LHCb Charm Mixing and CPV Measurements

Mixing and CPV from Wrong-Sign $D^0 \to K\pi$

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Mixing in a Nutshell

- Neutral Mesons produced as flavor eigenstates $\left(|D^0\rangle, |\overline{D}^0\rangle\right)$
- Time Evolution:

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} |D^0\rangle \\ |\overline{D}^0\rangle \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} |D^0\rangle \\ |\overline{D}^0\rangle \end{pmatrix}$$

- Mass/Lifetime Eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$, $|p|^2 + |q|^2 = 1$
- $m_{1,2}$ and $\Gamma_{1,2}$ are eigenvalues of mixing Hamiltonian
- Mixing occurs when mass/lifetime$\neq$flavor eigenstates

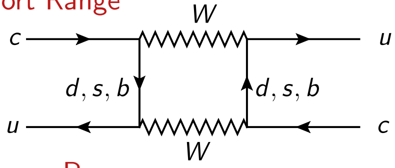
$$\boxed{x = \frac{m_2 - m_1}{\Gamma}} \quad \boxed{y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}}, \ \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

- CPV in mixing occurs when $\left|\frac{q}{p}\right| \neq 1$ and/or $\phi = \arg\left(\frac{q}{p}\right) \neq 0$

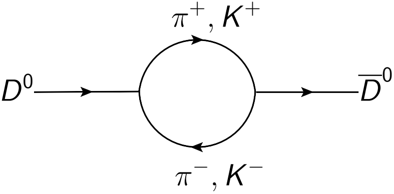
Why Charm Mixing?

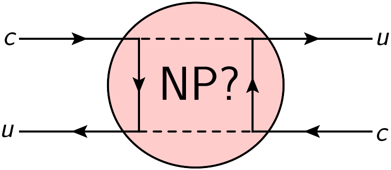
- Only up-type quark system with mixing/CPV
- Mixing enters at 1 loop level in SM, GIM and CKM suppressed
- Non-perturbative long-range effects may dominate short-range interactions, difficult to calculate
- $x, y \leq \mathcal{O}(10^{-3})$ in short distance, max $\sim \mathcal{O}(10^{-2})$ in long distance
- CPV expected to be $\leq \mathcal{O}(10^{-3})$ in SM
- If CPV observed at $\mathcal{O}(10^{-2})$ $\rightarrow$ New Physics (NP)

