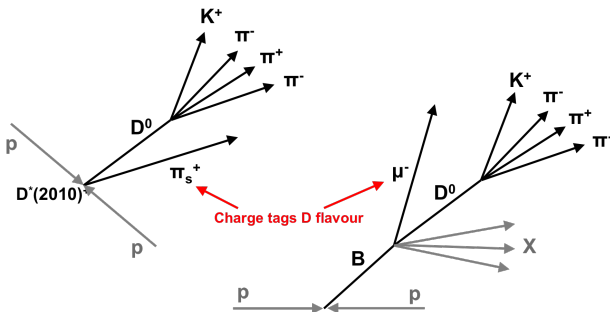
- ▶ **in mixing:** $\mathcal{P}(D^0 \rightarrow \bar{D}^0) \neq \mathcal{P}(\bar{D}^0 \rightarrow D^0)$
- ▶ **in interference:** $\arg\left(\frac{\mathcal{A}(D^0 \rightarrow f)}{\mathcal{A}(D^0 \rightarrow \bar{D}^0 \rightarrow f)}\right) \neq \arg\left(\frac{\mathcal{A}(\bar{D}^0 \rightarrow \bar{f})}{\mathcal{A}(\bar{D}^0 \rightarrow D^0 \rightarrow \bar{f})}\right)$
- ▶ Requires time-dependent analysis



No evidence for CPV in charm

Flavour Tagging

- ▶ In both mixing and CPV studies it's important to tag the D^0 flavour.
- ▶ Two methods at LHCb:
 - ▶ $D^{*(2010)^+} \rightarrow D^0 \pi_s^+$ decays [used for both analyses presented here].
 - ▶ Semileptonic B meson decays.



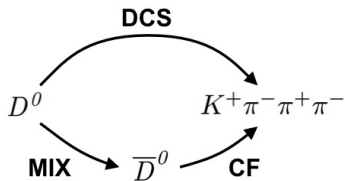
D-mixing in $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$ decays

Preliminary result: soon to be submitted to PRL

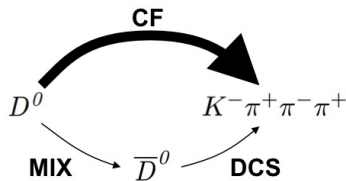
Formalism + Motivation

- ▶ Measure the time dependent ratio of WS to RS decays
- ▶ Sensitive to D-mixing (x, y), interference between CF and DCS amplitudes ($R_D^{K3\pi}, \delta_D^{K3\pi}$) and their relative magnitudes $r_D^{K3\pi}$.
- ▶ Use mixing parameters x, y as input to constrain $R_D^{K3\pi}, \delta_D^{K3\pi}$

Wrong Sign Decay



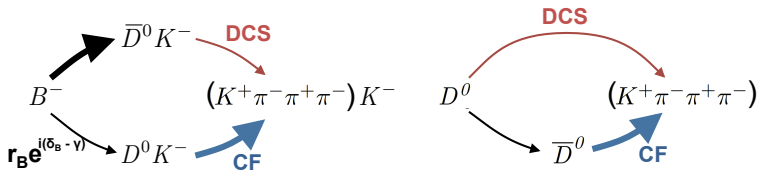
Right Sign Decay



$$\frac{WS(t)}{RS(t)} \approx (r_D^{K3\pi})^2 - r_D^{K3\pi} R_D^{K3\pi} (y \cos \delta_D^{K3\pi} - x \sin \delta_D^{K3\pi}) \Gamma t + \frac{x^2 + y^2}{4} (\Gamma t)^2$$

From charm mixing to CKM phase γ

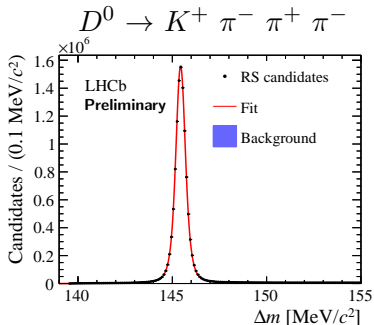
- ▶ Why are we interested in the relative magnitude and interference of CF and DCS amplitudes? ($R_D^{K3\pi}$, $\delta_D^{K3\pi}$ and $r_D^{K3\pi}$)
- ▶ If we look at the decay $B^- \rightarrow DK^-$, $D \rightarrow K^+\pi^-\pi^+\pi^-$ things look remarkably similar...



