

Charm Mixing and CPV at LHCb

Adam Davis

On behalf of the LHCb Collaboration

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Outline

Charm System

LHCb

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

Muon Tagged ΔA_{CP} **NEW!**

Conclusions

Mixing in a Nutshell

- ▶ Mixing in Neutral Mesons:
mass \neq flavor eigenstates

- ▶ Mass Eigenstates:

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle,$$

$$|p|^2 + |q|^2 = 1$$

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

3 Types of CPV

Direct CPV (Charged and Neutral)

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

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

CPV in Mixing (Neutral)

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

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

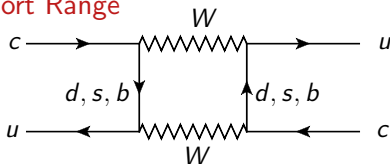
CPV in Interference between Mixing and Decay (Neutral)

$$\arg\left(\frac{q}{p} \frac{\bar{\mathcal{A}}_{\bar{f}}}{\mathcal{A}_f}\right) \neq 0$$

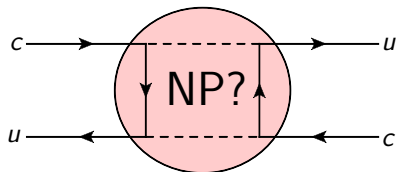
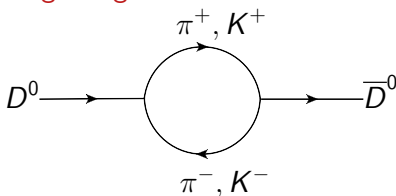
Charm Mixing in the SM

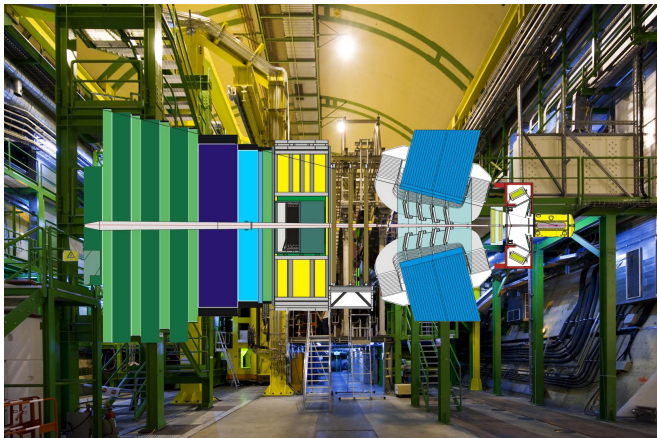
- ▶ Only up-type quark system with mixing/CPV
- ▶ Mixing enters at 1 loop level in SM, GIM and CKM suppressed
- ▶ Non-perturbative long-range effects may dominate short-range interactions, difficult to calculate
- ▶ x, y expected to be small in short and long range limits, CPV expected to be $\mathcal{O}(10^{-3})$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

Short Range



Long Range



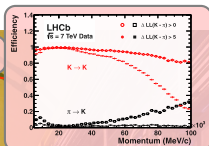


- ▶ $\sigma(c\bar{c})_{\text{LHCb}, 7\text{TeV}} = 1419 \pm 133 \mu\text{b}$
Nucl.Phys.B 871(2013), 1
- ▶ $\sigma(b\bar{b})_{\text{LHCb}, 7\text{TeV}} = 75.3 \pm 14.1 \mu\text{b}$
Phys. Lett. B 694 (2010), 209
- ▶ $> 1\text{B}$ reconstructed charm decays!



RICH: K/π Separation

Dipole Magnet:
Reversible Polarity



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

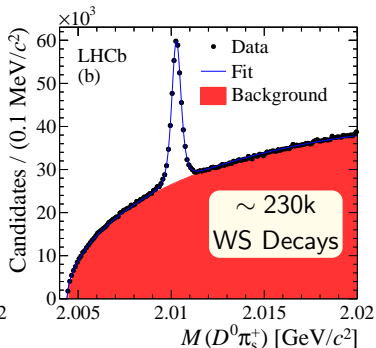
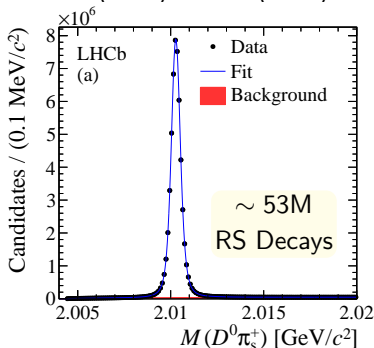
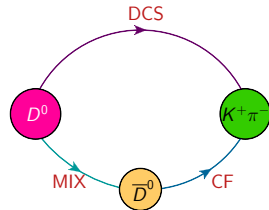
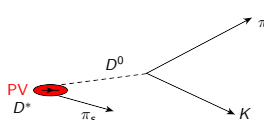
VELO:
20 μm IP resolution
40fs σ_t

