Charm mixing and *CP* violation at LHCb

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on behalf of the LHCb collaboration

13^{th}–19^{th} March 2016
Moriond EW, La Thuile

Introduction

Why charm?

- Mixing and *CP* violation established in kaon and *B* systems
- Only up-type quark where these effects may occur
- Expected to be very small effects in charm
- Sensitive to contributions from new physics

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Why LHCb?

- It is a true charm factory
- Excellent vertex resolution and particle identification

Charm cross-sections

In the LHCb acceptance $p_{\mathrm{T}} < 8\,\mathrm{GeV}$, $2 < y < 4.5$

$$\sigma(pp \to c\overline{c}) = \begin{array}{lcr} (1419 \pm 134)\,\mu\mathrm{b} & @ & 7\,\mathrm{TeV}\ [1] \\ (2940 \pm 240)\,\mu\mathrm{b} & @ & 13\,\mathrm{TeV}\ [2] \end{array}$$

Mixing and *CP* violation formalism

- Two mass and two flavour eigenstates

$$|D_{\mathrm{L,H}}\rangle = p\,|D^0\rangle \pm q\,|\overline{D}^0\rangle$$

- Mass and width splitting parameterised as

$$x = \frac{M_2 - M_1}{\Gamma}, \quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

- *CP* violation (CPV) manifests directly, indirectly, or as a superposition

$$\left|\frac{A_f}{\bar{A}_{\bar{f}}}\right| \neq 1, \quad \left|\frac{q}{p}\right| \neq 1, \quad \arg\left(\frac{qA_f}{p\bar{A}_{\bar{f}}}\right) \neq 0$$

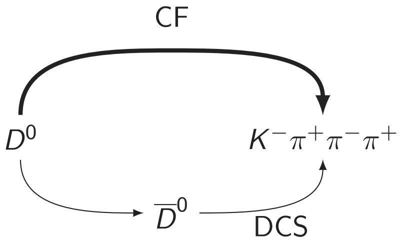
- Tag D^0 flavour with $D^{*+} \to D^0\pi^+$ or semileptonic decays of B hadrons

First observation of D^0–$\overline{D}^0$ oscillations in $D^0 \to K^+\pi^-\pi^+\pi^-$ decays and measurement of the associated coherence parameters

arXiv:1602.07224
Submitted to Phys. Rev. Lett.

D^0–$\overline{D}^0$ oscillations in $K^+\pi^-\pi^+\pi^-$

arXiv:1602.07224



Right-sign amplitude

D^0–$\overline{D}^0$ oscillations in $K^+\pi^-\pi^+\pi^-$

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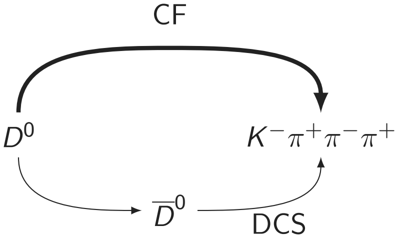

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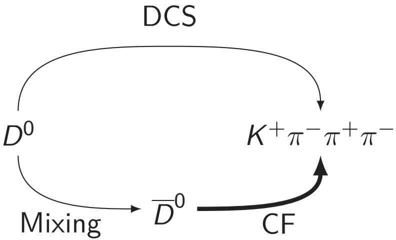

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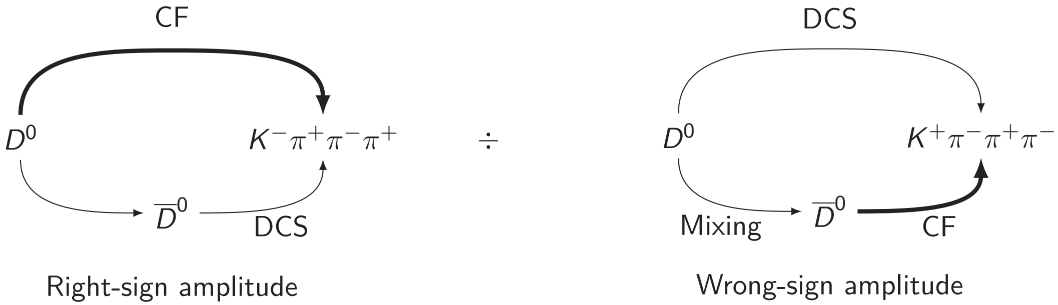