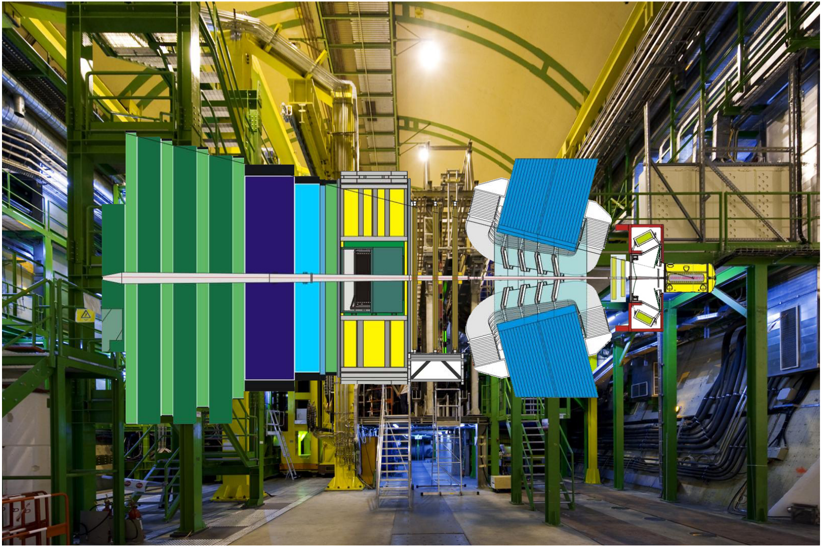
Short Range

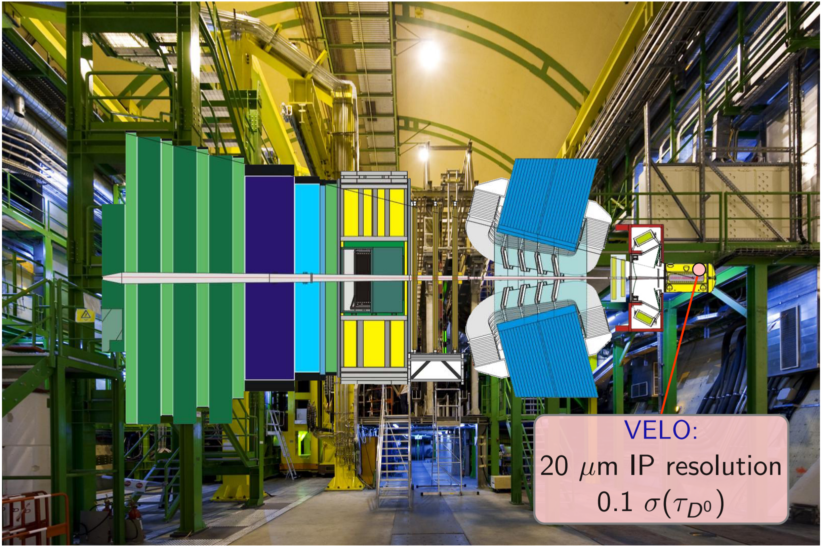


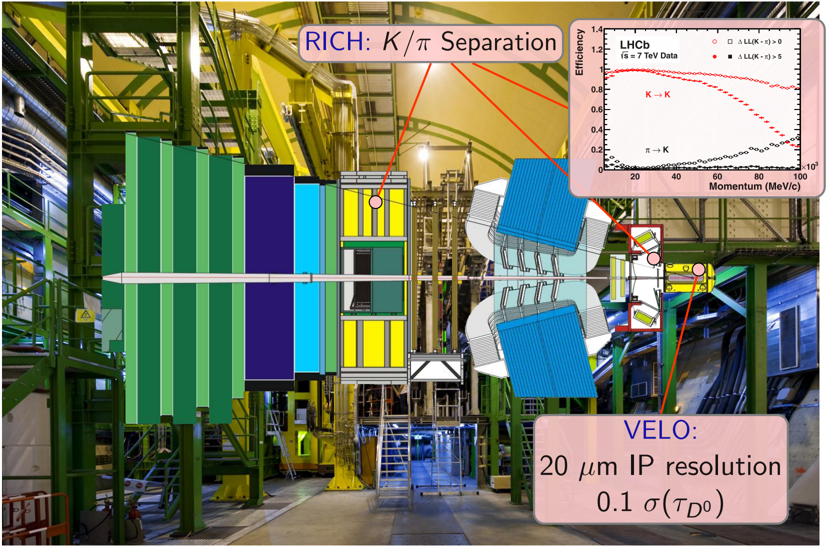
Long Range








VELO:
20 μm IP resolution
0.1 $\sigma(\tau_{D^0})$


RICH: K/π Separation
LHCb
$\sqrt{s}$ = 7 TeV Data
Δ LL(K - π) > 0
Δ LL(K - π) > 5
K → K
π → K
Efficiency
Momentum (MeV/c)
×10³
VELO:
20 μm IP resolution
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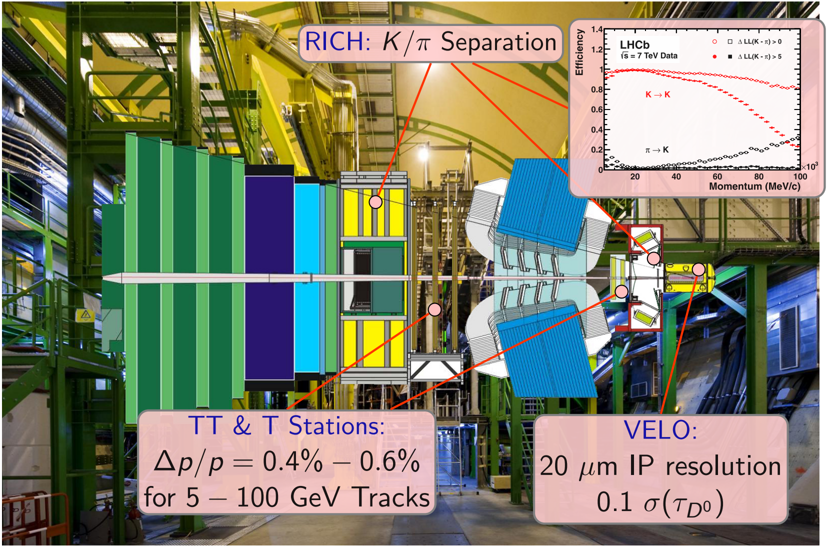
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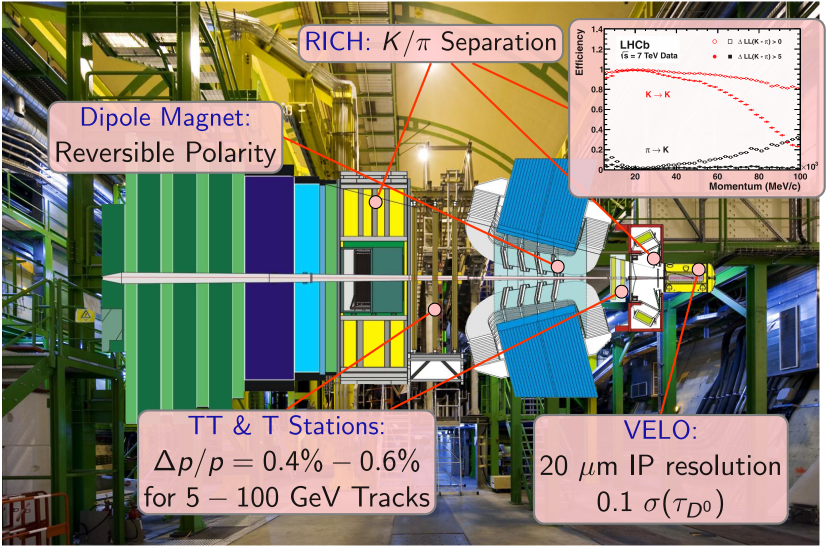
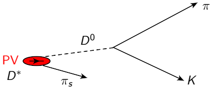
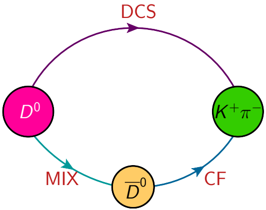
Momentum (MeV/c)
TT & T Stations:
$\Delta p/p = 0.4\% - 0.6\%$
for 5 – 100 GeV Tracks
VELO:
20 μm IP resolution
0.1 $\sigma(\tau_{D^0})$

