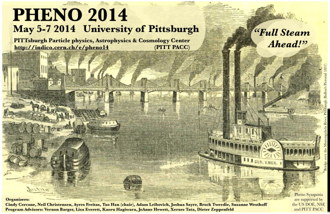
Charm Mixing and CPV at LHCb

Adam Davis
On behalf of the LHCb Collaboration

May 6, 2014



PHENO 2014
May 5-7 2014 University of Pittsburgh
PITTsburgh Particle physics, Astrophysics & Cosmology Center (PITT PACC)
http://indico.cern.ch/e/pheno14

Organizers:
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Outline

Charm System

LHCb

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

Muon Tagged ΔA_{CP} NEW!

Conclusions

Mixing in a Nutshell

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

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

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)

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

Weak Phase: $\phi = \arg\left(\frac{q}{p}\right)$

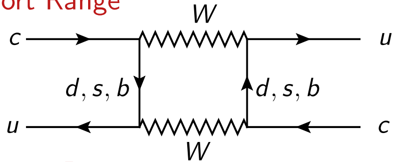
CPV in Interference between Mixing and Decay (Neutral)

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

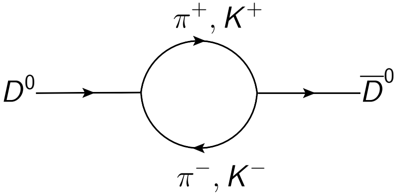
Charm Mixing in the SM

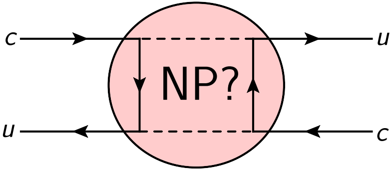
- Only up-type quark system with mixing/CPV
- Mixing enters at 1 loop level in SM, GIM and CKM suppressed
- Non-perturbative long-range effects may dominate short-range interactions, difficult to calculate
- x, y expected to be small in short and long range limits, CPV expected to be $\mathcal{O}(10^{-3})$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

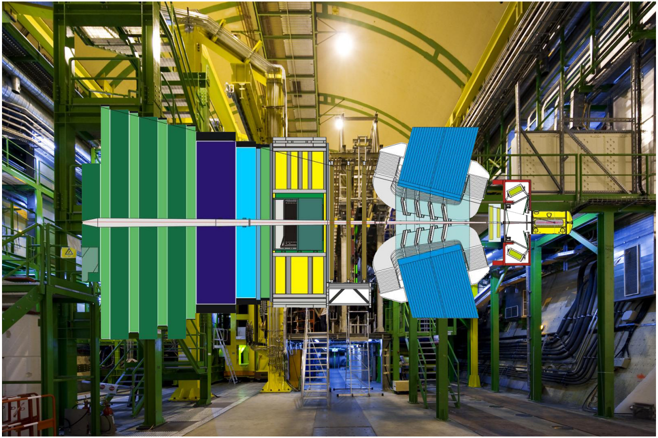
Short Range



Long Range



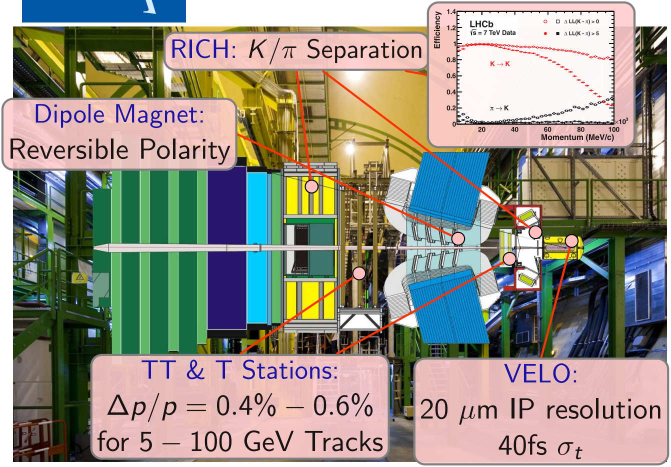




- $\sigma(c\bar{c})_{\text{LHCb, 7TeV}} = 1419 \pm 133\mu b$

  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
- > 1B reconstructed charm decays!



