Mixing and CP Violation in Charm Decays at LHCb

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On behalf of the LHCb Collaboration

August 4, 2016

Outline

NEW

Measurement of CP asymmetry in $D^0 \to K^- K^+$ decays
LHCb-PAPER-2016-035 (in preparation)

NEW

Search for Mixing and CP Violation with WS $D^0 \to K\pi$ from $\overline{B} \to \mu D^* X$
LHCb-PAPER-2016-033 (in preparation)

Some Theory and Expectations

Mixing in a Nutshell

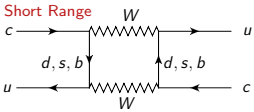
- Mixing in Neutral Mesons: mass≠flavor eigenstates
- Mass Eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$, $|p|^2 + |q|^2 = 1$
  $x = \frac{m_2 - m_1}{\Gamma}$, $y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$, $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$

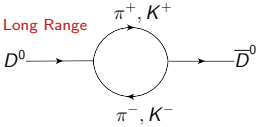
CP Violation

- Direct CPV: $\left|\frac{\overline{\mathcal{A}}_{\overline{f}}}{\mathcal{A}_f}\right| \neq 1$
  $\mathcal{A}_f = \langle f|\mathcal{H}|D\rangle, \overline{\mathcal{A}}_{\overline{f}} = \langle \overline{f}|\mathcal{H}|\overline{D}\rangle$
- CPV in Mixing: $\left|\frac{q}{p}\right| \neq 1$
  Weak Phase: $\phi = \arg\left(\frac{q}{p}\right) \neq 0$
- CPV in Interference between Mixing and Decay:
  $\arg\left(\frac{q}{p}\frac{\overline{\mathcal{A}}_f}{\mathcal{A}_f}\right) \neq 0$

Expectations

- Only up-type quark system with mixing
- 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 $\lesssim 0.5\%$
- CPV expected to be $\mathcal{O}(10^{-3})$ in SM
- If enhancement of CPV is seen, could be caused by New Physics



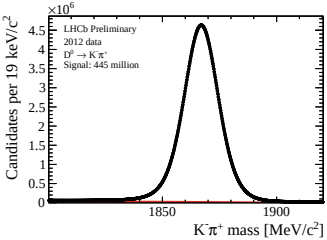


LHCb

Int. J. Mod. Phys. A 30, 1530022 (2015)

- LHCb acceptance: $2 < \eta < 5$
- Reconstructed 1.4 billion charm hadron decays in 2011-2015

LHCb-CONF-2016-005



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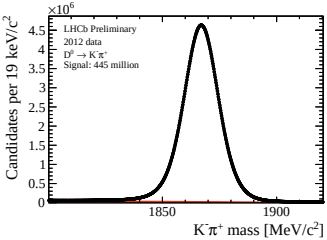

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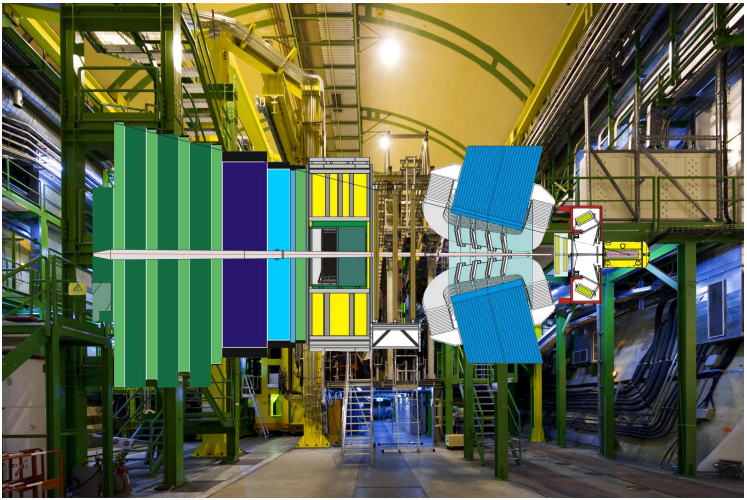

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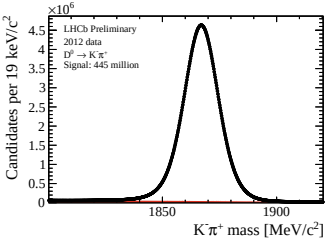

