Charm Mixing and CPV at LHCb

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On behalf of the LHCb Collaboration

August 15, 2013

Outline

Mixing in a Nutshell

- Mixing in Neutral Mesons: mass≠flavor eigenstates
- Mixing Hamiltonian: $H = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$
- Mass Eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$, $|p|^2 + |q|^2 = 1$

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

3 Types of CPV

Direct CPV (Charged and Neutral)

$\mathcal{A}_f = \langle f|\mathcal{H}|D\rangle, \overline{\mathcal{A}}_{\overline{f}} = \langle \overline{f}|\mathcal{H}|\overline{D}\rangle$

$$\boxed{\left|\frac{\overline{\mathcal{A}}_{\overline{f}}}{\mathcal{A}_f}\right| \neq 1}$$

CPV in Mixing (Neutral)

$$\boxed{\phi = \arg\left(\frac{q}{p}\right) \neq 0} \text{ (weak phase)}$$

or $\boxed{\left|\frac{q}{p}\right| \neq 1}$

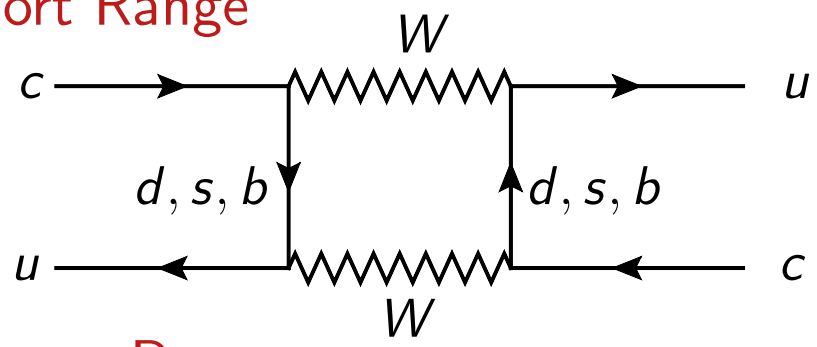
CPV in Interference (Neutral)

$$\boxed{\arg\left(\frac{q}{p}\frac{\overline{\mathcal{A}}_f}{\mathcal{A}_f}\right) \neq 0}$$

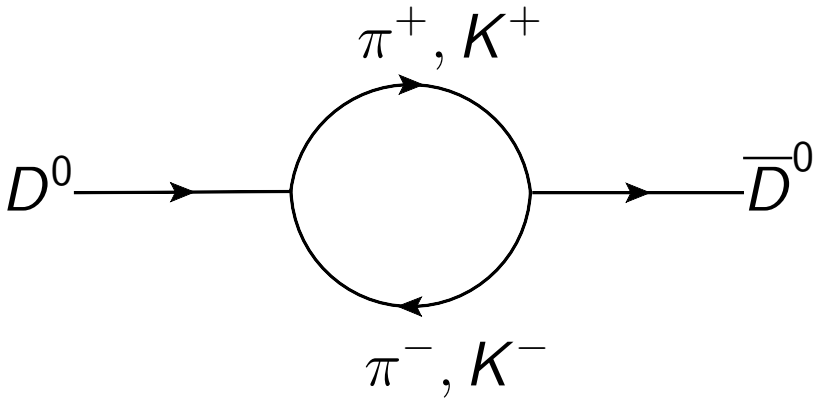
Charm Mixing in the SM

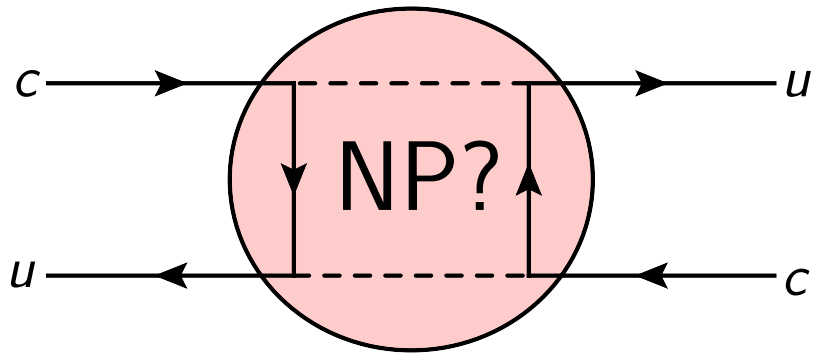
- Only up-type quark system with mixing/CPV
- Mixing enters at 1 loop level in SM, GIM and CKM suppressed
- Non-perturbative long-range effects may dominate short-range interactions, difficult to calculate
- x, y expected to be small in short and long range limits, CPV expected to be $\mathcal{O}(10^{-3})$ in SM
- If enhancement of CPV is seen, could be caused by New Physics (NP)