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 40fs σ_t

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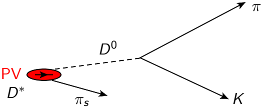
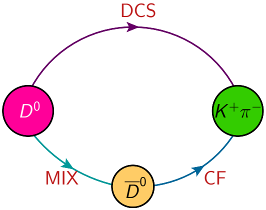
- $>$ 1B reconstructed charm decays!
- Today: Results from $\sqrt{s} = 7$ and 8 TeV 2011 and 2012 Data, 3fb^{-1}

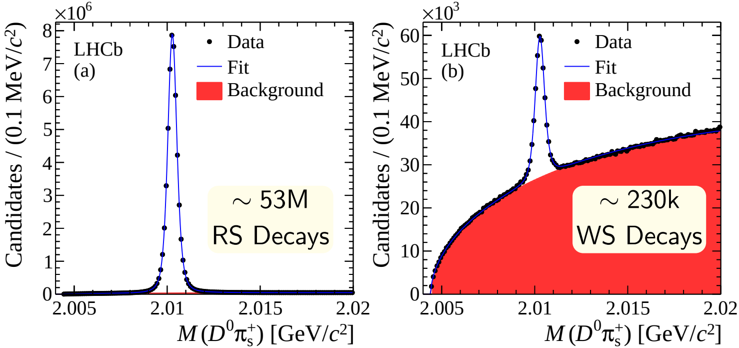
PRL 111, 251801 (2013) 2011+2012 Dataset

$D^0 - \overline{D^0}$ Mixing/CPV
Analysis Strategy

- Reconstruct $D^{*+} \to D^0 \pi_s^+$,
  - RS: $D^0 \to K^- \pi^+$
  - WS: $D^0 \to K^+ \pi^-$
- WS(t)/RS(t) →Separate mixing, DCS
- Split into $D^0(D^{*+})$ and $\overline{D}^0(D^{*-})$







~ 53M
RS Decays

~ 230k
WS Decays

PRL 111, 251801 (2013) 2011+2012 Dataset

CPV Fit Strategy

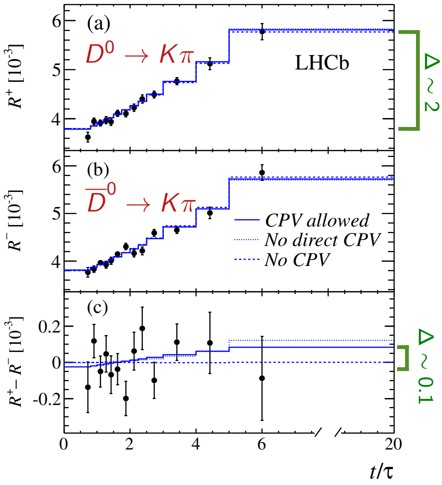
- For small x & y,

$$R(t)^{\pm} = \left(\frac{WS(t)}{RS(t)}\right)^{\pm}$$

$$= R_D^{\pm} + \sqrt{R_D^{\pm}}\, y'^{\pm} \left(\frac{t}{\tau}\right) + \frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4} \left(\frac{t}{\tau}\right)^2$$

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

- Direct CPV → $R_D^+ \neq R_D^-$
- Indirect CPV → $(x'^{2+}, y'^{+}) \neq (x'^{2-}, y'^{-})$
- $K\pi$ detection asymmetry and secondary decay accounted for in fit