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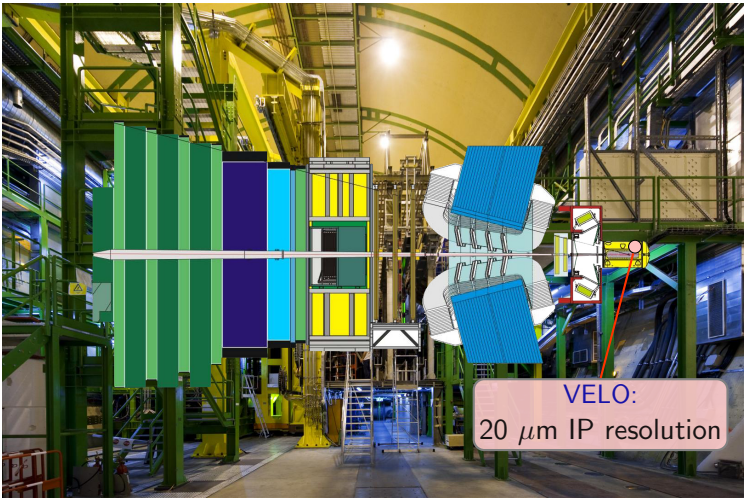

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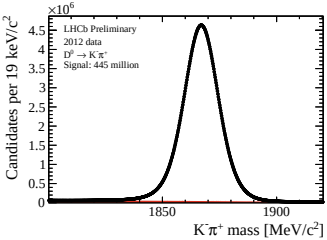

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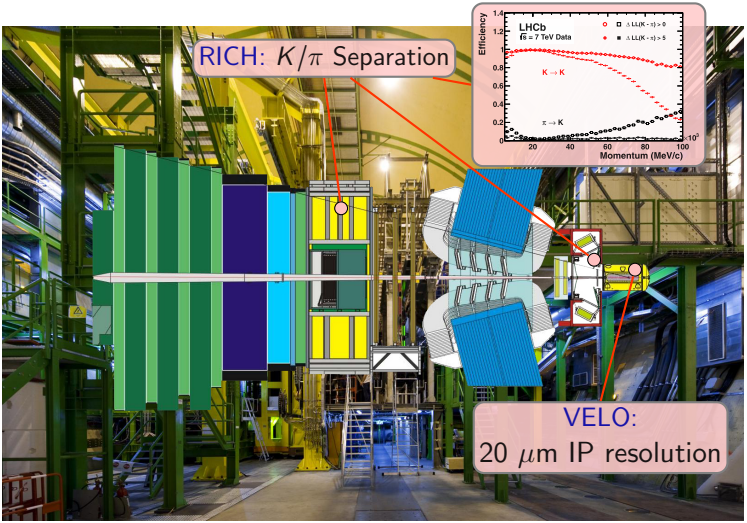

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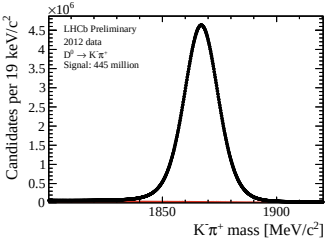

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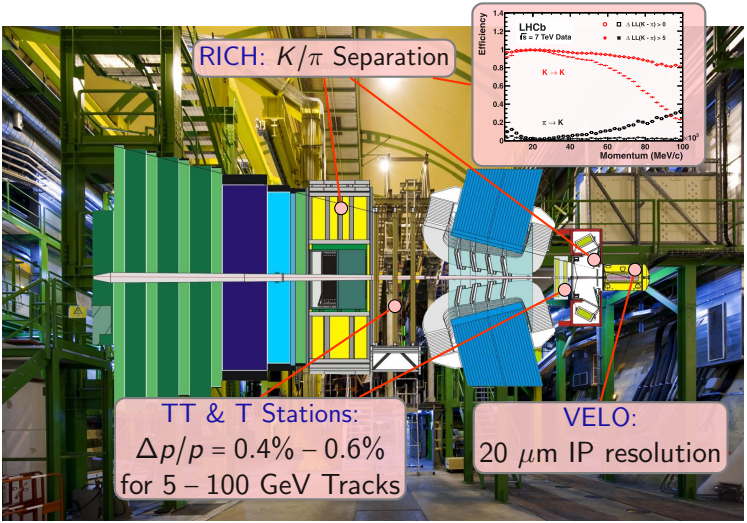

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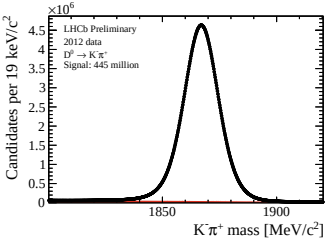