Short Range

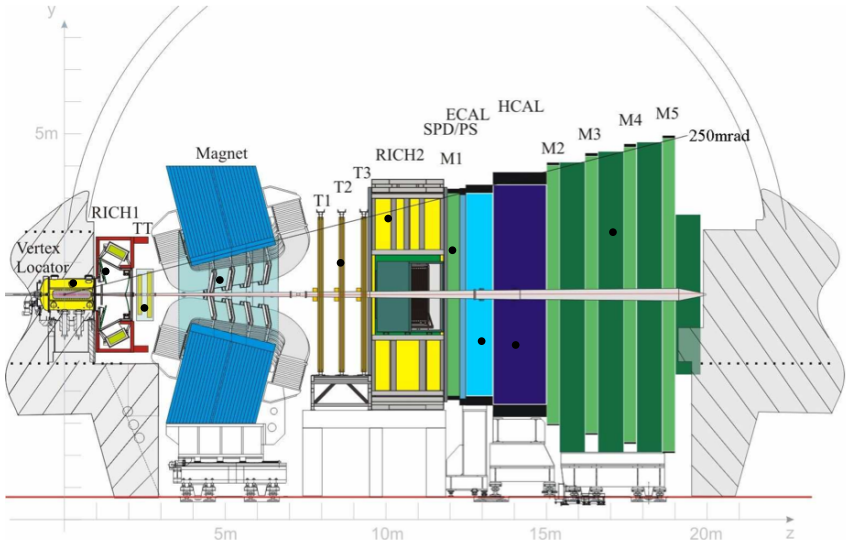


Long Range





The Detector



- $\sigma(c\bar{c})_{\text{LHCb, 7TeV}} = 1419 \pm 133\mu b$

  Nucl.Phys.B 871(2013), 1
- $\sigma(b\bar{b})_{\text{LHCb, 7TeV}} = 75.3 \pm 14.1\mu b$

  Phys. Lett. B 694 (2010), 209
- $\sim$ 350M reconstructed charm decays in 2011!

  (LHCb-TALK-2012-078)

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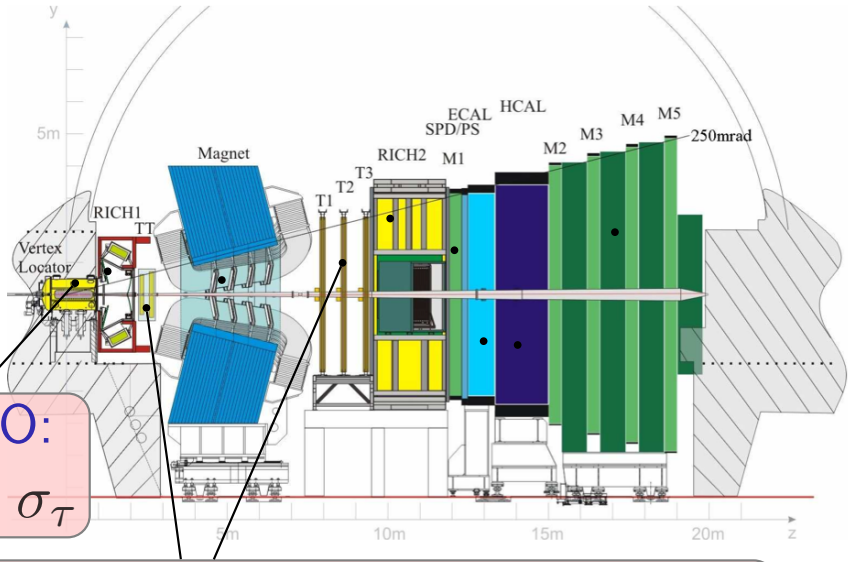

VELO:
40 fs σ_τ

TT & T Stations:
$\Delta p/p = 0.4\% - 0.6\%$ for $5 - 100$ GeV Tracks

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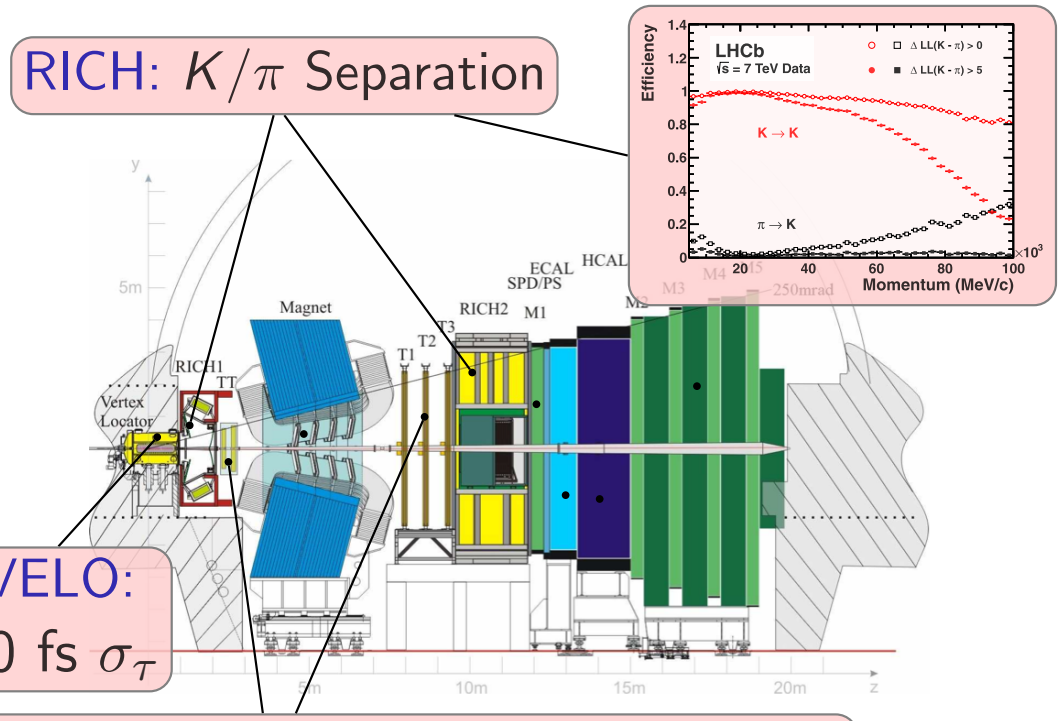