$$R(t) \approx r_D^2 + R_D r_D y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

$$x' = x\cos\delta + y\sin\delta, \quad y' = y\cos\delta - x\sin\delta$$

$$R_D e^{-i\delta} \equiv \langle\cos\delta\rangle + i\langle\sin\delta\rangle$$

D^0–$\overline{D}^0$ oscillations in $K^+\pi^-\pi^+\pi^-$

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- Using $3\,\text{fb}^{-1}$ of luminosity collected in Run 1
- Experimentally challenging
  - Lower reconstruction efficiency
  - Higher combinatorial background
  - Five-dimensional phase space to parameterise

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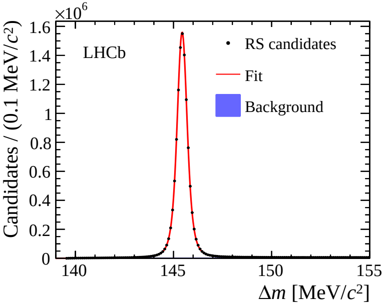

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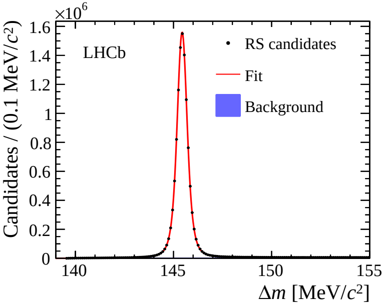
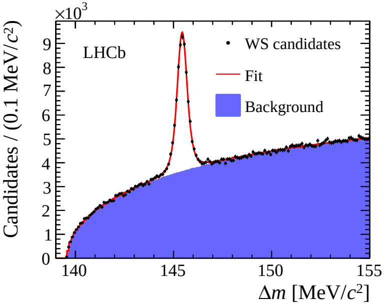
- 11×10^6 RS and 42×10^3 WS signal candidates





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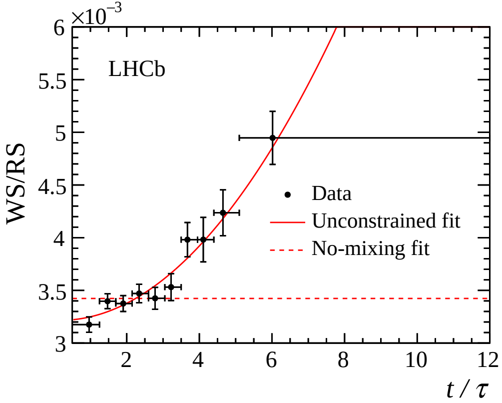

No-mixing hypothesis rejected at $8.2\,\sigma$

D^0–$\overline{D}^0$ oscillations in $K^+\pi^-\pi^+\pi^-$

arXiv:1602.07224

- Can measure γ with measurements of $B^\pm \to DK^\pm$

$$\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$$

- Compare rates of same final state with D^0 and $\overline{D}^0$
- Sensitivity increases with large strong phases differences between $D^0/\overline{D}^0$ decays
- This analysis is sensitive to this difference

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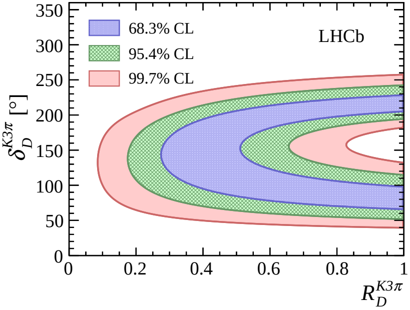
- Use HFAG inputs for x and y



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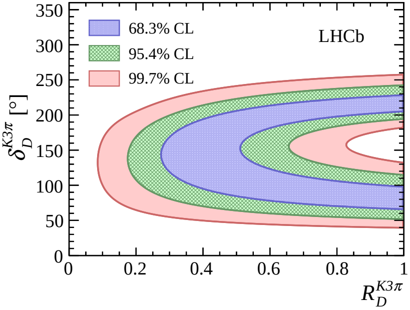

See Malcolm John's talk "CKM angle γ at LHCb"