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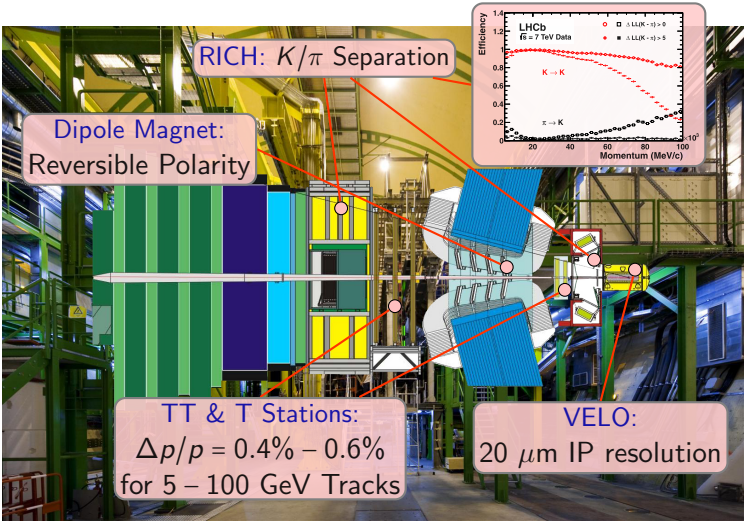

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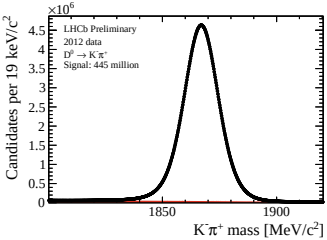

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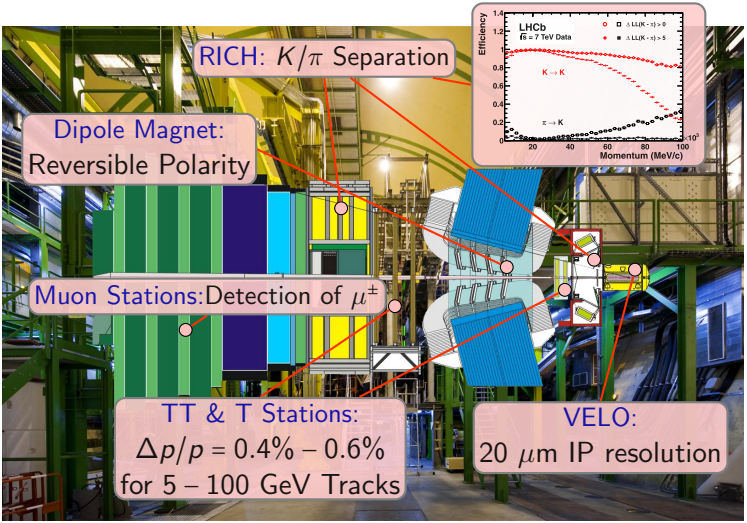
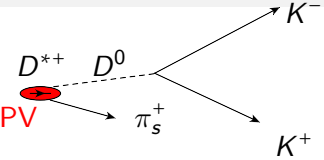


NEW

Measurement of CP asymmetry in $D^0 \to K^- K^+$ decays
LHCb-PAPER-2016-035 (in preparation)

$A_{CP}(D^0 \to KK)$ Method

- Define $A_{\text{raw}}(D^0 \to f) = \dfrac{N(D^0 \to f) - N(\overline{D}^0 \to \overline{f})}{N(D^0 \to f) + N(\overline{D}^0 \to \overline{f})}$
- Measure $A_{CP}(D^0 \to KK)$, Tag using prompt $D^{*}+ \to D^0\pi_s^+$



$$A_{CP}(D^0 \to KK) = A_{\text{raw}}(D^0 \to KK) - A_P(D^{*+}) - A_D(\pi_s^+) + \mathcal{O}(A^3)$$

- Eliminate detection/production asymmetries using control channels $D^{*+} \to D^0(\to K^-\pi^+)\pi_s^+$, $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \overline{K}^0\pi^+$

$$\boxed{\begin{aligned} A_{CP}(D^0 \to KK) =& A_{\text{raw}}(D^0 \to KK) - A_{\text{raw}}(D^0 \to K^-\pi^+) \\ &+ A_{\text{raw}}(D^+ \to K^-\pi^+\pi^+) - A_{\text{raw}}(D^+ \to \overline{K}^0\pi^+) + A_D(\overline{K}^0) \end{aligned}}$$

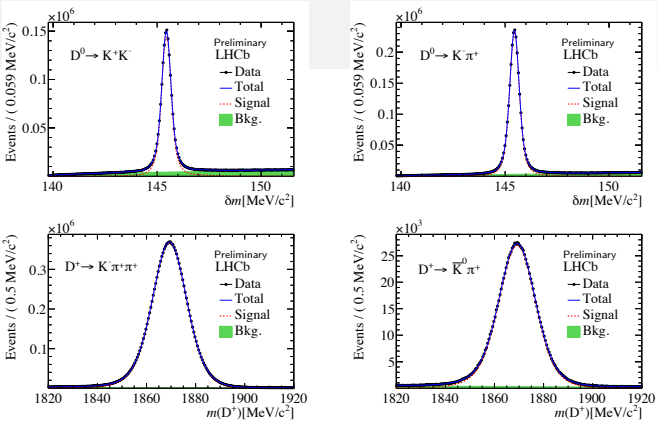
- Also measure $A_{CP}(\pi^-\pi^+)$, derived from previous result PRL 116, 191601

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

- Combine with muon tagged results JHEP (2014) 2014: 41

Yields and Weighting

LHCb-PAPER-2016-035 (in prep.)



