Measurements of charm mixing and CP violation using $D^0 \to K^\pm\pi^\mp$ decays

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On Behalf of the LHCb Collaboration

Overview

Mixing

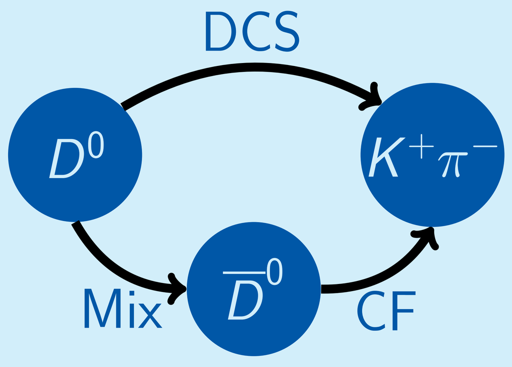
- Mixing in neutral mesons: mass≠flavor eigenstates
- $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$, $|p|^2+|q|^2=1$
- $x = \frac{m_2-m_1}{\Gamma}$, $y = \frac{\Gamma_2-\Gamma_1}{2\Gamma}$, $\Gamma = \frac{\Gamma_1+\Gamma_2}{2}$
- for $D^0\to K\pi$: $\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$

CP Violation

Direct CPV	CPV in Mixing	CPV in Interference
$\left\lvert\frac{\overline{A}_f}{A_f}\right\rvert \neq 1$	$\left\lvert\frac{q}{p}\right\rvert \neq 1$ or $\phi = \arg\left(\frac{q}{p}\right) \neq 0$	$\arg\left(\frac{q\overline{A}_f}{pA_f}\right) \neq 0$

$D^0 \to K^\pm\pi^\mp$

- RS decays: dominated by Cabibbo favored decay
- WS decays: two routes



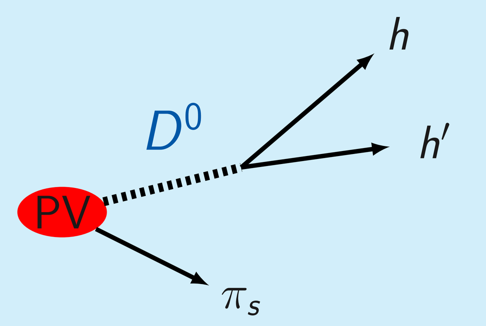
- Time dependent WS/RS ratio for $D^0(+)$ and $\overline{D}^0(-)$

$$R(t)^\pm = \frac{WS(t)^\pm}{RS(t)^\pm} \simeq R_D^\pm + \sqrt{R_D^\pm}y'^\pm\left(\frac{t}{\tau}\right) + \frac{x'^{\pm2}+y'^{\pm2}}{4}\left(\frac{t}{\tau}\right)^2$$

This Measurement [1]

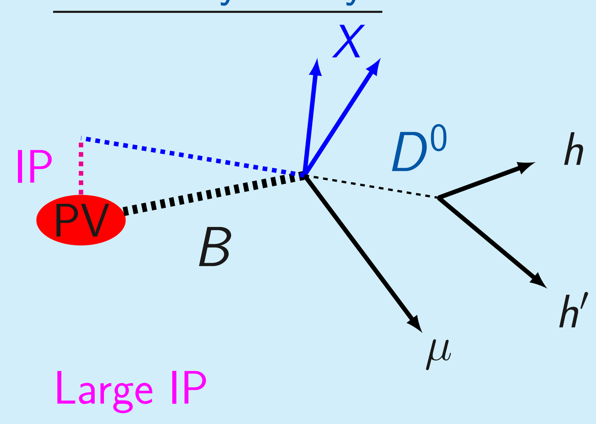
- Charm decay reconstruction

Prompt Decays



Impact Parameter (IP)∼0

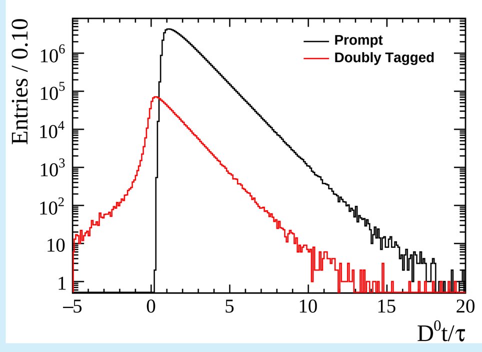
Secondary Decays



Large IP

- Search for mixing and CPV using decay chain

$B \to \mu^- D^{*+} X$, $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^\pm\pi^\pm$