Measurement of the difference of time-integrated CP asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays

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See Andreas Weiden's talk at YSF 1

Direct *CP* violation with ΔA_{CP}

arXiv:1602.03160

- Direct CPV if $|A_f/\bar{A}_{\bar{f}}| \neq 1$

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to \bar{f})}$$

- Can measure difference in yields experimentally

$$A_{\text{Raw}}(f) = \frac{N(D^{*+} \to (D^0 \to f)\pi^+) - N(D^{*-} \to (\overline{D}^0 \to \bar{f})\pi^-)}{N(D^{*+} \to (D^0 \to f)\pi^+) + N(D^{*-} \to (\overline{D}^0 \to \bar{f})\pi^-)}$$
$$\approx A_{CP}(f) + A_{\text{Production}}(D^{*+}) + A_{\text{Detection}}(\pi^+) + A_{\text{Detection}}(f)$$

- Experimentally robust to measure a difference with *CP* eigenstates

$$\Delta A_{CP} = A_{\text{Raw}}(K^-K^+) - A_{\text{Raw}}(\pi^-\pi^+)$$
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Direct CP violation with ΔA_{CP}

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- First measurement using $0.6\,\mathrm{fb}^{-1}$ of D^{*+}-tagged D^0 decays [1]

$$\Delta A_{CP} = (-0.82 \pm 0.21\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst}))\,\%$$

- Following measurements with B-tagged decays with $1\,\mathrm{fb}^{-1}$ and then $3\,\mathrm{fb}^{-1}$ [2]

$$\Delta A_{CP} = (0.14 \pm 0.16\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst}))\,\%$$

Direct CP violation with ΔA_{CP}

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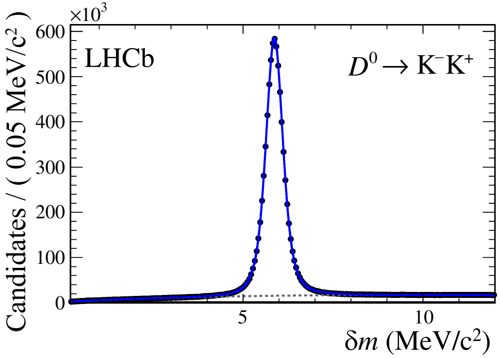
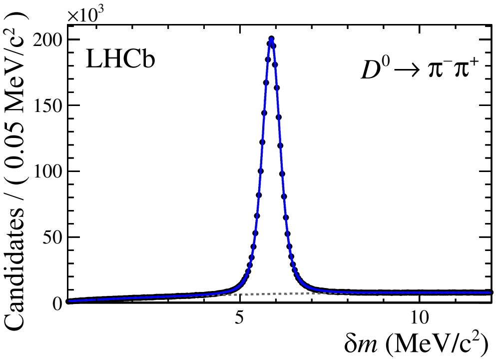
- New measurement using $3\,\text{fb}^{-1}$ of D^{*+}-tagged D^0 decays
- 7.7×10^6 $D^0 \to K^- K^+$ and 2.5×10^6 $D^0 \to \pi^- \pi^+$ signal candidates





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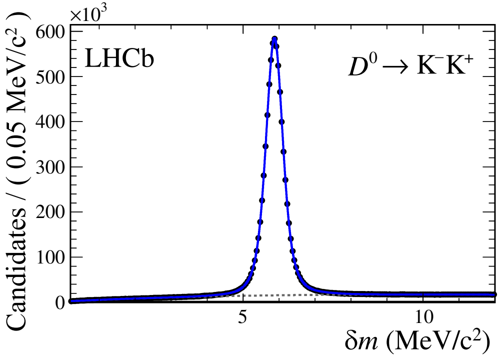

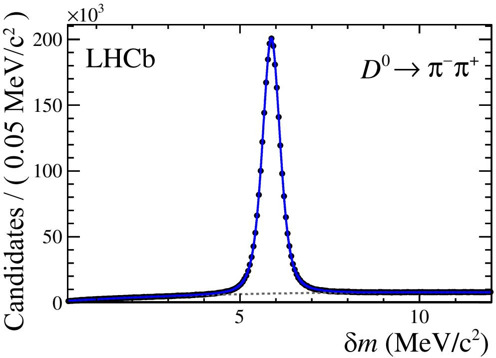

$$\Delta A_{CP} = (-0.10 \pm 0.08\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst}))\,\%$$