- Extract yields with binned maximum likelihood fit to δm for D^* modes, or $m(D^+)$
- Simultaneous fit to +/− tags
- Order weighting to cancel production asymmetry and maximize statistical sensitivity
  1. $D^+ \to K^-\pi^+\pi^+$ weighted to $D^+ \to \overline{K}^0\pi^+$
  2. $D^0 \to K^-\pi^+$ weighted to $D^+ \to K^-\pi^+\pi^+$
  3. $D^0 \to KK$ weighted to $D^0 \to K^-\pi^+$

δm Fit Model: Double Gaussian + Bifurcated Gaussian+ Exponential
D^+ Fit Model: Triple Gaussian + Empirical Background

Channel	Before Weighting	After Weighting
$D^0 \to KK$	5.56 M	1.63 M
$D^0 \to K\pi$	32.4 M	2.61 M
$D^+ \to K\pi\pi$	37.5 M	13.7 M
$D^+ \to \overline{K}^0\pi$	1.06 M	-

Results

Category	Systematic uncertainty[%]
Extraction of raw asymmetries:	
Fit model	0.025
Peaking background	0.015
Cancellation of nuisance asymmetries:	
Additional fiducial cuts	0.040
Weighting configuration	0.062
Weighting simulation	0.054
Secondary charm meson	0.039
Neutral Kaon asymmetry	0.014
Quadratic sum	0.10

$$A_{CP}(KK) = (+0.14 \pm 0.15 \pm 0.10)\%$$

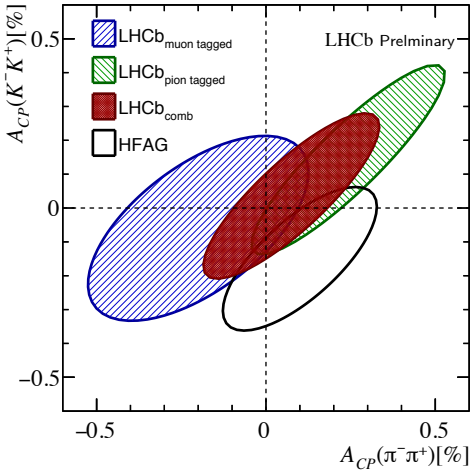
- Using $\Delta(A_{CP})$ from PRL 116, 191601

$$A_{CP}(\pi\pi) = (0.24 \pm 0.15 \pm 0.11)\%$$

- Combine with muon tagged $A_{CP}(KK, \pi\pi)$ with full correlations

$$A_{CP}^{\text{comb}}(KK) = (0.04 \pm 0.12 \pm 0.10)\%$$

$$A_{CP}^{\text{comb}}(\pi\pi) = (0.07 \pm 0.14 \pm 0.11)$$



Consistent with CP Conservation

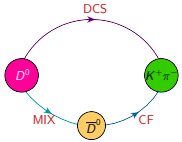
NEW

Search for Mixing and CP Violation with WS $D^0 \to K\pi$ from $\overline{B} \to \mu D^* X$
LHCb-PAPER-2016-033 (in preparation)

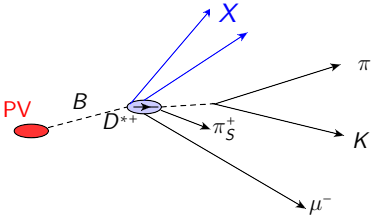
DT WS Mixing/CPV: Method

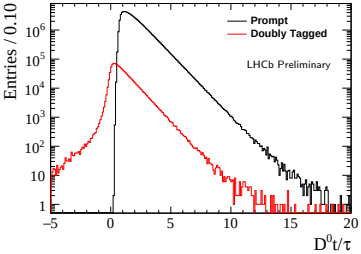
$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