[2]

- Doubly Tagged: μ^- and π_S^+ tag the D^0 at production
- Extremely clean
- Complements prompt $D^{*+}\to D^0\pi_s^+$ measurement [3]

Goals:

- Measure $WS(t)^\pm/RS(t)^\pm$ using DT sample only
- Combined fit with prompt result

Fit Variations

- No CPV: $R_D^+ = R_D^-$, $y'^+ = y'^-$, $(x'^+)^2 = (x'^-)^2$
- No Direct CPV: $R_D^+ = R_D^-$
- All CPV allowed: all parameters free

Inclusion of Detector Effects

- Incorporate detector effects, backgrounds

$$R^{obs\pm} = R(t)^\pm(1-\Delta_p^\pm)\left(\frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)}\right)^{\pm1} + p_{other}^\pm$$

What we want	∝Fraction of Prompt in DT Sample	$K\pi$ Detection Efficiency	Double MisID, other peaking

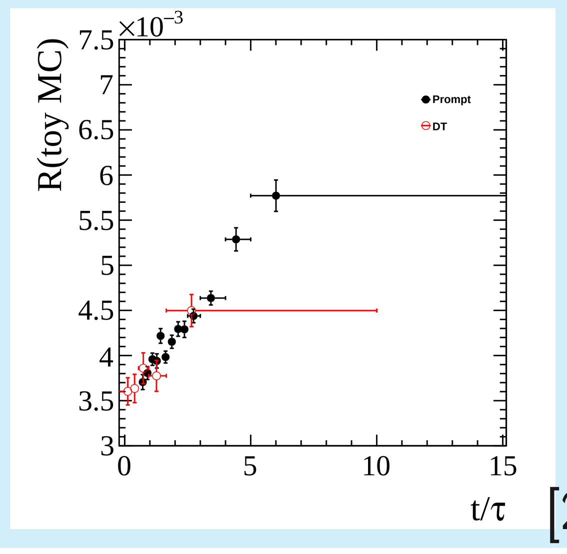
Expectations

Theoretical Expectations

- Mixing at 1 loop level in SM, GIM and CKM suppressed
- Long-range effects may dominate short-range interactions, difficult to calculate
- Short- and long-range calculations: $x, y \lesssim 0.5\%$
- CPV expected to be $\mathcal{O}(10^{-3})$ in SM [4, 5, 6, 7]
- Any enhancement could be New Physics

Experimental Expectations

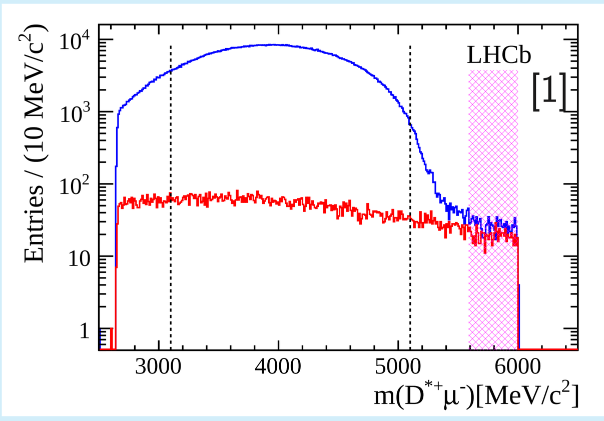
- From pseudo-experiments, statistics alone will reduce errors on R_D, y' by 17% and 15%
- Gain comes from low decay-time lever arm



[2]