PRL 111, 251801 (2013) 2011+2012 Dataset

Results

Direct and indirect CPV	
$R_D^+[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$
$y'^+[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$
$x'^{2+}[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$
$R_D^-[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$
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$x'^{2-}[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$
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	
$R_D[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
$y'[10^{-3}]$	$4.8 \pm 0.8 \pm 0.5$
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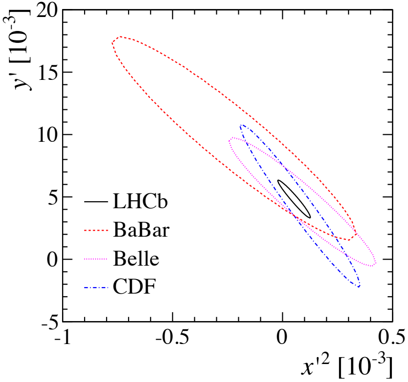
χ^2/ndf	86.4/101



BaBar: PRL 98 (2007) 211802

Belle: arXiv:1401.3402

CDF: PRL 111 (2013) 231802

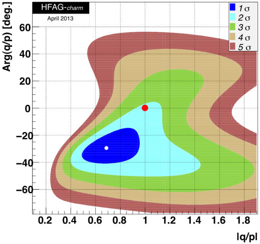
Results consistent with CP Conservation

PRL 111, 251801 (2013) 2011+2012 Dataset

World Average, All-CPV allowed

April 2013

LHCb 2011 1 fb^{-1} $D^0 \to K\pi$

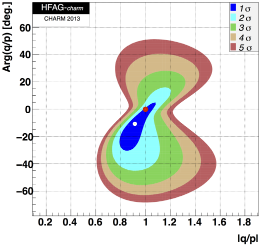


$|q/p| = 0.69 \pm 0.16$

November 2013

LHCb 2011+2012, 3 fb^{-1} $D^0 \to K\pi$

and LHCb 2011, 1 $\text{fb}^{-1} A_\Gamma$



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

Indirect CPV

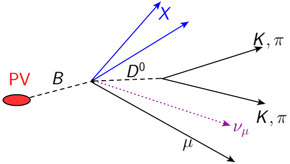
- In the case of no Direct CPV, ϕ and $|q/p|$ are related (superweak constraint)

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

Dataset	$\lvert q/p\rvert[\%]$	$\phi[^\circ]$
HFAG April 2013	100.4 ± 6.5	-1.6 ± 2.5
HFAG Nov. 2013	100.8 ± 1.4	-0.3 ± 0.5

NEW LHCb-PAPER-2014-013 (in prep.) 2011+2012 Dataset

Muon Tagged ΔA_{CP} and A_{CP} Review



- Define

$$A_{\mathrm{raw}} = \frac{N(D \to f) - N(\overline{D} \to \overline{f})}{N(D \to f) + N(\overline{D} \to \overline{f})}$$

- Use $B \to D^0 \mu X$, with SCS $D^0 \to KK$ and $D^0 \to \pi\pi$

$$A_{\mathrm{raw}} = A_{CP} + A_D(\mu) + A_P(B) + \mathcal{O}(A^3)$$

What we want

Cancel in difference
(if kinematics agree)

$$\boxed{\Delta A_{CP} = A_{\mathrm{raw}}(KK) - A_{\mathrm{raw}}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)}$$