- Measure time dependent WS/RS ratio of $D^0 \to K\pi$
  $R(t)^{\pm} = \frac{WS(t)^{\pm}}{RS(t)^{\pm}} \simeq R_D^{\pm} + \sqrt{R_D^{\pm}} y'^{\pm} \frac{t}{\tau} + \frac{x'^{\pm 2} + y'^{\pm 2}}{4} \left(\frac{t}{\tau}\right)^2$
- Use:
  $\overline{B} \to \mu^- D^{*+} X$
  $D^{*+} \to D^0 \pi_S^+$
  $D^0 \to K\pi$



- Doubly Tagged: μ^- and π_S^+ tag the D^0 production flavor
- Extremely clean
- Complements previous measurement using "prompt" $D^{*+} \to D^0 \pi_S^+$
  PRL 111, 251801 (2013)
- Goal: Measure Mixing/CPV parameters with DT only sample and combination of prompt and DT

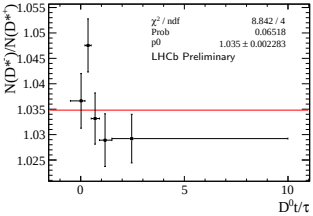




LHCb-PAPER-2016-033 (in prep.)

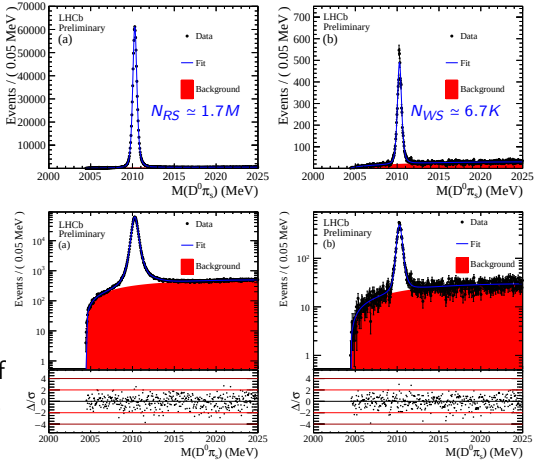
Data Samples and Selection

- Extract $N_{RS,WS}$ from binned maximum likelihood fit to D^* invariant mass
- Strategy:
  - Fit RS time integrated sample, fix signal shape
  - Split into $D^{*+}(D^0)$ and $D^{*-}(\overline{D}^0)$
  - fit RS and WS in each bin of decay time
- Subtract combinatoric μ background
- Veto candidates in both DT and prompt datasets



- Find decay time variation of RS D^{*-}/D^{*+} ratio, account for in systematics

RS WS

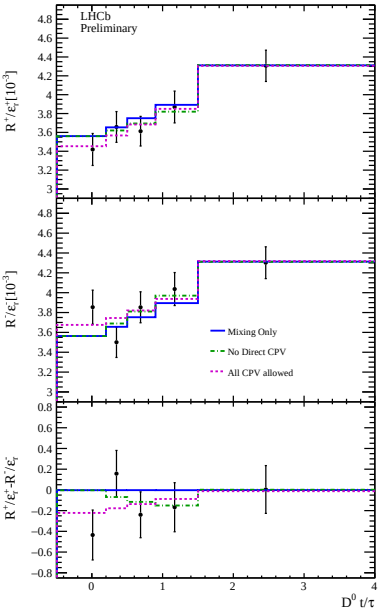


Fit Model: Triple Gaussian + Johnson + ARGUS like background

DT Only Result

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

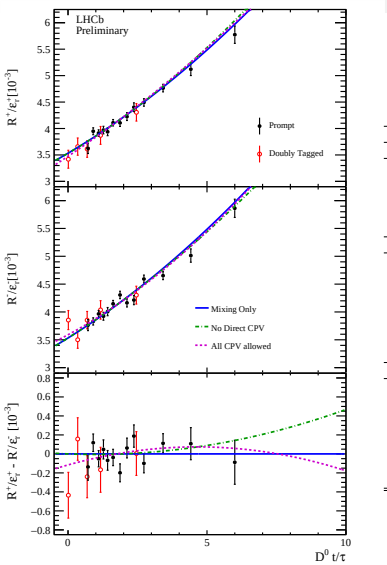
- Mixing Only: $R_D^+ = R_D^-$, $x'^{+2} = x'^{-2}$, $y'^+ = y'^-$
- No Direct CPV: $R_D^+ = R_D^-$
- All CPV allowed: All +/- free
- $K\pi$ detection asymmetry, peaking backgrounds accounted for in fit
- Systematic uncertainties: combinatoric μ subtraction, prompt veto, fit model variation and time dependent asymmetry
- Consistent with mixing only fit