Selection

- Kinematically constrain daughter K,π to same vertex, constrain μ, π_S and D^0 to come from same vertex
- Veto candidates which appear in both Prompt and DT samples
- Subtract random muon and muon mistag shape using $B\to\mu^+D^{*+}X$ (Unphysical "Same Sign" sample)
- Scale to sideband in each decay time bin



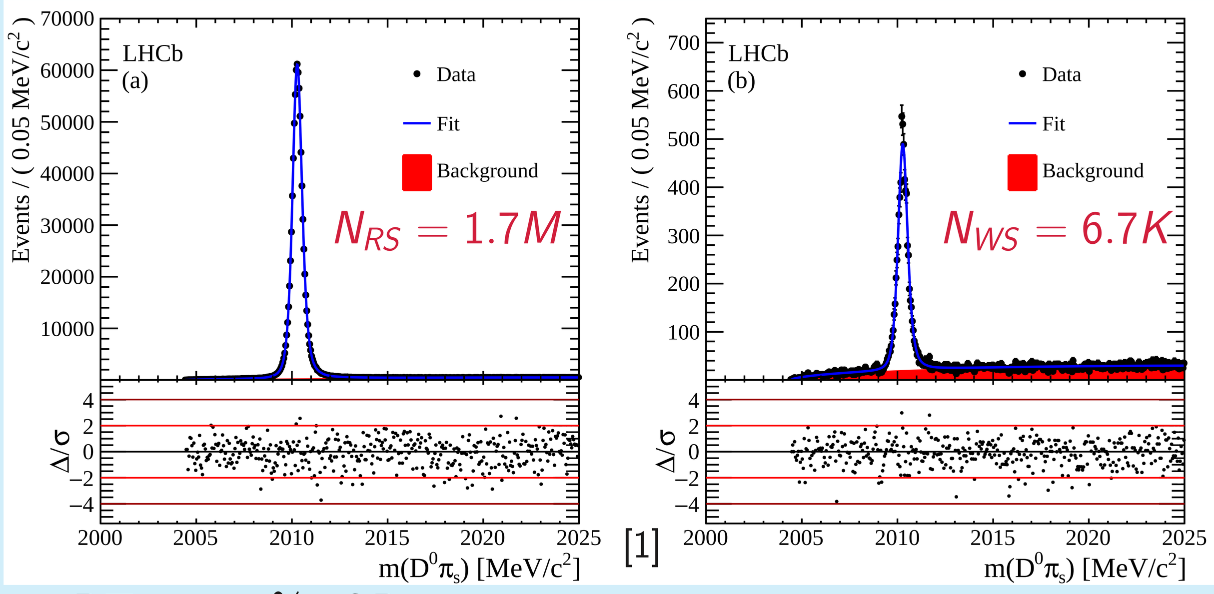
[1]

- Gauge systematic uncertainty by setting scaling factor to 1

These requirements set $\Delta_p^\pm = 0$

Yield Extraction

- Binned Maximum Likelihood Fit
- Signal: 3 Gaussian Core + 1 Johnson S_U [8]
- Background: Empirical shape
- Strategy: Fit full RS sample, fix signal shape, fit RS and WS in each of 5 decay time bins



[1]

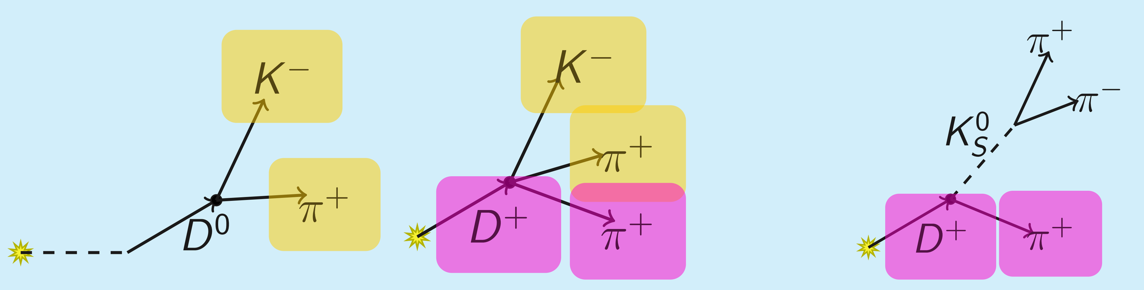
- DT = ∼ 3% of Prompt

Detection Asymmetries

$$A_{K\pi} = \frac{\epsilon(K^+\pi^-)-\epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-)+\epsilon(K^-\pi^+)}$$
$$\approx A(K_S^0\pi)_{raw} - A(K\pi\pi)_{raw} - A(\overline{K}^0) + A_{\text{Muon Trigger}}$$