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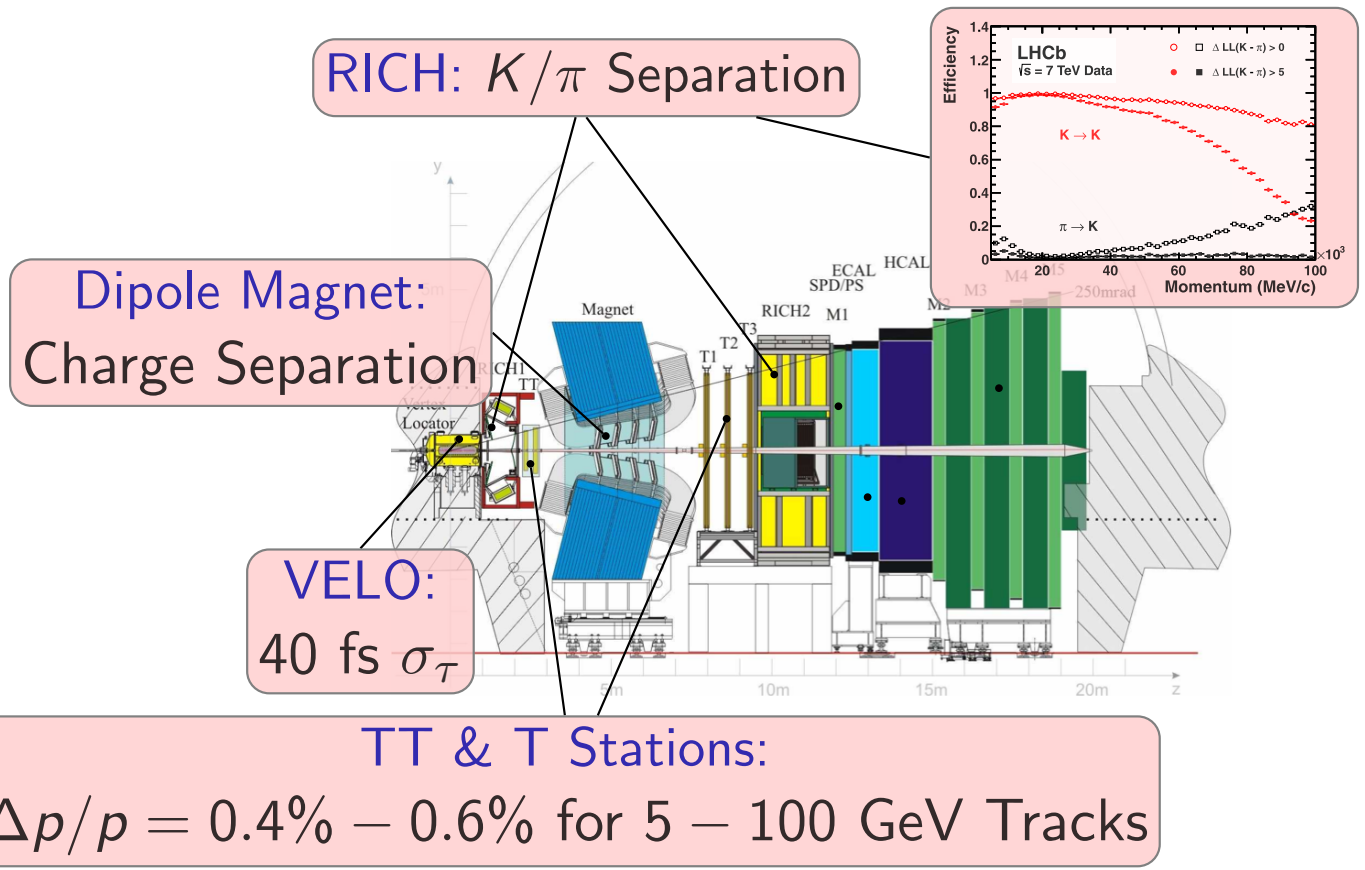

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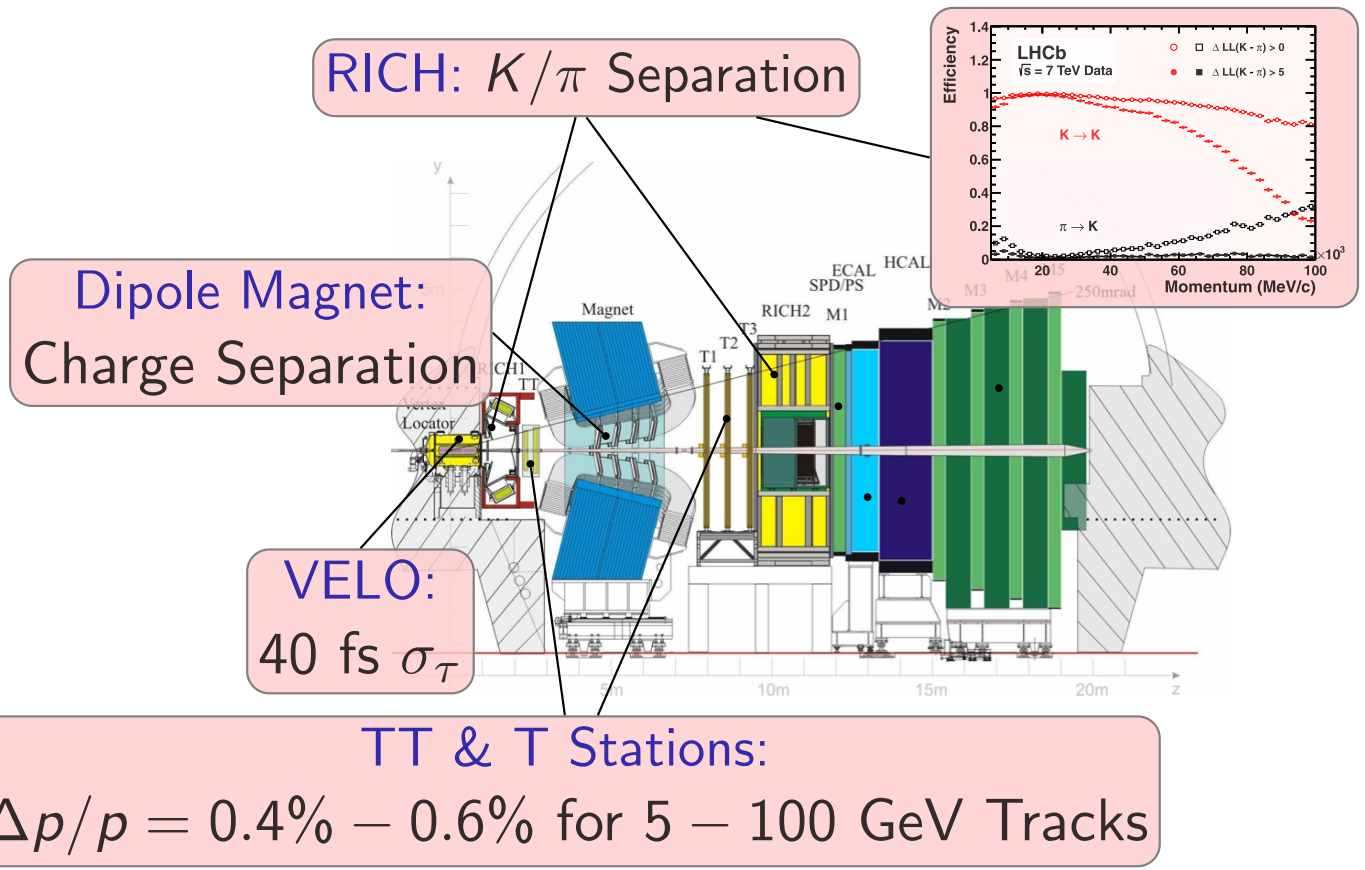