- Can also get $A_{CP}(K^-K^+)$ using $B \to (D^0 \to K^-\pi^+)\mu X$

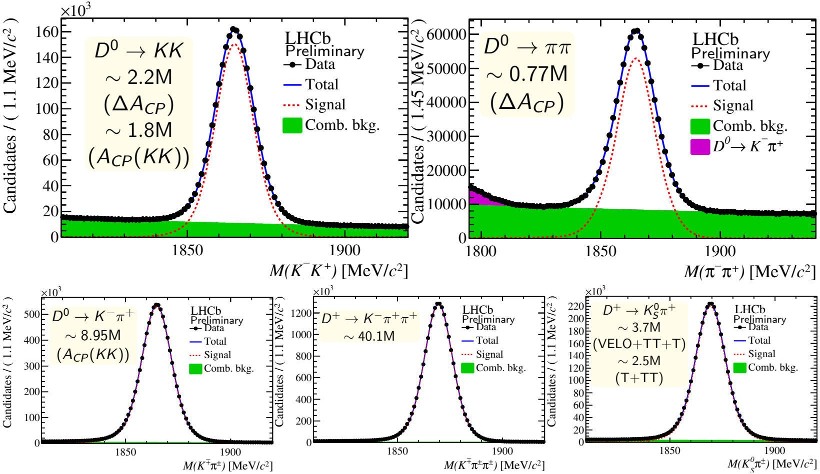
$$\boxed{A_{CP}(K^-K^+) = A_{\mathrm{raw}}(K^-K^+) - A_{\mathrm{raw}}(K^-\pi^+) + A_D(K^-\pi^+)}$$

- And $A_{CP}(\pi^-\pi^+)$, derived using

$$\boxed{A_{CP}(\pi^-\pi^+) = A_{CP}(K^-K^+) - \Delta A_{CP}}$$

NEW LHCb-PAPER-2014-013 (in prep.) 2011+2012 Dataset

Analysis: Yields



$D^0 \to KK$
$\sim$ 2.2M
(ΔA_{CP})
$\sim$ 1.8M
($A_{CP}(KK)$)

$D^0 \to \pi\pi$
$\sim$ 0.77M
(ΔA_{CP})

$D^0 \to K^-\pi^+$
$\sim$ 8.95M
($A_{CP}(KK)$)

$D^+ \to K^-\pi^+\pi^+$
$\sim$ 40.1M

$D^+ \to K^0_S\pi^+$
$\sim$ 3.7M
(VELO+TT+T)
$\sim$ 2.5M
(T+TT)

Signal: Gaussian + Crystal Ball. Background: Exponential

NEW LHCb-PAPER-2014-013 (in prep.) 2011+2012 Dataset

Nuisance Asymmetries

- CP asymmetries do not depend on kinematics
- Must remove nuisance asymmetries (kinematic dependent)
  - Control modes not needed for ΔA_{CP}

Reweight $D^0(p_T, \eta)$ from $D^0 \to KK$ to match $D^0 \to \pi\pi$
$A_D(\mu), A_P(B)$

$$\Delta A_{CP} = A_{\text{raw}}(KK) - A_{\text{raw}}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

  - $A_{CP}(KK)$: 3 modes for full cancellation

$D^0(p_T, \eta)$ from $D^0 \to K\pi$ to match $D^0 \to KK$ $A_D(\mu), A_P(B)$	$K, \pi_{notTrigger}(p_T, \eta)$ from prompt $D^+ \to K\pi\pi$ to match $D^0 \to K\pi$ $A(K\pi)$	$D^+, \pi_{Trigger}(p_T, \eta)$ from prompt $D^+ \to \overline{K}^0\pi$ to match $D^+ \to K\pi\pi$ $A(D^+), A(\pi)$

$$A_{CP}(KK) = A_{\text{raw}}(KK) - A_{\text{raw}}(K^-\pi^+) + A_{\text{raw}}(K^-\pi^+\pi^+) - A_{\text{raw}}(\overline{K}^0\pi^+) - A_D(K^0)$$

- Measure detection asymmetries
  $A_D(K^0) = (0.054 \pm 0.014)\%$, $A_D(K^-\pi^+) = (-1.17 \pm 0.12)\%$