[9, 10]

- $A(\overline{K}^0) = -(0.05\pm0.01)\%$ from [9]
- $A_{\text{Muon Trigger}}$ directly from DT data
- To cancel $D^\pm$ production asymmetry, must weight samples



$A(K\pi) = [0.90\pm0.18\pm0.10]\%$

Peaking Backgrounds

- Divide low and high D^0 sidebands into 6 regions each
- Fit $m(D^*)$ in each bin, extract the number of peaking events
- Project into signal region, extract number of peaking events. Total: 128 ± 31
- Integrated over decay time due to limited statistics
- Fraction of doubly misidentified D^0 to RS yield: $(7.4\pm1.8)\times10^{-5} \equiv p_{\text{other}}$

CPV Fit Strategy

- Fit by minimizing

$$\chi^2 = \sum_{i\in\text{Time Bins}}\left[\left(\frac{r_i^+ - \widetilde{R}(t_i)^+}{\sigma_i^+}\right)^2 + \left(\frac{r_i^- - \widetilde{R}(t_i)^-}{\sigma_i^-}\right)^2\right] + \chi^2_\epsilon + \chi^2_{\text{peaking}} + \chi^2_{\text{other}}$$

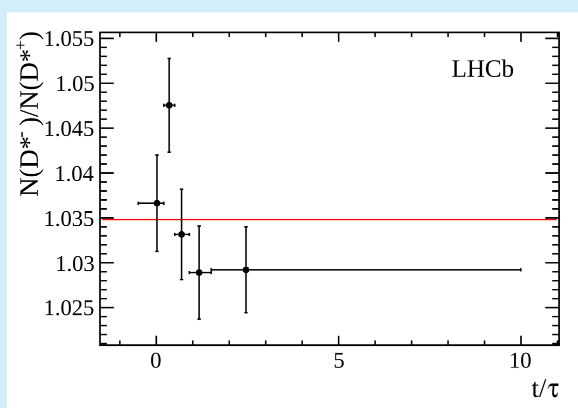
- $r_i^\pm$ = measured $WS^\pm/RS^\pm$, with error $\sigma_i^\pm$
- $\widetilde{R}(t_i)^\pm$ = Expected value from $R^{obs\pm}$ averaged over bin
- $(\chi^2_\epsilon + \chi^2_{\text{peaking}} + \chi^2_{\text{other}})$ are gaussian constraints on $A(K\pi)$, $\Delta_p = 0$, and p_{other}

Systematic Uncertainties

Source of systematic uncertainty	Uncertainty on parameter					
No CPV	$R_D[10^{-3}]$	$y'[10^{-3}]$	$x'^2[10^{-4}]$			
$D^{*+}\mu^+$ scaling	0.01	0.04	0.04			
$A(K\pi)$ time dependence	0.01	0.07	0.04			
RS fit model time variation	0.00	0.01	0.03			
No prompt veto	0.01	0.16	0.09			
Total	0.01	0.18	0.11			
No direct CPV	$R_D[10^{-3}]$	$y'^+[10^{-3}]$	$(x'^+)^2[10^{-4}]$	$y'^-[10^{-3}]$	$(x'^-)^2[10^{-4}]$	
$D^{*+}\mu^+$ scaling	0.01	0.04	0.04	0.03	0.04	
$A(K\pi)$ time dependence	0.01	1.17	0.98	1.64	1.67	
RS fit model time variation	0.00	0.02	0.03	0.01	0.03	
No prompt veto	0.01	0.11	0.00	0.19	0.19	
Total	0.01	1.17	0.98	1.66	1.68	
All CPV allowed	$R_D^+[10^{-3}]$	$y'^+[10^{-3}]$	$(x'^+)^2[10^{-4}]$	$R_D^-[10^{-3}]$	$y'^-[10^{-3}]$	$(x'^-)^2[10^{-4}]$
$D^{*+}\mu^+$ scaling	0.01	0.03	0.04	0.01	0.04	0.04
$A(K\pi)$ time dependence	0.06	0.25	0.03	0.07	0.28	0.03
RS fit model time variation	0.00	0.01	0.01	0.00	0.04	0.05
No prompt veto	0.01	0.09	0.01	0.01	0.21	0.19
Simulated DT coverage	0.00	0.18	0.30	0.00	0.18	0.33
Total	0.06	0.32	0.31	0.07	0.40	0.38

