CP violation and mixing in charm from LHCb

Sam Harnew

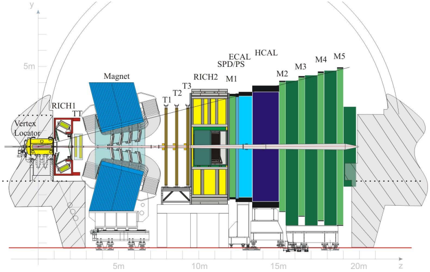
Outline

- Charm at LHCb.
- Introduction to charm mixing and CPV.
- D-mixing in $D \to K\pi\pi\pi$ decays [preliminary result].
- ΔA_{CP} in $D \to hh$ 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* $\sigma(c\bar{c}) = 1419 \pm 12(\text{stat}) \pm 116(\text{syst}) \pm 65\ (\text{frag})\,\mu\text{b}$ [1]
Run2 @ 13TeV* $\sigma(c\bar{c}) = 2940 \pm 3\ (\text{stat}) \pm 180(\text{syst}) \pm 160(\text{frag})\,\mu\text{b}$ [2]

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

- High COM collision energy gives D mesons a large flight distance in LHCb.
- Tracking within $5\,\text{mm}$ 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

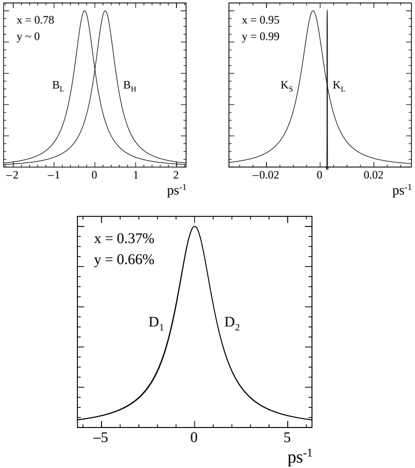
- Mass eigenstates are a superposition of flavour eigenstates:

$$|D_1\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\overline{D}^0\rangle$$

- Mixing depends on the mass and width difference:

$$x \equiv (m_2 - m_1)/\Gamma$$
$$y \equiv (\Gamma_2 - \Gamma_1)/2\Gamma$$

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



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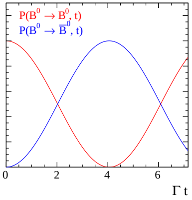
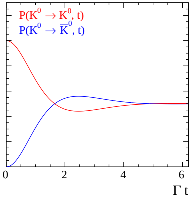
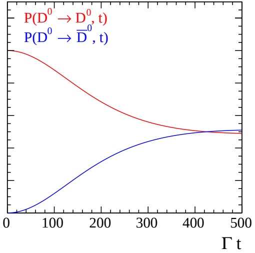






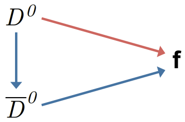
CPV in charm

Direct CPV: $\left|\mathcal{A}(D^0 \to f)\right| \neq \left|\mathcal{A}(\overline{D}^0 \to \bar{f})\right|$

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

Indirect CPV:

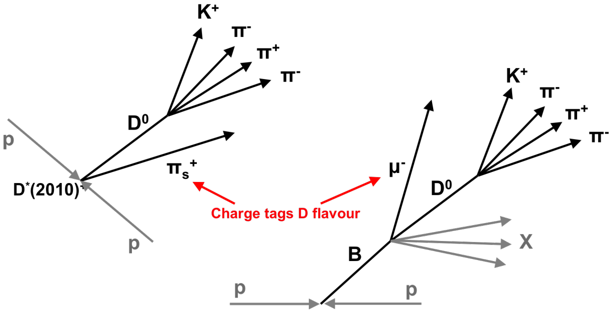
- **in mixing:** $\mathcal{P}(D^0 \to \overline{D}^0) \neq \mathcal{P}(\overline{D}^0 \to D^0)$
- **in interference:** $\arg\left(\frac{\mathcal{A}(D^0 \to f)}{\mathcal{A}(D^0 \to \overline{D}^0 \to f))}\right) \neq \arg\left(\frac{\mathcal{A}(\overline{D}^0 \to \bar{f})}{\mathcal{A}(\overline{D}^0 \to D^0 \to \bar{f})}\right)$
- 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:
  - $D^*(2010)^+ \to D^0\pi_s^+$ decays [used for both analyses presented here].
  - Semileptonic B meson decays.