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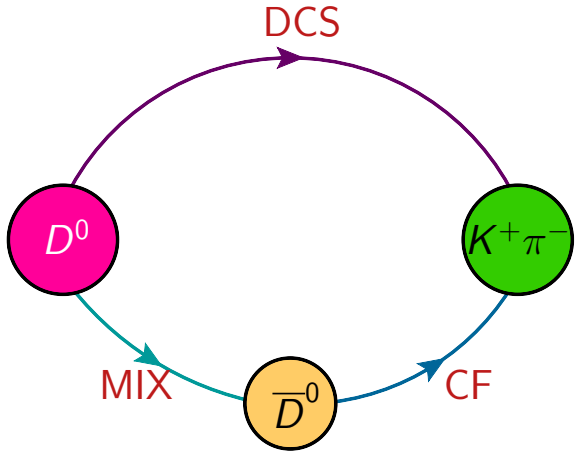
  (LHCb-TALK-2012-078)
- Results presented today from $\sqrt{s} = 7$ TeV 2011 Data, 1fb^{-1}

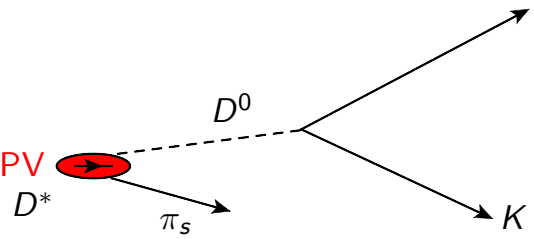
PRL 110, 101802 (2013)