Direct CP violation with ΔA_{CP}

arXiv:1602.03160

- Can parameterise ΔA_{CP} into direct and indirect components

$$\Delta A_{CP} = \Delta a_{CP}^{\text{dir}} \left(1 + \frac{\overline{\langle t \rangle}}{\tau}\right) y_{CP} + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{\text{ind}}$$

- Also measure $\overline{\langle t \rangle}$, $\Delta \langle t \rangle$
- Use LHCb measurements of $A_{\Gamma} \approx -a_{CP}^{\text{ind}}$ and y_{CP} [1,2]

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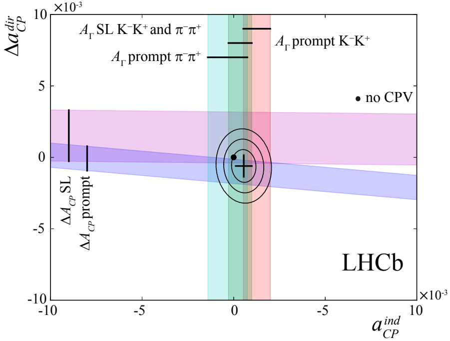

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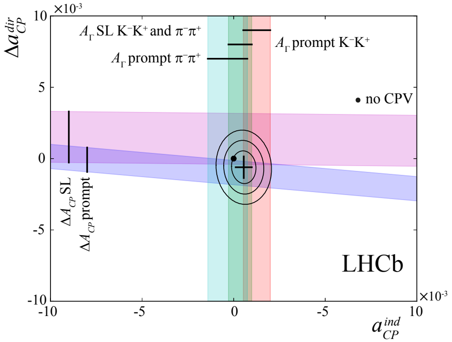

Consistent with CP conservation hypothesis with $p = 0.32$

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

arXiv:1510.01664, submitted to JHEP

- Novel model-independent measurement of x and y
- Uses strong phase measurements from resonant $\psi(3770)$ production
- Method now validated on $1\,\text{fb}^{-1}$ of data

$$x = (-0.86 \pm 0.53\,(\text{stat}) \pm 0.17\,(\text{syst}))\,\%,$$
$$y = (0.03 \pm 0.46\,(\text{stat}) \pm 0.13\,(\text{syst}))\,\%$$

Direct CP asymmetry with $D^0 \to K^0_S K^0_S$

JHEP 10 (2015) 055

- Measurement of yield asymmetry A_{CP}
- Theory predicts $\mathcal{O}(1\%)$ [1], single previous measurement $A_{CP} = (23 \pm 19)\,\%$ [2]
- Challenging: many K^0_S decay outside the vertex locator

$$A_{CP} = (-2.9 \pm 5.2\,(\text{stat}) \pm 2.2\,(\text{syst}))\,\%$$

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Summary

- LHCb is making many interesting charm measurements
- Very high precision
- New techniques
- Still more to come from Run 1
- Run 2 will bring a lot more data, a lot more interesting physics

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

Backup

D^0–$\overline{D}^0$ oscillations

Fit Type	Parameter	Fit result	Correlation coefficient			
χ^2/ndf (p-value)			$r_D^{K3\pi}$	$R_D^{K3\pi} \cdot y'_{K3\pi}$	$\frac{1}{4}(x^2+y^2)$	
Unconstrained	$r_D^{K3\pi}$	$(5.67 \pm 0.12) \times 10^{-2}$	1	0.91	0.80	
7.8/7 (0.35)	$R_D^{K3\pi} \cdot y'_{K3\pi}$	$(0.3 \pm 1.8) \times 10^{-3}$		1	0.94	
	$\frac{1}{4}(x^2+y^2)$	$(4.8 \pm 1.8) \times 10^{-5}$			1	
			$r_D^{K3\pi}$	$R_D^{K3\pi} \cdot y'_{K3\pi}$	x	y
Mixing-constrained	$r_D^{K3\pi}$	$(5.50 \pm 0.07) \times 10^{-2}$	1	0.83	0.17	0.10
11.2/8 (0.19)	$R_D^{K3\pi} \cdot y'_{K3\pi}$	$(-3.0 \pm 0.7) \times 10^{-3}$		1	0.34	0.20
	x	$(4.1 \pm 1.7) \times 10^{-3}$			1	-0.40
	y	$(6.7 \pm 0.8) \times 10^{-3}$				1