Parameter	Value
No CPV	
$R_D[10^{-3}]$	$3.48 \pm 0.10 \pm 0.01$
$x'^2[10^{-4}]$	$0.28 \pm 3.10 \pm 0.11$
$y'[10^{-3}]$	$4.60 \pm 3.70 \pm 0.18$
χ^2/NDF	6.293/7
No Direct CPV	
$R_D[10^{-3}]$	$3.48 \pm 0.10 \pm 0.01$
$x'^{2+}[10^{-4}]$	$1.94 \pm 3.67 \pm 1.17$
$y'^+[10^{-3}]$	$2.79 \pm 4.27 \pm 0.98$
$x'^{2-}[10^{-4}]$	$-1.53 \pm 4.04 \pm 1.68$
$y'^-[10^{-3}]$	$6.51 \pm 4.38 \pm 1.66$
χ^2/NDF	5.589/5
All CPV Allowed	
$R_D^+[10^{-3}]$	$3.38 \pm 0.15 \pm 0.06$
$x'^{2+}[10^{-4}]$	$-0.19 \pm 4.46 \pm 0.32$
$y'^+[10^{-3}]$	$5.81 \pm 5.25 \pm 0.31$
$R_D^-[10^{-3}]$	$3.60 \pm 0.15 \pm 0.07$
$x'^{2-}[10^{-4}]$	$0.79 \pm 4.31 \pm 0.38$
$y'^-[10^{-3}]$	$3.32 \pm 5.21 \pm 0.40$
χ^2/NDF	4.473/4

DT and Prompt combination

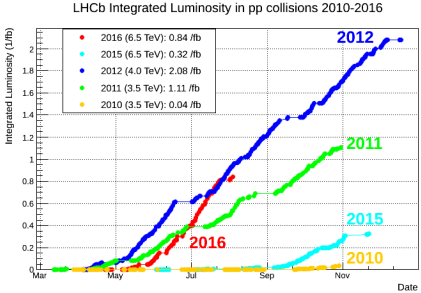
- Modify original fit to include both DT and prompt combinations
- Add errors in quadrature as original reported errors are not the same as here.
- Errors ~ 10 – 20% lower for combined fit
- Consistent with mixing only fit



Parameter	DT+prompt combination	Prompt alone	% Error Improvement
	No CPV		
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067	19
$x'^2[10^{-5}]$	3.6 ± 4.3	5.5 ± 4.9	12
$y'[10^{-3}]$	5.23 ± 0.84	4.80 ± 0.94	11
χ^2/NDF	96.594/111		
	No Direct CPV		
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067	19
$x'^{2+}[10^{-5}]$	4.9 ± 5.0	6.4 ± 5.6	11
$y'^{+}[10^{-3}]$	5.14 ± 0.91	4.80 ± 1.08	16
$x'^{2-}[10^{-5}]$	2.4 ± 5.0	4.6 ± 5.5	9
$y'^{-}[10^{-3}]$	5.32 ± 0.91	4.8 ± 1.08	16
χ^2/NDF	96.147/109		
	All CPV Allowed		
$R_D^+[10^{-3}]$	3.474 ± 0.081	3.545 ± 0.095	15
$x'^{2+}[10^{-5}]$	1.1 ± 6.5	4.9 ± 7.0	7
$y'^{+}[10^{-3}]$	5.97 ± 1.25	5.10 ± 1.38	9
$R_D^-[10^{-3}]$	3.591 ± 0.081	3.591 ± 0.090	10
$x'^{2-}[10^{-5}]$	6.1 ± 6.1	6.0 ± 6.8	10
$y'^{-}[10^{-3}]$	4.50 ± 1.21	4.50 ± 1.39	13
χ^2/NDF	94.960/108		

Conclusion

- Today:
  - Measurement of CP asymmetry in $D^0 \to K^- K^+$ decays LHCb-PAPER-2016-035 (in preparation)
  - Search for Mixing and CP Violation with WS $D^0 \to K\pi$ from $\overline{B} \to \mu D^* X$ LHCb-PAPER-2016-033 (in preparation)
- Still no CPV in sight
- The future:



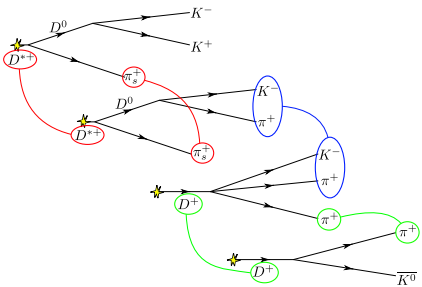
- 4.6 billion charm decays reconstructed in 2011-2015
- LHC is running very efficiently
- Datataking is ongoing
- Expect many more exciting charm results to come!
- Thanks for your attention!