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- ▶ $\sigma(b\bar{b})_{\text{LHCb}, 7\text{TeV}} = 75.3 \pm 14.1 \mu\text{b}$
Phys. Lett. B 694 (2010), 209
- ▶ > 1B reconstructed charm decays!
- ▶ Today: Results from $\sqrt{s} = 7$ and 8 TeV
2011 and 2012 Data, 3fb^{-1}

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

Analysis Strategy

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



CPV Fit Strategy

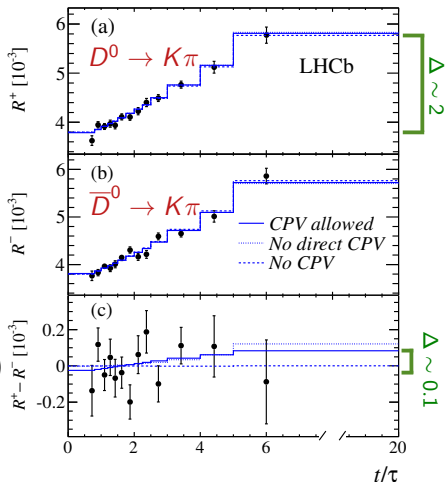
- ▶ For small x & y ,

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

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

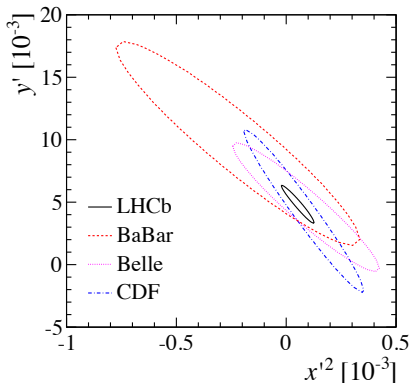
$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos \delta & \sin \delta \\ -\sin \delta & \cos \delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

- ▶ Direct CPV $\rightarrow R_D^+ \neq R_D^-$
- ▶ 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		No direct CPV		No CPV	
$R_D^+[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$	$R_D[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$	$R_D[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
$y'^+[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$	$y'^+[10^{-3}]$	$4.8 \pm 0.9 \pm 0.6$	$y'[10^{-3}]$	$4.8 \pm 0.8 \pm 0.5$
$x'^{2+}[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$	$x'^{2+}[10^{-5}]$	$6.4 \pm 4.7 \pm 3.0$	$x'^2[10^{-5}]$	$5.5 \pm 4.2 \pm 2.6$
$R_D^-[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$	$y'^-[10^{-3}]$	$4.8 \pm 0.9 \pm 0.6$	χ^2/ndf	$86.4/101$
$y'^-[10^{-3}]$	$4.5 \pm 1.2 \pm 0.7$	$x'^{2-}[10^{-5}]$	$4.6 \pm 4.6 \pm 3.0$		
$x'^{2-}[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$	χ^2/ndf	$86.0/99$		
χ^2/ndf	$85.9/98$				



BaBar: PRL 98 (2007) 211802

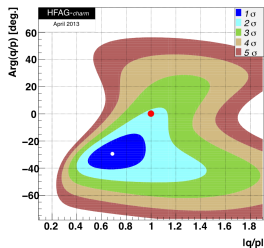
Belle: arXiv:1401.3402

CDF: PRL 111 (2013) 231802

Results consistent with CP Conservation

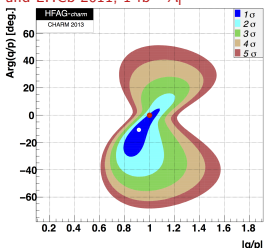
World Average, All-CPV allowed

April 2013

LHCb 2011 1 fb⁻¹ $D^0 \rightarrow K\pi$ 

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

November 2013

LHCb 2011+2012, 3 fb⁻¹ $D^0 \rightarrow K\pi$ and LHCb 2011, 1 fb⁻¹ A_T 

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

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	$ q/p $ [%]	ϕ [°]
HFAG April 2013	100.4 ± 6.5	-1.6 ± 2.5
HFAG Nov. 2013	100.8 ± 1.4	-0.3 ± 0.5

Muon Tagged ΔA_{CP} and A_{CP} Review

- Define

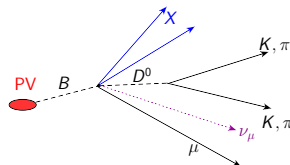
$$A_{\text{raw}} = \frac{N(D \rightarrow f) - N(\bar{D} \rightarrow \bar{f})}{N(D \rightarrow f) + N(\bar{D} \rightarrow \bar{f})}$$