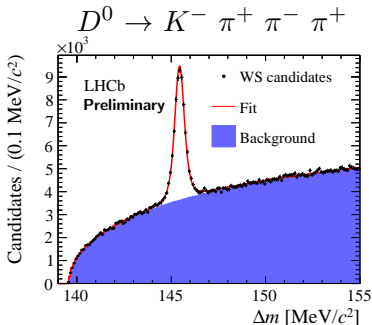
- ▶ This mode is sensitive to the CKM phase γ , but requires prior knowledge of $R_D^{K3\pi}$, $\delta_D^{K3\pi}$ and $r_D^{K3\pi}$.
- ▶ Constraints will be used for future determinations of γ in this decay mode.

Data sample

- ▶ Using full Run1 dataset (3 fb^{-1}).
- ▶ Huge number of RS decays reconstructed with a high purity.



$$N(\text{RS}) = 11\,383\,000 \pm 4600$$

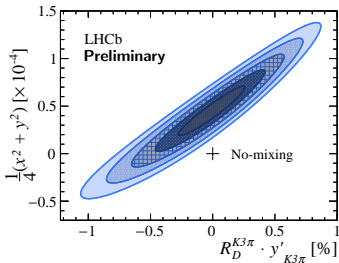
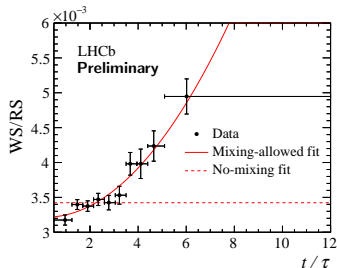


$$N(\text{WS}) = 42\,500 \pm 320$$

Mixing Significance

- ▶ Evaluate the mixing significance by comparing the χ^2 between mixing and no mixing hypotheses:

- ▶ Mixing-allowed: $r(t) = \overbrace{(r_D^{K3\pi})^2}^a - r_D^{K3\pi} \overbrace{R_D^{K3\pi} y'_{K3\pi}}^b t + \overbrace{\frac{1}{4}(x^2 + y^2)}^c t^2$
- ▶ No-mixing: $r(t) = (r_D^{K3\pi})^2$



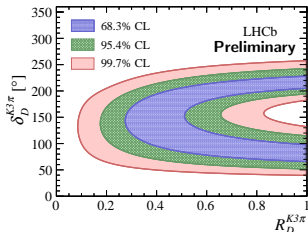
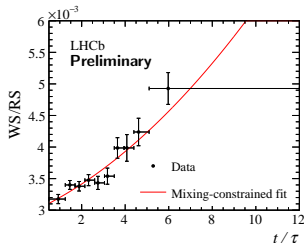
8.2 σ Mixing Significance

Mixing-constrained fit

- ▶ Also perform a mixing-constrained fit where external constraints are included for mixing parameters x and y (HFAG)

$$r(t) = (r_D^{K3\pi})^2 - r_D^{K3\pi} R_D^{K3\pi} (y \cos \delta_D^{K3\pi} - x \sin \delta_D^{K3\pi}) t + \frac{1}{4} (x^2 + y^2) t^2$$

- ▶ This allows constraints in the $(R_D^{K3\pi}, \delta_D^{K3\pi})$ plane.
 - ▶ Previous constraints from $\psi(3770) \rightarrow D_{CP+} D_{CP-}$ at CLEO-c [1].
 - ▶ Naive combination gives a factor ~ 2 improvement on constraints.



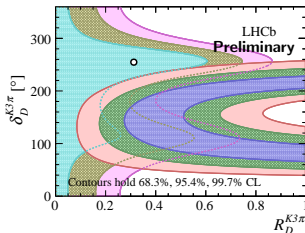
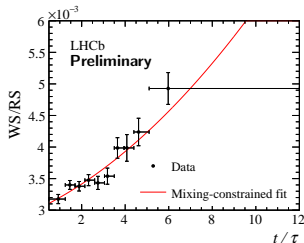
[1] Phys. Lett. B, Section B 731 (2014), pp. 197

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Time integrated asymmetries in
 $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ decays.

arXiv:1602.03160 submitted to PRL

Formalism

- ▶ First define $A_{\text{CP}}(f)$ for some final state f .

$$A_{\text{CP}}(f) \equiv \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow \bar{f})} \equiv a_{\text{CP}}^{\text{dir}}(f) \left(1 + \frac{\langle t(f) \rangle}{\tau} y_{\text{CP}} \right) + \frac{\langle t(f) \rangle}{\tau} a_{\text{CP}}^{\text{ind}}$$

- ▶ Then define ΔA_{CP} between $D^0 \rightarrow \pi^+ \pi^-$ and $D^0 \rightarrow K^+ K^-$.

$$\Delta A_{\text{CP}} \equiv A_{\text{CP}}(K^+ K^-) - A_{\text{CP}}(\pi^+ \pi^-) \equiv \Delta a_{\text{CP}}^{\text{dir}} \left(1 + \frac{\langle \bar{t} \rangle}{\tau} y_{\text{CP}} \right) + \frac{\Delta \langle t \rangle}{\tau} a_{\text{CP}}^{\text{ind}}$$

- ▶ Contributions from indirect CPV are either negligible ($y_{\text{CP}} \sim 0.5\%$) or cancel.
- ▶ SM predicts $a_{\text{CP}}^{\text{dir}}(\pi^+ \pi^-) \sim -a_{\text{CP}}^{\text{dir}}(K^+ K^-)$ so direct CPV contributions are enhanced ($< 10^{-2}$ within SM).