Backup Slides

$D^0 \to KK$ cancellation of asymmetries

- Control Channels to cancel:

$$A_{CP}(D^0 \to KK) = A_{\text{raw}}(D^0 \to KK) - A_P(D^{*+}) - A_D(\pi_s^+) + \mathcal{O}(A^3)$$
$$A_{\text{raw}}(D^0 \to K^-\pi^+) = A_P(D^{*+}) + A_D(\pi_s^+) + A_D(K^-) + A_D(\pi^+)$$
$$A_{\text{raw}}(D^+ \to K^-\pi^+\pi^+) = A_P(D^+) + A_D(K^-) + A_D(\pi^+) + A_D(\pi^+)$$
$$A_{\text{raw}}(D^+ \to \overline{K}^0\pi^+) = A_P(D^+) + A_D(\overline{K}^0) + A_D(\pi^+)$$



$A_{CP}(KK)$ Weighting checks

- Nominal weighting is in
  1. $D^+ \to K^-\pi^+\pi^+$ weighted to $D^+ \to \overline{K}^0\pi^+$
  2. $D^0 \to K\pi$ weighted to $D^+ \to K^-\pi^+\pi^+$
  3. $D^0 \to KK$ weighted to $D^0 \to K\pi$
- Variables weighted: $D^{*+}(p_T, \eta, \phi)$, $D^+(p_T, \eta)$,π_{bachelor}, high$p\pi inK\pi\pi(\eta, \phi)$, $K, \pi(p_T, \eta, \phi)$

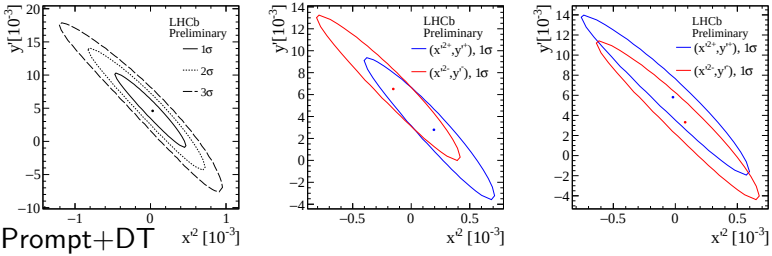
Systematic check	$\mathbf{A_{CP}(K^-K^+)}$ **[%]**
Default	0.143 ± 0.153
Weighting only in p_T,η	0.161 ± 0.144
Weighting with 15 bins	0.204 ± 0.150
Weighting with 25 bins	0.182 ± 0.154
Set high weights in each step to 1	0.143 ± 0.140
Maximal difference	0.062

Correlations for $A_{CP}(KK)$

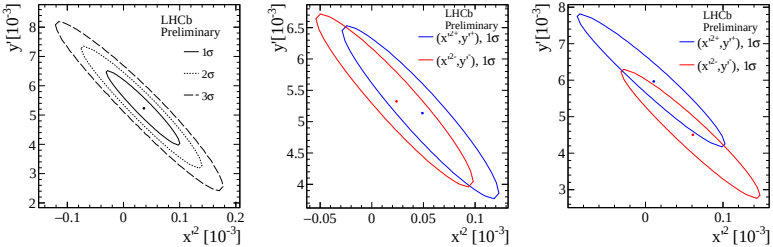
- Statistical Correlation between Muon tagged and Pion tagged: 0.36
- Correlation between pion tagged $A_{CP}(D^0 \to KK)$ and $\Delta A_{CP} = 0.24$

Contours for (x'^2, y')

DT Only



Prompt+DT



What do we measure?

- Assuming factorizable efficiencies, we measure

$$N^{\text{obs}}_{RS+} = N_{D^{*+}}\mathcal{B}(D^{*+} \to D^0\pi^+_s)\mathcal{B}(D^0 \to K^-\pi^+)\epsilon(\mu^-)\epsilon(\pi^+_s)\epsilon(K^-\pi^+)$$
$$N^{\text{obs}}_{WS+} = N_{D^{*+}}\mathcal{B}(D^{*+} \to D^0\pi^+_s)\mathcal{B}(D^0 \to K^+\pi^-)\epsilon(\mu^-)\epsilon(\pi^+_s)\epsilon(K^+\pi^-)$$
$$N^{\text{obs}}_{RS-} = N_{D^{*-}}\mathcal{B}(D^{*-} \to \overline{D}^0\pi^-_s)\mathcal{B}(\overline{D}^0 \to K^+\pi^-)\epsilon(\mu^+)\epsilon(\pi^-_s)\epsilon(K^+\pi^-)$$
$$N^{\text{obs}}_{WS-} = N_{D^{*-}}\mathcal{B}(D^{*-} \to \overline{D}^0\pi^-_s)\mathcal{B}(\overline{D}^0 \to K^-\pi^+)\epsilon(\mu^+)\epsilon(\pi^-_s)\epsilon(K^-\pi^+)$$