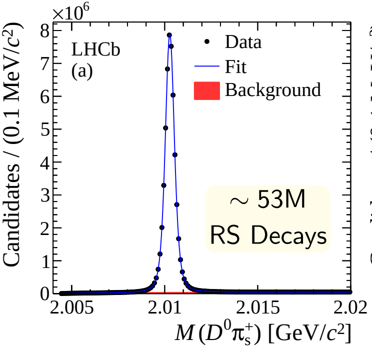

RICH: K/π Separation
Dipole Magnet:
Reversible Polarity
TT & T Stations:
$\Delta p/p = 0.4\% - 0.6\%$
for $5 - 100$ GeV Tracks
VELO:
20 μm IP resolution
0.1 $\sigma(\tau_{D^0})$
Efficiency
LHCb
$\sqrt{s}$ = 7 TeV Data
ΔLL(K - π) > 0
ΔLL(K - π) > 5
K → K
π → K
Momentum (MeV/c)
$\times 10^3$

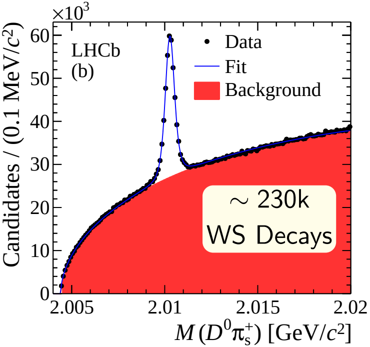
Analyis Strategy

- Reconstruct $D^{*+} \to D^0 \pi_s^+$,
- RS: $D^0 \to K^- \pi^+$
- WS: $D^0 \to K^+ \pi^-$
- 2011+2012 Dataset: 3 fb^{-1}