Production and detection asymmetries

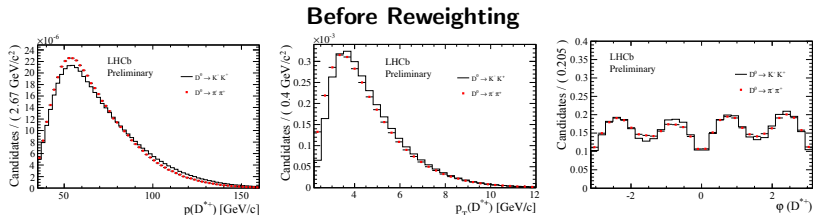
- ▶ What we actually measure is:

$$A_{\text{CP}}^{\text{RAW}}(f) \equiv A_{\text{CP}}(f) + \overbrace{A_{\text{D}}(f)}^{=0} + \overbrace{A_{\text{D}}(\pi_s^+)}^{\lesssim 1\%} + \overbrace{A_{\text{P}}(D^{*+})}^{\sim 1\%}$$

- ▶ Giving:

$$\Delta A_{\text{CP}}^{\text{RAW}} \equiv A_{\text{CP}}(f) + \Delta A_{\text{D}}(\pi_s^+) + \Delta A_{\text{P}}(D^{*+})$$

- ▶ For a given kinematical region of the D^{*+} , $\Delta A_{\text{D}}(\pi_s^+)$ and $\Delta A_{\text{P}}(D^{*+})$ are zero.



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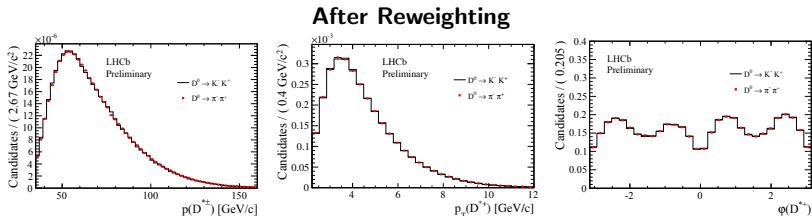
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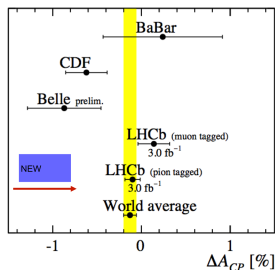
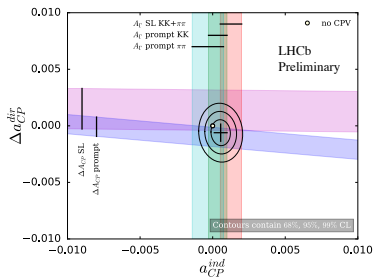
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Result

$$\Delta A_{CP} = (-0.10 \pm 0.08(\text{stat}) \pm 0.03(\text{sys})\%)$$

- Most precise determination of ΔA_{CP} , and compatible with muon-tagged result.



Phys. Rev. Lett. 100, 061803

Phys. Rev. Lett. 109, 111801

arXiv:121.5320

JHEP 07 (2014) 041

LHCb-PAPER-2015-055
to be submitted to PRL

No evidence for direct or indirect CPV in charm.

Conclusions

- ▶ LHCb has the world's largest sample of charm decays.
- ▶ Large number of publications, too many to cover here...
- ▶ First observation of D -mixing in $D \rightarrow K^+ \pi^- \pi^+ \pi^-$ decays.
 - ▶ Also provides constraints on charm interference parameters that are useful input for CKM phase γ determination.
- ▶ Most precise determination of a time-integrated CP asymmetry in charm.
 - ▶ Sadly, no hints of CPV.
- ▶ Run 2 of the LHC has started - many new and updated results to come soon!

Backup

Detection asymmetries.

- ▶ Trajectories of soft pion are bent in different directions for +ve and -ve.
- ▶ At LHCb it is possible to flip the magnet polarity, cancelling out such asymmetries.
 - ▶ but we do not rely on this cancellation - remove areas of large asymmetry.