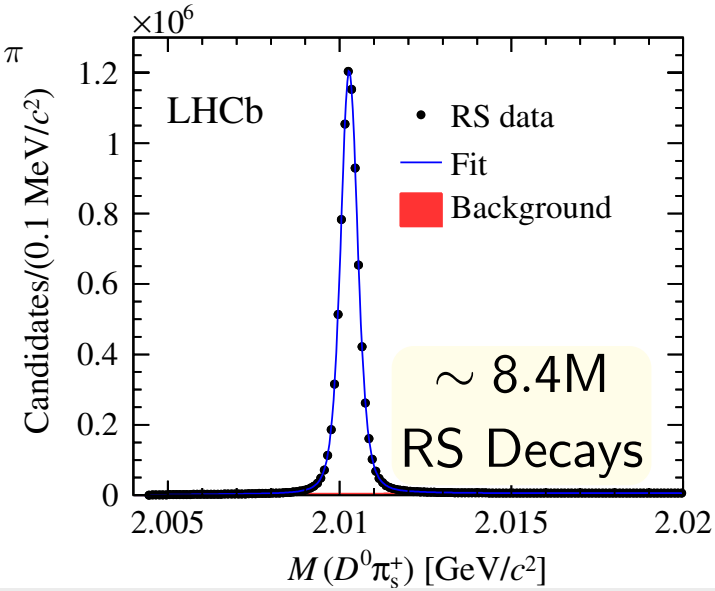
$D^0 - \overline{D}^0$ Mixing

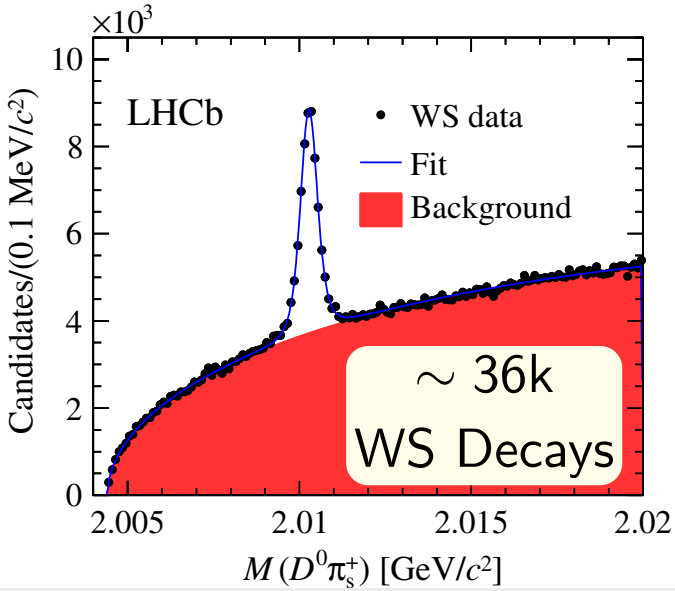
- Use Decay $D^{*+} \to D^0\pi_s^+(+c.c.)$, use π_s to tag D^0 flavor
- $D^0 \to K^-\pi^+$ (Right Sign)
- $D^0 \to K^+\pi^-$(Wrong Sign)



$$R(t) = \frac{N(WS(t))}{N(RS(t))} \approx R_D + \sqrt{R_D}y'\Gamma t + \frac{x'^2+y'^2}{4}(\Gamma t)^2$$





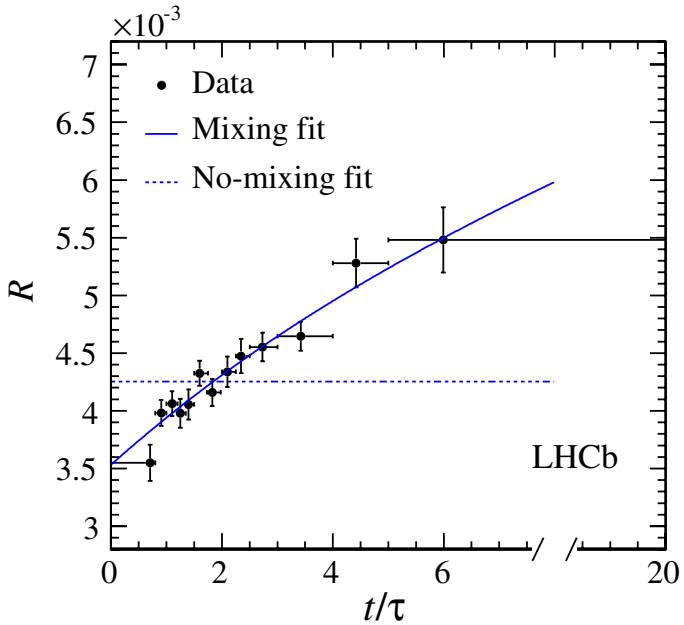


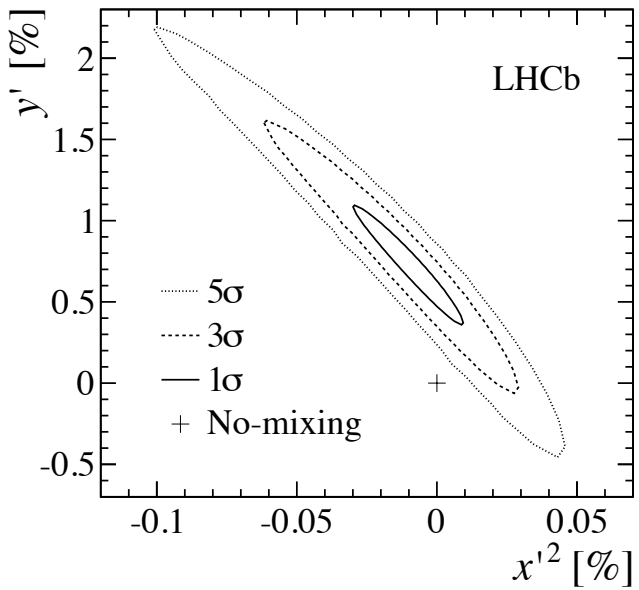
PRL 110, 101802 (2013)

$D^0 - \overline{D}^0$ Mixing

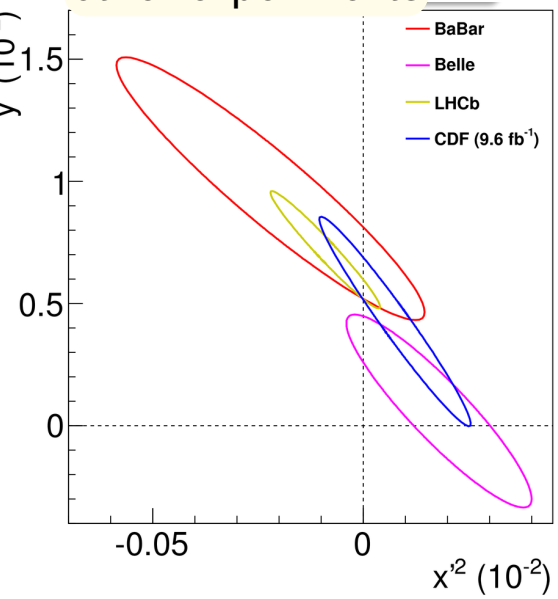
$$R(t) = \frac{N(WS(t))}{N(RS(t))} \approx R_D + \sqrt{R_D}y'\Gamma t + \frac{x'^2+y'^2}{4}(\Gamma t)^2$$