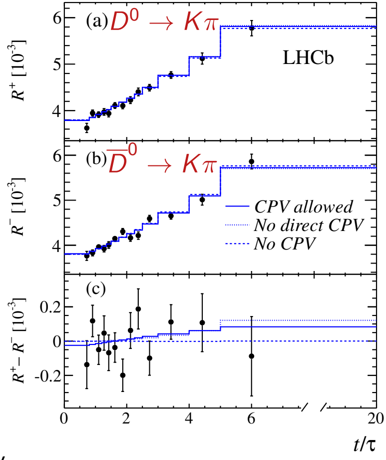




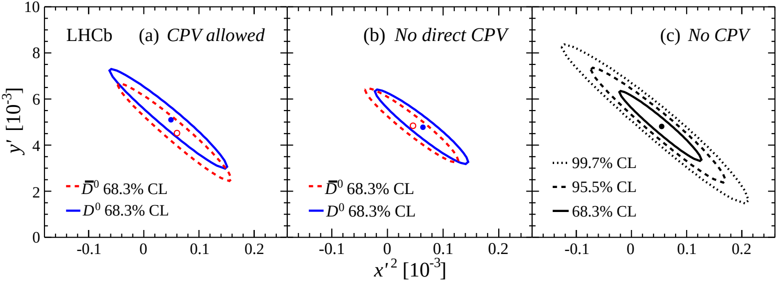


CPV Fit Stragegy

- For small x & y, $R(t) = \frac{WS(t)}{RS(t)} =$
  $R_D + \sqrt{R_D} y' \left(\frac{t}{\tau}\right) + \frac{(x'^2+y'^2)}{4} \left(\frac{t}{\tau}\right)^2$
  $\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$
- Split sample into $D^0(D^{*+})$ and $\overline{D}^0(D^{*-})$
- $R(t)^{\pm} = \left(\frac{WS(t)}{RS(t)}\right)^{\pm} =$
  $R_D^{\pm} + \sqrt{R_D^{\pm}} y'^{\pm} \left(\frac{t}{\tau}\right) + \frac{(x'^{\pm})^2+(y'^{\pm})^2}{4} \left(\frac{t}{\tau}\right)^2$
- Direct CPV $\rightarrow R_D^+ \neq R_D^-$
- Indirect CPV $\rightarrow (x'^{2+}, y'^{+}) \neq (x'^{2-}, y'^{-})$
- $K\pi$ detection asymmetry and secondary decay accounted for in fit



Results



Direct and indirect CPV	
$R_D^+[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$
$y'^+[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$
$x'^{2+}[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$
$R_D^-[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$
$y'^-[10^{-3}]$	$4.5 \pm 1.2 \pm 0.7$
$x'^{2-}[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$
χ^2/ndf	85.9/98

No direct CPV	
$R_D[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
$y'^+[10^{-3}]$	$4.8 \pm 0.9 \pm 0.6$
$x'^{2+}[10^{-5}]$	$6.4 \pm 4.7 \pm 3.0$
$y'^-[10^{-3}]$	$4.8 \pm 0.9 \pm 0.6$
$x'^{2-}[10^{-5}]$	$4.6 \pm 4.6 \pm 3.0$
χ^2/ndf	86.0/99

No CPV	
$R_D[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
$y'[10^{-3}]$	$4.8 \pm 0.8 \pm 0.5$
$x'^2[10^{-5}]$	$5.5 \pm 4.2 \pm 2.6$
χ^2/ndf	86.4/101

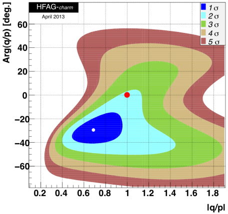
Results consistent with CP Conservation

The Impact: World Average, All-CPV allowed

April 2013

(w/ LHCb 2011 1 fb^{-1}

$D^0 \to K\pi$)

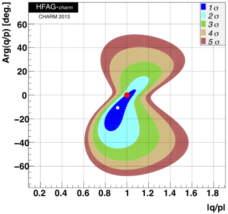


- $|q/p| = 0.69 \pm 0.16$

September 2013

(LHCb 2011+2012, 3 fb^{-1}

$D^0 \to K\pi$)



- $|q/p| = 0.91 \pm 0.10$

Indirect CPV

- In the case of Indirect CPV, ϕ and $|q/p|$ are related (superweak constraint)

$$\tan\phi = \left(1 - \frac{q}{p}\right)\frac{x}{y}$$

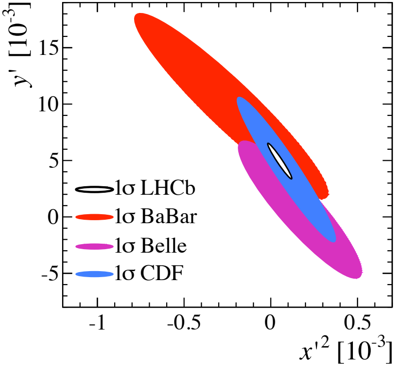
Dataset	$\lvert q/p\rvert[\%]$	$\phi[^\circ]$
HFAG April 2013	100.4 ± 6.5	-1.6 ± 2.5
LHCb $D^0 \to K\pi$ CPV (no other CPV params)	100.9 ± 1.6	-0.5 ± 0.8
LHCb CPV + prior measurements	99.3 ± 1.3	$+0.4 \pm 0.7$

Summary

- We are in the era of precision neutral charm mixing and CPV
- LHCb is leading the way
  (as it is in many other flavor physics measurements)

Backup Slides

The Impact: Comparison to other experiments



HFAG-like Fit: Formalism

- Construct χ^2 for combining all results

$$\chi^2 = \vec{\epsilon}^T \sigma^{-1} \vec{\epsilon} \tag{1}$$

- $\vec{\epsilon} = \vec{m} - \vec{p}$, where m_i is a measurement and p_i is the proposed value.
- $\sigma = e_i c_{ij} e_j$ is $N \times N$ matrix, N is number of measurements e is each individual error and c_{ij} is the correlation coefficient.
- If uncorrelated, get $\sum_i \chi_i^2$