NEW LHCb-PAPER-2014-013 (in prep.) 2011+2012 Dataset

(Preliminary) Results

Source of Uncertainty	ΔA_{CP}	$A_{CP}(K^-K^+)$
Production Asymmetry:		
Difference in b-hadron mixture	0.02%	0.02%
Difference in B decay time acceptance	0.02%	0.02%
Production and Detection Asymmetry:		
Different weighting	0.02%	0.05%
Non-cancellation	-	0.03%
Neutral kaon asymmetry	-	0.01%
Background from real D^0 mesons:		
Mistag asymmetry	0.03%	0.03%
Background from fake D^0 mesons:		
D^0 mass fit model	0.06%	0.06%
Wrong background modeling	0.03%	0.03%
Quadratic Sum	0.08%	0.10%

$$\boxed{\Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08)\%}$$

Correlation $(\Delta A_{CP}, A_{CP}(KK))$

$\rho = 0.28$

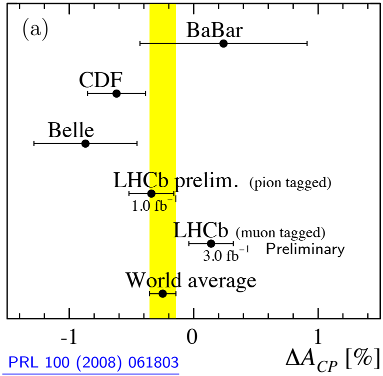
$$\boxed{A_{CP}(K^-K^+) = (-0.06 \pm 0.15 \pm 0.10)\%}$$

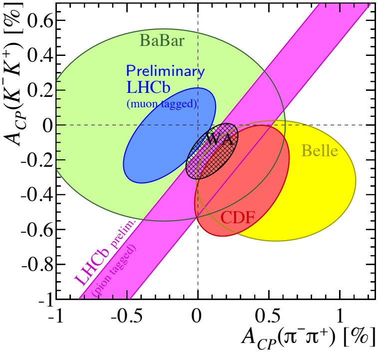
$$\boxed{A_{CP}(\pi^-\pi^+) = (-0.20 \pm 0.19 \pm 0.10)\%}$$

Consistent with CP Symmetry

NEW LHCb-PAPER-2014-013 (in prep.) 2011+2012 Dataset

World Averages





PRL 100 (2008) 061803

PRL 109 (2012) 111801

arXiv:1212.1975

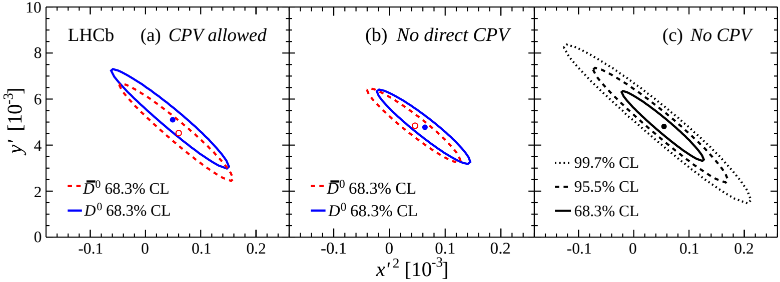
LHCb-CONF-2013-003

Conclusions

- With 3 fb^{-1}, LHCb has
  - Searched for CPV in $D^0 - \overline{D}^0$ system
  - Given tight constraints on $\Delta A_{CP}, A_{CP}(KK)$ and $A_{CP}(\pi\pi)$
  - No sign of CPV yet
  - and much more
- Many analyses in progress on full 3 fb^{-1} sample
- 2015 is just around the corner! Stay tuned!

Backup Slides

Results



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χ^2/ndf	86.4/101

Results consistent with CP Conservation

NEW LHCb-PAPER-2014-013 (in prep.) 2011+2012 Dataset

$\Delta A_{CP} \to A_{CP}$

- Can get $A_D(\mu)$ and $A_P(B)$ from μ-tagged $D^0 \to K^-\pi^+$

$$A_{\rm raw}(K^-\pi^+) = A_D(\mu) + A_P(B) + A_D(K^-\pi^+)$$

$$A_D(K^-\pi^+) = A_{\rm raw}(K^-\pi^+\pi^+) - A_{\rm raw}(\overline{K}^0\pi^+) - A_D(K^0)$$