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





Comparison to other experiments

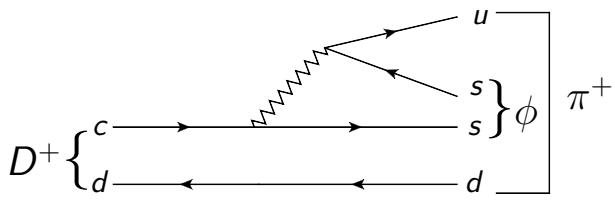


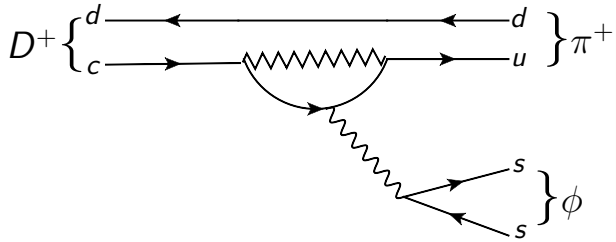
No mixing excluded at 9.1σ

JHEP06(2013)112

CPV in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$

- Interference between Cabibbo-suppressed tree level and penguin amplitudes
- $A_{CP}(D^+ \to K_S^0\pi^+) \approx 0.01\%$ and no penguins→assume no CPV





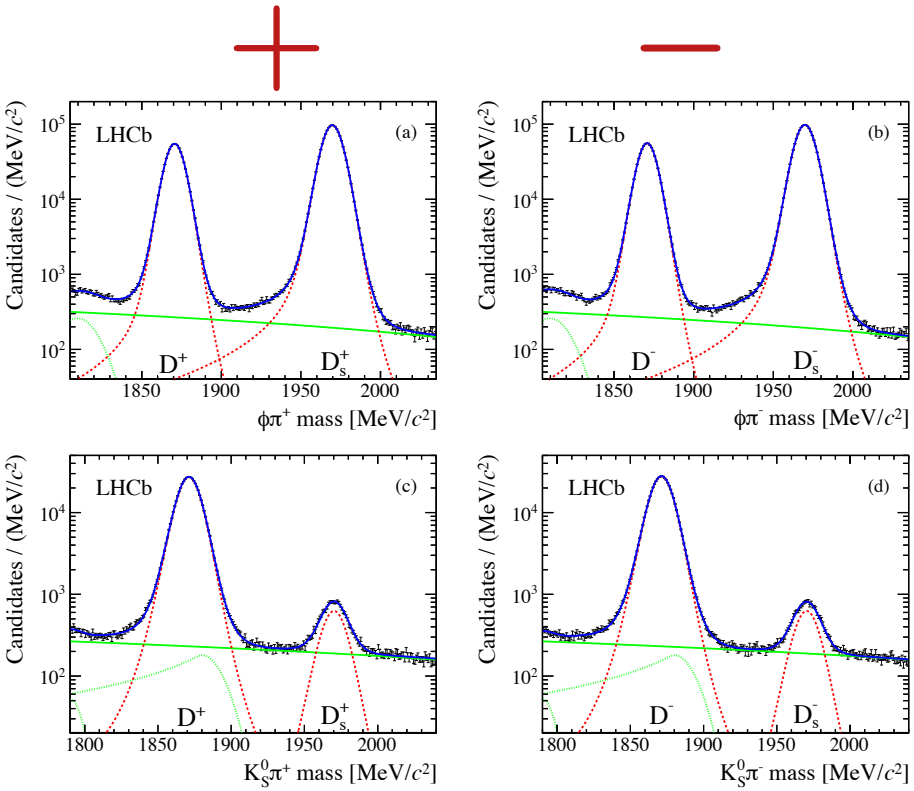
$$A_{CP}\left(D^+ \to \phi\pi^+\right) = A_{\text{raw}}\left(D^+ \to \phi\pi^+\right) - A_{\text{raw}}\left(D^+ \to K_S^0\pi^+\right) + A_{CP}\left(K^0/\overline{K}^0\right)$$

$$\frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}}$$

$-0.028 \pm 0.028\%$
Phys Lett.B718(2013)902

$$A_{CP}\left(D_s^+ \to K_S^0\pi^+\right) = A_{\text{raw}}\left(D_s^+ \to K_S^0\pi^+\right) - A_{\text{raw}}\left(D_s^+ \to \phi\pi^+\right) + A_{CP}\left(K^0/\overline{K}^0\right)$$

- Fit invariant mass distributions to extract signal events



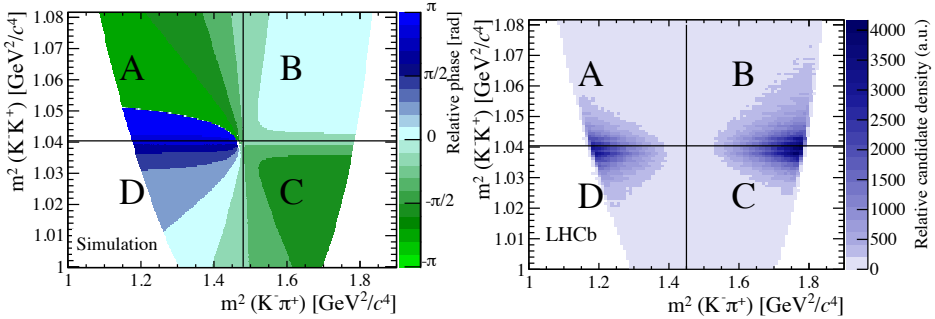
$$A_{CP}(D^+ \to \phi\pi^+) = (-0.04 \pm 0.14 \pm 0.14)\%$$

$$A_{CP}(D_s^+ \to K_S^0\pi^+) = (+0.61 \pm 0.83 \pm 0.14)\%$$

JHEP06(2013)112

- Strong phase varies rapidly across ϕ resonance in Dalitz plot, could cancel A_{CP}
- Define observable which doesn't vary across Dalitz plot