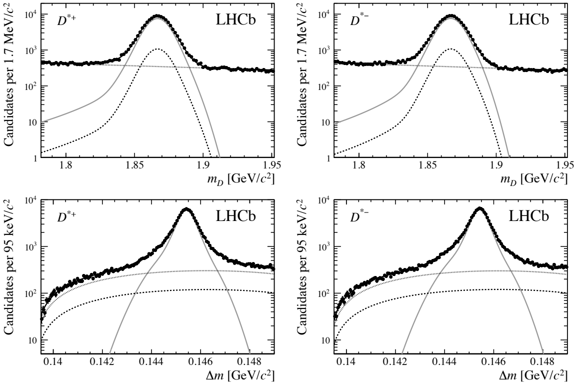
Fit results with and without constraints from HFAG x and y

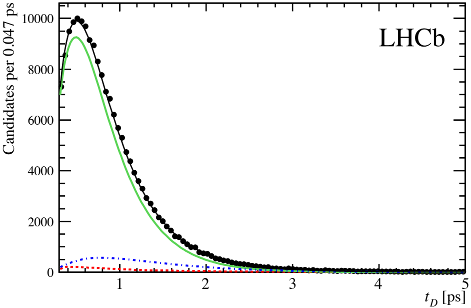
Direct CP violation with ΔA_{CP}

polarity	trigger	$\sqrt{s}$ [TeV]	ΔA_{CP} [%]
up	TOS	7	-0.40 ± 0.35
up	nTOS	7	-0.19 ± 0.29
down	TOS	7	-0.31 ± 0.29
down	nTOS	7	-0.06 ± 0.24
up	TOS	8	-0.11 ± 0.21
up	nTOS	8	-0.22 ± 0.17
down	TOS	8	-0.22 ± 0.21
down	nTOS	8	$+0.24 \pm 0.17$
average			-0.10 ± 0.08

Measurements of ΔA_{CP} on disjoint subsets of the data

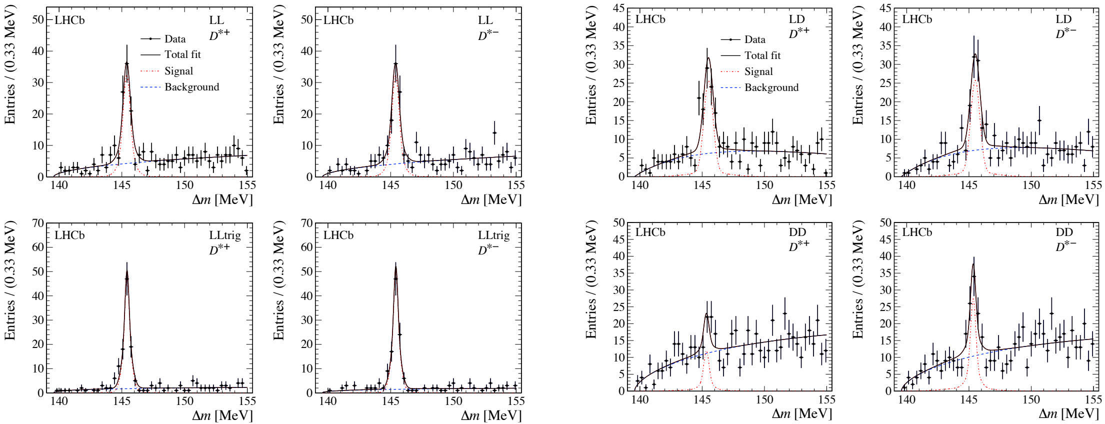
Mixing parameters with $D^0 \to K_S^0\pi^+\pi^-$





Fits to the mass difference Δm and decay time t for $D^0 \to K_S^0\pi^+\pi^-$

Direct CP asymmetry with $D^0 \to K^0_S K^0_S$



Fits to the mass difference Δm for different K^0_S vertex positions