From Prompt $D^+ \to K^-\pi^+\pi^+$

From Prompt $D^+ \to \overline{K}^0\pi^+$

Measure in this analysis.
Test removal by splitting by magnet polarity

$$\boxed{\Delta A_{CP} = A_{\rm raw}(KK) - A_{\rm raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)}$$

$$\boxed{A_{CP}(KK) = A_{\rm raw}(KK) - A_{\rm raw}(K^-\pi^+) + A_D(K^-\pi^+)}$$

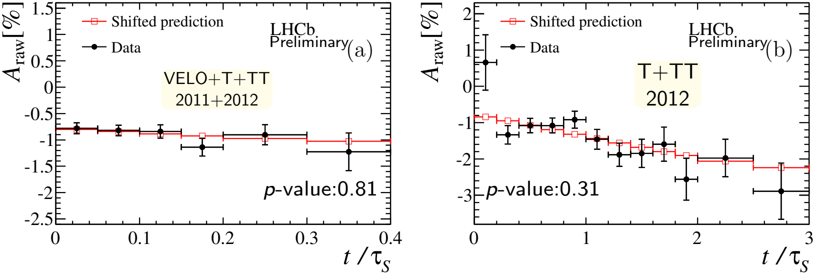
$\boxed{A_{CP}(\pi\pi) = A_{CP}(KK) - \Delta A_{CP}}$, Accounting for Correlation

Final Result: Weighted Average of 2011+2012

NEW LHCb-PAPER-2014-013 (in prep.) 2011+2012 Dataset

Neutral Kaon Asymmetry, $A_D(K^0)$

- Detect K^0_S, dominated by decay to $\pi\pi$
- Need to describe mixing, CPV and absorption in detector
- Calculate by dividing into steps using LHCb Material Map and



- VELO+T+TT, 2011+2012: result, 2012 T+TT: systematic
- Includes overall shift to account for $A_P(D^+)$ and $A_{\rm Tracking}(\pi)$

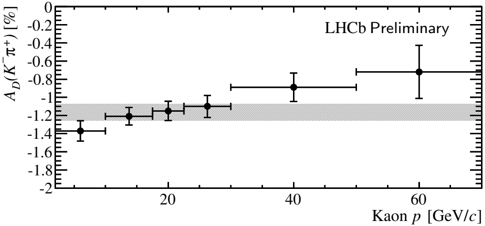
$$\boxed{A_D(K^0) = (0.054 \pm 0.014(syst))\%}$$

NEW LHCb-PAPER-2014-013 (in prep.) 2011+2012 Dataset

$A_D(K^-\pi^+)$

- Have all the info to calculate $A_D(K^-\pi^+)$

Asymmetry	Magnet Up [%]	Magnet Down [%]	Mean [%]
$A_D(\overline{K}^0)$	-0.054 ± 0.014	-0.054 ± 0.014	-0.054 ± 0.014
$A_{\mathrm{raw}}(K^-\pi^+\pi^+)$	-1.969 ± 0.033	-1.672 ± 0.032	-1.827 ± 0.023
$A_{\mathrm{raw}}(\overline{K}^0\pi^+)$	-0.94 ± 0.17	-0.51 ± 0.16	-0.71 ± 0.12
$A_D(K^-\pi^+)$	-1.08 ± 0.17	-1.22 ± 0.16	-1.17 ± 0.12

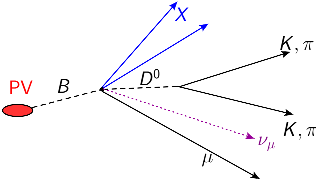


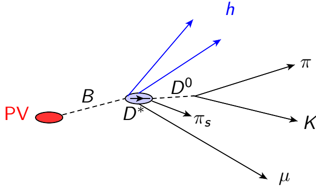
- Driven by different $\sigma_{\mathrm{Interaction}}(K)$ in matter
- Decreases with increasing $p(K)$, as expected