$$A_{CP|S} \equiv \frac{1}{2}(A_{CP}^A + A_{CP}^C - A_{CP}^B - A_{CP}^D)$$



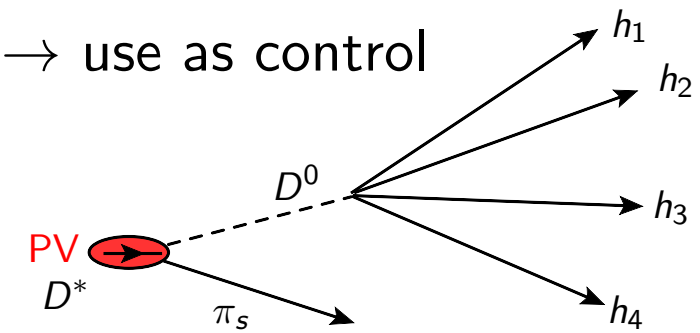
$$A_{CP|S} = (-0.18 \pm 0.17 \pm 0.18)\%$$

Constrains CPV

LHCb-PAPER-2013-041(in prep.)

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

- 4-body decay: many resonances
  - $KK\pi\pi : D^0 \to \phi\rho, K_1(1270)^{\pm}K^{\mp}, K^*(1410)^{\pm}K^{\mp}$,etc
  - $4\pi : D^0 \to \rho\rho, a_1(1260)^+\pi^-$, etc
- Tree-level and penguin SCS amplitudes
- Look for Direct CPV in regions of 4-body phase space
  $\to$5 combinations of 2- and 3-body invariant mass squared
- $D^0 \to (1,2,3,4) : s(1,2), s(2,3), s(3,4), s(1,2,3), s(2,3,4)$
- Identical particles assigned randomly
- No Direct CPV in $D^0 \to K^-\pi^+\pi^+\pi^-$ $\to$ use as control channel



LHCb-PAPER-2013-041(in prep.)

Analysis Strategy

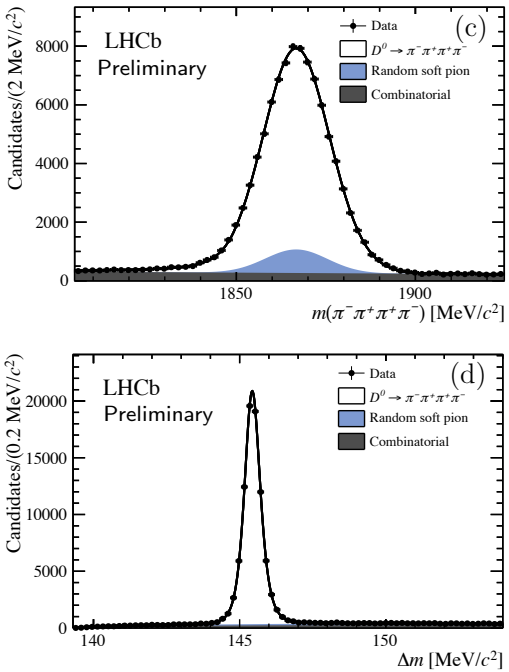
- Signal extraction via ${}_s\mathcal{P}lot$ technique
- Fit $(m, \Delta m)$ plane to extract ${}_s\mathcal{W}eights$ $(m(4h),\ \Delta m \equiv m(4h\pi_s) - m(4h))$

- Significance in equally populated bins of 5D phase space

$$S^i_{CP} = \frac{N_i(D^0) - \alpha N_i(\overline{D}^0)}{\sqrt{\alpha(\sigma_i^2(D^0) + \sigma_i^2(\overline{D}^0))}},\ \alpha = \frac{\sum_i N_i(D^0)}{\sum_i N_i(\overline{D}^0)}$$