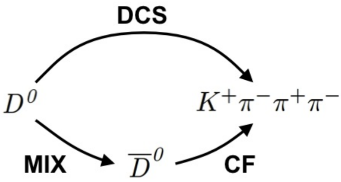
D-mixing in $D^0 \to K^+\pi^-\pi^+\pi^-$ decays

Preliminary result: soon to be submitted to PRL

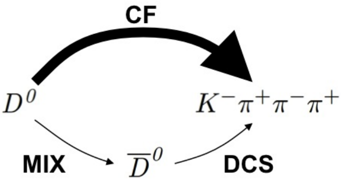
Formalism + Motivation

- 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



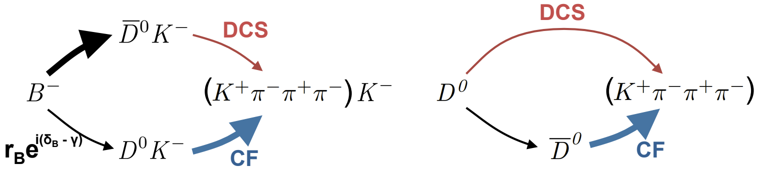
Right Sign Decay



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

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 $B^- \to DK^-, D \to K^+\pi^-\pi^+\pi^-$ things look remarkably similar...

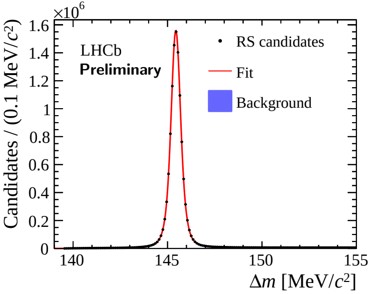


- This mode is sensitive to the CKM phase γ, but requires prior knowledge of $R_D^{K3\pi}$, $\delta_D^{K3\pi}$ and $r_D^{K3\pi}$.
- Constraints will be used for future determinations of γ in this decay mode.

Data sample

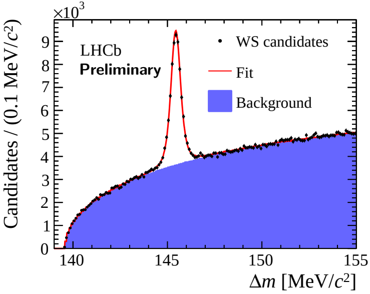
- Using full Run1 dataset ($3\,\text{fb}^{-1}$).
- Huge number of RS decays reconstructed with a high purity.

$D^0 \to K^+ \pi^- \pi^+ \pi^-$



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

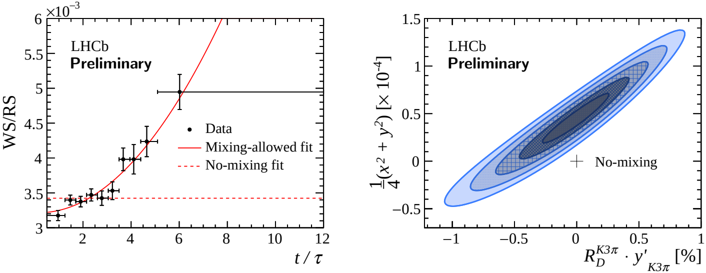
$D^0 \to K^- \pi^+ \pi^- \pi^+$



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

Mixing Significance

- Evaluate the mixing significance by comparing the χ^2 between mixing and no mixing hypotheses:
  - Mixing-allowed: $r(t) = (\overbrace{r_D^{K3\pi}}^{a})^2 - r_D^{K3\pi}\overbrace{R_D^{K3\pi} y'_{K3\pi}}^{b}\, t + \overbrace{\frac{1}{4}(x^2+y^2)}^{c}\, t^2$
  - No-mixing: $r(t) = (r_D^{K3\pi})^2$