$A(K\pi)$ time dependence

- Find variation in RS^-/RS^+ ratio
- Consistent with flat line at $p = 0.06$
- Assess systematic uncertainty by adding decay-time variation to $A(K\pi)$

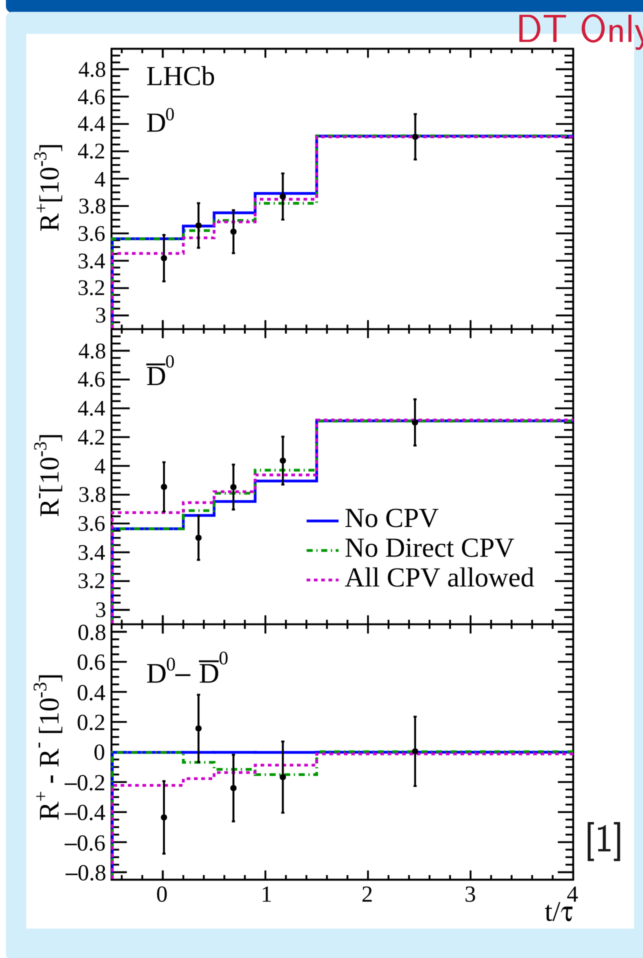


[1]