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

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

What we
want

Cancel in difference
(if kinematics agree)



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

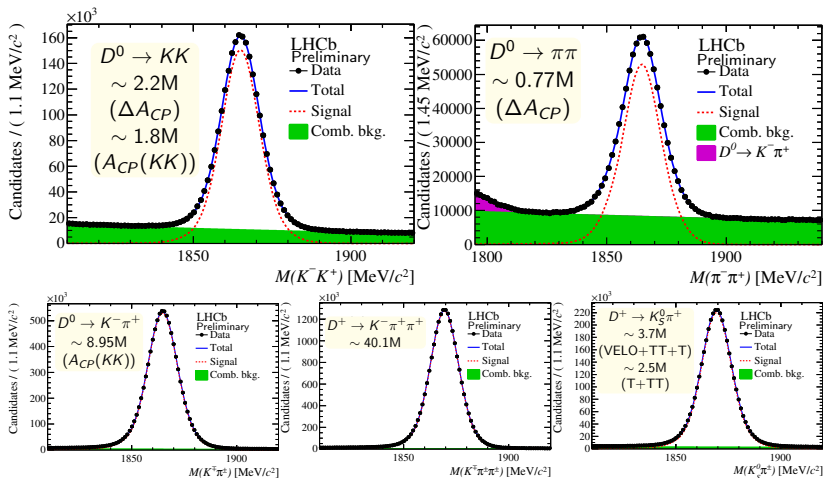
- Can also get $A_{CP}(K^-K^+)$ using $B \rightarrow (D^0 \rightarrow K^- \pi^+) \mu X$

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

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

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

Analysis: Yields



Signal: Gaussian + Crystal Ball. Background: Exponential

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 $D^0 \rightarrow KK$ to match $D^0 \rightarrow \pi\pi$

$$A_D(\mu), A_P(B)$$

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

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

$D^0(p_T, \eta)$ from
 $D^0 \rightarrow K\pi$
to match $D^0 \rightarrow KK$

$$A_D(\mu), A_P(B)$$

$K, \pi_{\text{not Trigger}}(p_T, \eta)$ from
prompt $D^+ \rightarrow K\pi\pi$
to match $D^0 \rightarrow K\pi$

$$A(K\pi)$$

$D^+, \pi_{\text{Trigger}}(p_T, \eta)$ from
prompt $D^+ \rightarrow \bar{K}^0\pi$
to match $D^+ \rightarrow K\pi\pi$

$$A(D^+), A(\pi)$$

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

- ▶ Measure detection asymmetries

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

(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%

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

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

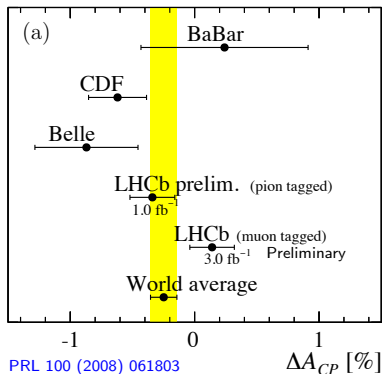
$$\rho = 0.28$$

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

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

Consistent with CP Symmetry

World Averages

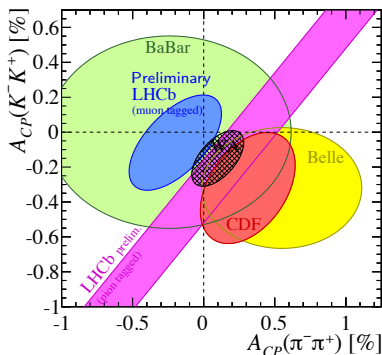


[PRL 100 \(2008\) 061803](#)

[PRL 109 \(2012\) 111801](#)

[arXiv:1212.1975](#)

[LHCb-CONF-2013-003](#)

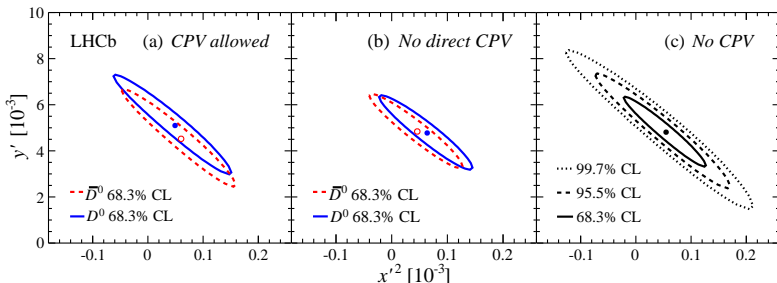


Conclusions

- ▶ With 3 fb^{-1} , LHCb has
 - ▶ Searched for CPV in $D^0 - \bar{D}^0$ system
 - ▶ Given tight constraints on ΔA_{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



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

$\Delta A_{CP} \rightarrow A_{CP}$

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

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

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

From Prompt

$$D^+ \rightarrow K^- \pi^+ \pi^+$$

From Prompt

$$D^+ \rightarrow \bar{K}^0 \pi^+$$

Measure in this analysis.