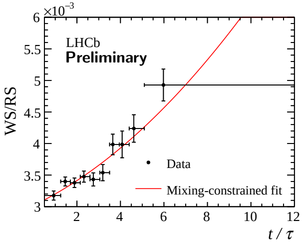
8.2σ Mixing Significance

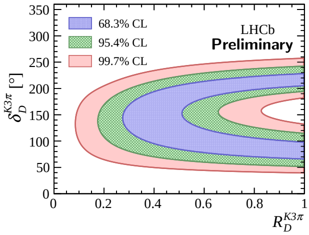
Mixing-constrained fit

- 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 $\psi(3770) \to D_{\mathrm{CP}+} D_{\mathrm{CP}-}$ 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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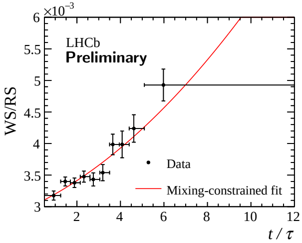
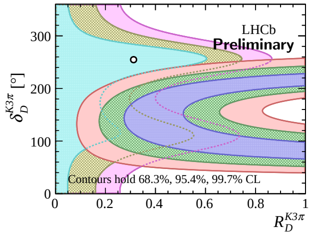




[1] Phys. Lett. B, Section B 731 (2014), pp. 197

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

arXiv:1602.03160 submitted to PRL

Formalism

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

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

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

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

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

Production and detection aysmmetries

- What we actually measure is:

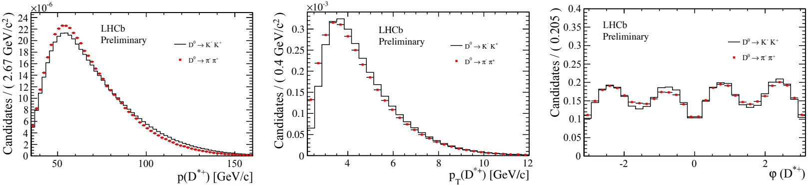
$$A_{\mathrm{CP}}^{\mathrm{RAW}}(f) \equiv A_{\mathrm{CP}}(f) + \overbrace{A_{\mathrm{D}}(f)}^{=0} + \overbrace{A_{\mathrm{D}}(\pi_s^+)}^{\lesssim 1\%} + \overbrace{A_{\mathrm{P}}(D^{*+})}^{\sim 1\%}$$

- Giving:

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

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

Before Reweighting



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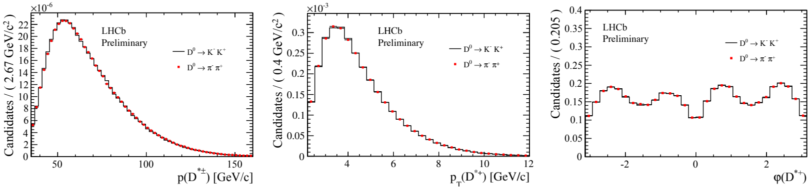
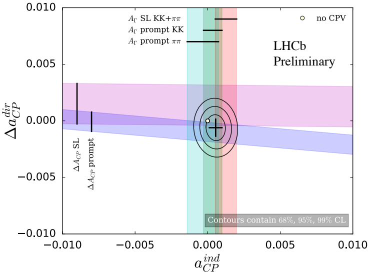
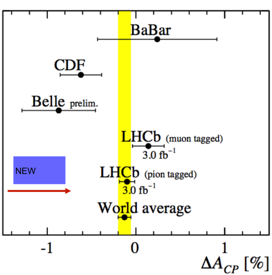


Result

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

- 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

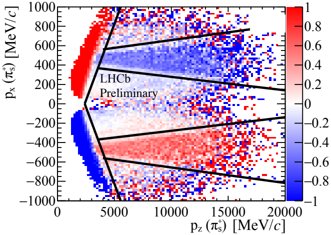
- LHCb has the world's largest sample of charm decays.
- Large number of publications, too many to cover here...
- First observation of D-mixing in $D \to K^+\pi^-\pi^+\pi^-$ decays.
  - Also provides constraints on charm interference parameters that are useful input for CKM phase γ determination.
- 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.

Magnet Up



Magnet Down