Results

Consistent with No CPV

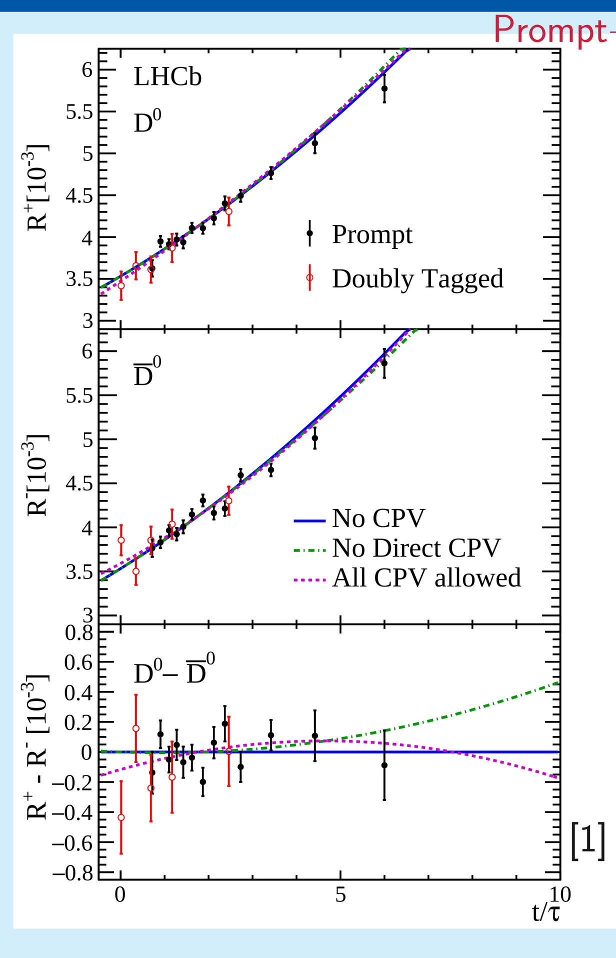
DT Only



[1]

Parameter	Value
No CPV	
$R_D[10^{-3}]$	$3.48\pm0.10\pm0.01$
$x'^2[10^{-4}]$	$0.28\pm3.10\pm0.11$
$y'[10^{-3}]$	$4.60\pm3.70\pm0.18$
χ^2/ndf	6.3/7
No direct CPV	
$R_D[10^{-3}]$	$3.48\pm0.10\pm0.01$
$(x'^+)^2[10^{-4}]$	$1.94\pm3.67\pm1.17$
$y'^+[10^{-3}]$	$2.79\pm4.27\pm0.98$
$(x'^-)^2[10^{-4}]$	$-1.53\pm4.04\pm1.68$
$y'^-[10^{-3}]$	$6.51\pm4.38\pm1.66$
χ^2/ndf	5.6/5
All CPV allowed	
$R_D^+[10^{-3}]$	$3.38\pm0.15\pm0.06$
$(x'^+)^2[10^{-4}]$	$-0.19\pm4.46\pm0.32$
$y'^+[10^{-3}]$	$5.81\pm5.25\pm0.31$
$R_D^-[10^{-3}]$	$3.60\pm0.15\pm0.07$
$(x'^-)^2[10^{-4}]$	$0.79\pm4.31\pm0.38$
$y'^-[10^{-3}]$	$3.32\pm5.21\pm0.40$
χ^2/ndf	4.5/4

Prompt+DT



[1]

Parameter	DT + Prompt	Prompt-only	Improvement
No CPV			
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067	19%
$x'^2[10^{-4}]$	0.36 ± 0.43	0.55 ± 0.49	12%
$y'[10^{-3}]$	5.23 ± 0.84	4.8 ± 0.9	11%
χ^2/ndf	96.6/111	86.4/101	
No direct CPV			
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067	19%
$(x'^+)^2[10^{-4}]$	0.49 ± 0.50	0.64 ± 0.56	11%
$y'^+[10^{-3}]$	5.14 ± 0.91	4.8 ± 1.1	16%
$(x'^-)^2[10^{-4}]$	0.24 ± 0.50	0.46 ± 0.55	9%
$y'^-[10^{-3}]$	5.32 ± 0.91	4.8 ± 1.1	16%
χ^2/ndf	96.1/109	86.0/99	
All CPV allowed			
$R_D^+[10^{-3}]$	3.474 ± 0.081	3.545 ± 0.095	15%
$(x'^+)^2[10^{-4}]$	0.11 ± 0.65	0.49 ± 0.70	7%
$y'^+[10^{-3}]$	5.97 ± 1.25	5.1 ± 1.4	9%
$R_D^-[10^{-3}]$	3.591 ± 0.081	3.591 ± 0.090	10%
$(x'^-)^2[10^{-4}]$	0.61 ± 0.61	0.60 ± 0.68	10%
$y'^-[10^{-3}]$	4.50 ± 1.21	4.5 ± 1.4	13%
χ^2/ndf	95.0/108	85.9/98	

References

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