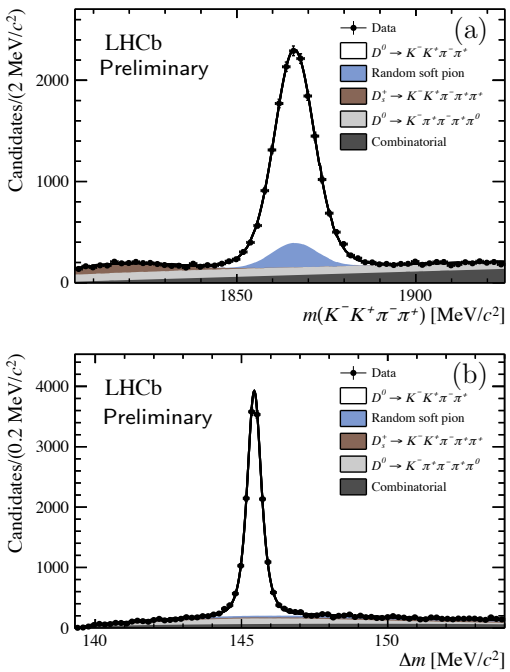
- No CPV = Gaussian distribution

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



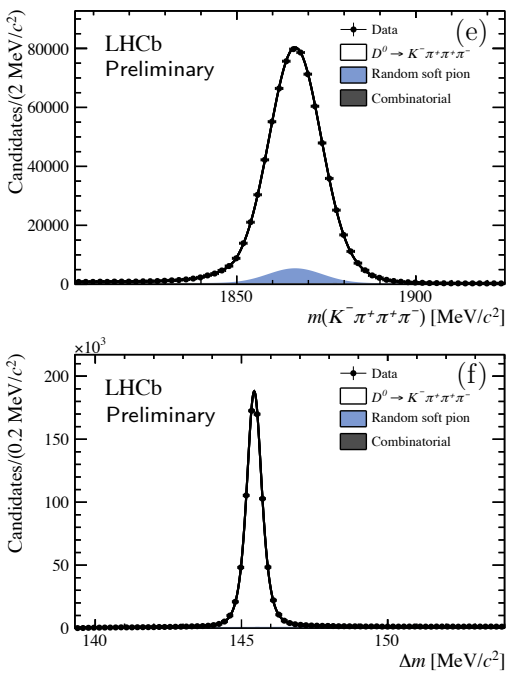
57k Signal

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



330k Signal

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

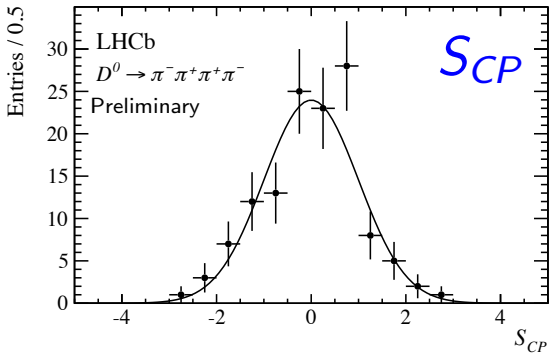


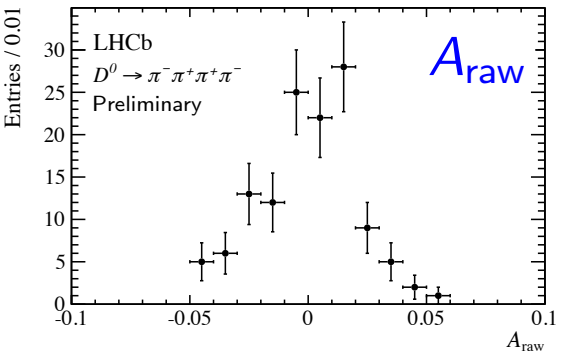
2.9M Signal

LHCb-PAPER-2013-041(in prep.)

Results

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

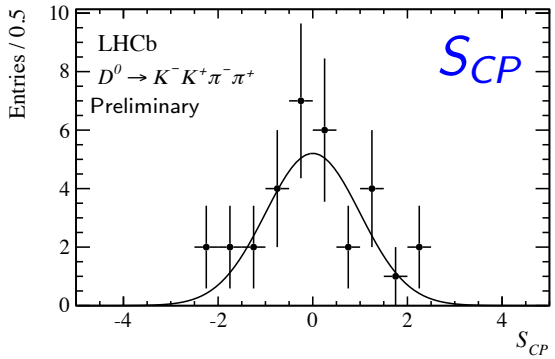


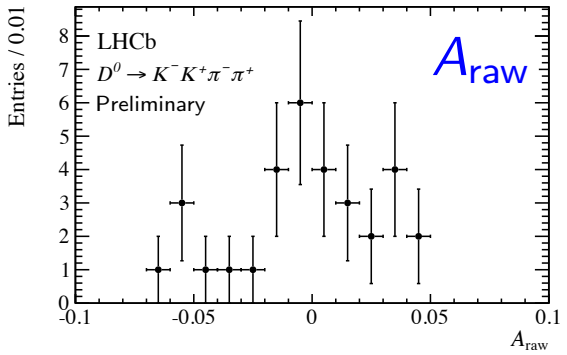


LHCb Preliminary Results		
Bins	χ^2/ndf	$p-$value(%)
64	68.8/63	28.8
128	130.0/127	41.0
256	247.7/255	61.7

Consistent with no CPV

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

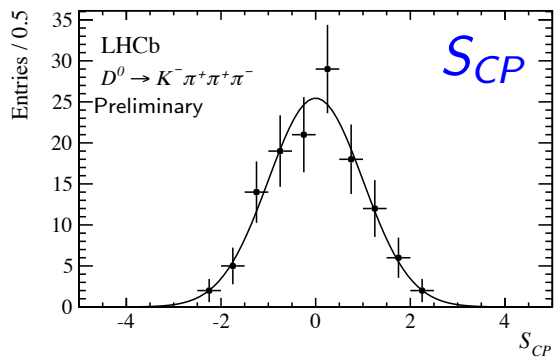


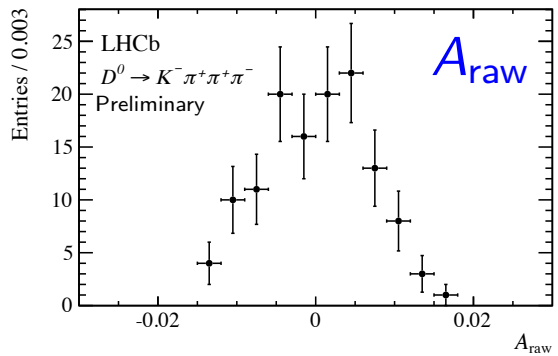


LHCb Preliminary Results		
Bins	χ^2/ndf	$p-$value(%)
16	22.7/15	9.1
32	42.0/31	9.1
64	75.7/63	13.1

Consistent with no CPV

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





LHCb Preliminary Results		
Bins	χ^2/ndf	$p-$value(%)
16	16.5/15	34.8
128	113.4/127	80.0
1024	1057.5/1023	22.1

No evidence for local asymmetries

Summary

- With 1 fb^{-1} of 2011 LHCb data:
  - $D^0 - \overline{D}^0$ mixing verified (9.1σ)
  - CPV constrained in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$
  - No evidence for CPV in 5D phase space of $D^0 \to K^-K^+\pi^+\pi^-$ or $D^0 \to \pi^-\pi^+\pi^+\pi^-$
- 2 fb^{-1} of 2012 data are currently being analyzed.
- Stay tuned for much more soon!

Backup Slides