NEW LHCb-PAPER-2014-013 (in prep.) 2011+2012 Dataset

μ Mistag Probability

- No handle on $m(B) \to$ possible μ mis-id
- Dilutes observed asymmetry
  $$\Delta A_{CP} = (1+2\omega)[A_{\text{raw}}(KK) - A_{\text{raw}}(\pi\pi)]$$
  $$A_{CP}(KK) = (1+2\omega)[A_{\text{raw}}(KK) - A_{\text{raw}}(K\pi)] + (1-2R)A_D(K\pi)$$
- $R = (R^+ + R^-)/2 = (0.389 \pm 0.003)\%$, from Mixing/CPV, time integrated
- Extract with $D^0 \to K^-\pi^+$, take CPV/Mixing into account
- Cross Check with $B \to \mu(D^* \to D^0\pi_s)X$ subsample





$$\boxed{\omega(\Delta A_{CP}) = (0.988 \pm 0.006)\%}$$

$$\boxed{\omega(A_{CP}(K^-K^+)) = (0.791 \pm 0.006)\%}$$

(Preliminary) Results

	Magnet Up[%]	Magnet Down[%]	Mean[%]
$A_{\text{raw}}(K^-K^+)$	-0.46 ± 0.11	-0.43 ± 0.11	-0.44 ± 0.08
$A_{\text{raw}}(\pi^-\pi^+)$	-0.45 ± 0.20	-0.66 ± 0.19	-0.58 ± 0.14
ΔA_{CP}	-0.01 ± 0.23	$+0.24 \pm 0.22$	0.14 ± 0.16
$A_{\text{raw}}(K^-K^+)$	-0.45 ± 0.12	-0.41 ± 0.12	-0.43 ± 0.08
$A_{\text{raw}}(K^-\pi^+)$	-1.41 ± 0.05	-1.59 ± 0.05	-1.51 ± 0.04
$A_D(K^-\pi^+)$	-1.08 ± 0.07	-1.22 ± 0.16	-1.17 ± 0.12
$A_{CP}(K^-K^+)$	-0.09 ± 0.21	-0.01 ± 0.21	-0.06 ± 0.15

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Mistag asymmetry	0.03%	0.03%
Background from fake D^0 mesons:		
D^0 mass fit model	0.06%	0.06%
Wrong background modeling	0.03%	0.03%
Quadratic Sum	0.08%	0.10%

$$\boxed{\Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08)\%}$$

$$\boxed{A_{CP}(K^-K^+) = (-0.06 \pm 0.15 \pm 0.10)\%}$$

$$\rho = 0.28$$

$$\boxed{A_{CP}(\pi^-\pi^+) = (-0.20 \pm 0.19 \pm 0.10)\%}$$

Consistent with CP Conservation

Semileptonic ΔA_{CP} Calculation of Asymmetries

- All production/detector asymmetries must cancel
- Reweight Kinematic distributions to remove residual production/detector asymmetries
  - Weight D^0 (p_T and η) distributions of KK to match $\pi\pi$
    → 8% reduction in statistical power
- Additional reweighting for $A_{CP}(KK)$ to cancel D^+ asymmetries
  - $A_D(\mu), A_P(B)$:$D^0 \to K\pi$ (p_T, η) reweighted to match $D^0 \to KK$
    →3% further reduction
  - $A(K\pi)$:$D^+ \to K\pi\pi$ (p_T, η) reweighted to match $D^0 \to K\pi$
    → No loss of power due to high stats
  - Residual $A(D^+), A(\pi)$: $D^+ \to \overline{K}^0\pi^+$, D^+ and π^+ (p_T, η) reweighted to match $D^+ \to K^-\pi^+\pi^+$
    → 77% reduction in statistical power
- Needed to ensure full cancellation of detector/production asymmetries