Test removal by splitting by magnet polarity

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

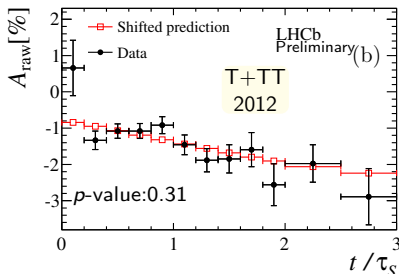
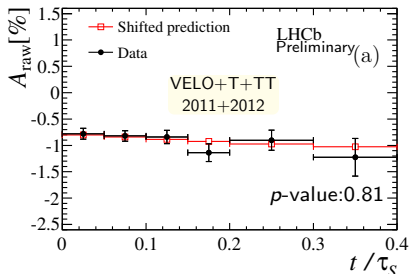
$$A_{CP}(KK) = A_{\text{raw}}(KK) - A_{\text{raw}}(K^- \pi^+) + A_D(K^- \pi^+)$$

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

Final Result: Weighted Average of 2011+2012

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

- ▶ Detect K_S^0 , 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



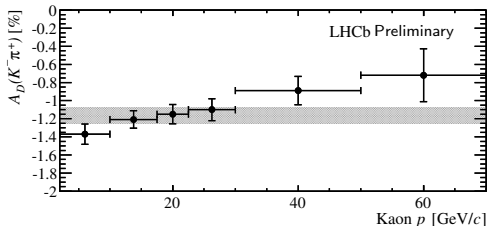
- ▶ VELO+T+TT, 2011+2012: result, 2012 T+TT: systematic
- ▶ Includes overall shift to account for $A_P(D^+)$ and $A_{\text{Tracking}}(\pi)$

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

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

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

Asymmetry	Magnet Up [%]	Magnet Down [%]	Mean [%]
$A_D(\bar{K}^0)$	-0.054 ± 0.014	-0.054 ± 0.014	-0.054 ± 0.014
$A_{\text{raw}}(K^- \pi^+ \pi^+)$	-1.969 ± 0.033	-1.672 ± 0.032	-1.827 ± 0.023
$A_{\text{raw}}(\bar{K}^0 \pi^+)$	-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 $\sigma_{\text{Interaction}}(K)$ in matter
- ▶ Decreases with increasing $p(K)$, as expected

μ Mistag Probability

- ▶ No handle on $m(B) \rightarrow$ possible μ mis-id

- ▶ Dilutes observed asymmetry

$$\Delta A_{CP} = (1 + 2\omega)[A_{\text{raw}}(KK) - A_{\text{raw}}(\pi\pi)]$$

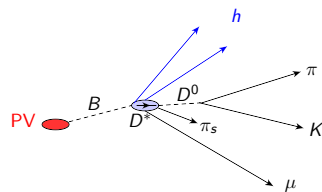
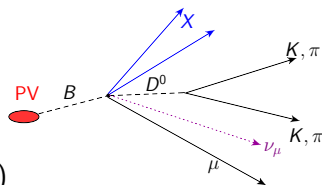
$$A_{CP}(KK) =$$

$$(1+2\omega)[A_{\text{raw}}(KK) - A_{\text{raw}}(K\pi)] + (1-2R)A_D(K\pi)$$

- ▶ $R = (R^+ + R^-)/2$
 $= (0.389 \pm 0.003)\%$, from Mixing/CPV, time integrated
- ▶ Extract with $D^0 \rightarrow K^- \pi^+$, take CPV/Mixing into account
- ▶ Cross Check with $B \rightarrow \mu(D^* \rightarrow D^0 \pi_s) X$ subsample

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

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



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

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

$$\rho = 0.28$$

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

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
 - ▶ $A_D(\mu), A_P(B): D^0 \rightarrow K\pi$ (p_T, η) reweighted to match
 $D^0 \rightarrow KK$
 → 3% further reduction
 - ▶ $A(K\pi): D^+ \rightarrow K\pi\pi$ (p_T, η) reweighted to match $D^0 \rightarrow K\pi$
 → No loss of power due to high stats
 - ▶ Residual $A(D^+), A(\pi): D^+ \rightarrow \bar{K}^0\pi^+, D^+$ and π^+ (p_T, η)
 reweighted to match $D^+ \rightarrow K^-\pi^+\pi^+$
 → 77% reduction in statistical power
- ▶ Needed to ensure full cancellation of detector/production asymmetries