- The ratio then becomes

$$R^{\text{obs}\pm} = \frac{N^{\text{obs}}_{WS\pm}}{N^{\text{obs}}_{RS\pm}} = R^{\pm}\left(\frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)}\right)^{\pm 1}$$

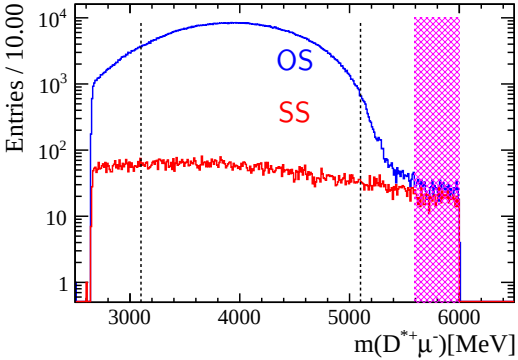
- Allowing for background contributions, this becomes

$$R^{\text{obs}\pm} = R^{\pm}(1 - \Delta^{\pm}_{\text{p}})\left(\frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)}\right)^{\pm 1} + p^{\pm}_{\text{other}}$$

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

Selection Criteria and Backgrounds from B

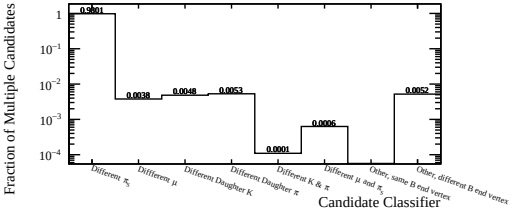
- Kinematically constrain daughter K, π to same vertex, constrain μ, π_S and D^0 to come from same vertex
- Veto candidates which appear in both Prompt and DT samples
- Extract random muon and muon mistag shape from $B \to \mu^+ D^{*+} X$ (Unphysical)
- Call this the Same Sign (SS) sample.
- Scale to sideband in $5.6 < m(\mu D^*) < 6.0$GeV in each decay time bin
- Gauge systematic uncertainty by setting scaling factor to 1

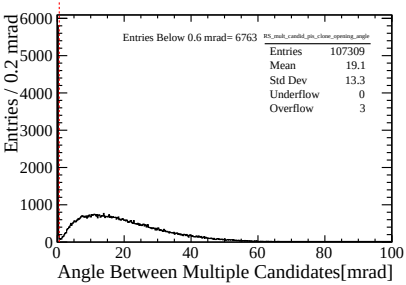


$$R^{\text{obs}\pm} = R^{\pm}(1 - \cancel{\Delta_p^{\pm}}^{\,0})\left(\frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)}\right)^{\pm 1} + p^{\pm}_{\text{other}}$$

Multiple Candidates

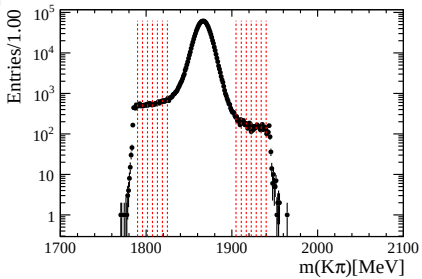
- To understand multiple candidates, match explicitly momenta of final state particles, varying individually to find differences
- Find 109,484 multiple candidates, almost all are due to a slow pion being wrong.
- Wrong μ subtracted
- Different D^0 daughters will not peak in $m(D^*)$, same with different D^0 or different μ and π_S
- Explicitly use all multiple candidates
- Look for π_S candidates consistent with being a clone: momentum vectors aligned within 0.6 mrad
- Choose one clone randomly

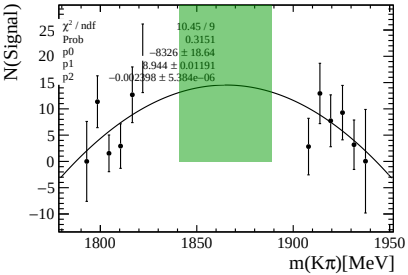




Extraction of Peaking Backgrounds

- WS peaking background not well described by double misID alone
- Divide D^0 sidebands into 6 regions for low and high sidebands
- Fit $m(D^*)$ in each bin, extract the number of peaking events
- Extract number of events in the signal region. Total: 128 ± 31
- Due to limited statistics, can only do integrated over decay time
- Fraction of doubly misidentified D^0 to WS yield $(1.9 \pm 0.7)\%$
- Fraction of doubly misidentified D^0 to RS yield: $(7.4 \pm 1.8) \times 10^{-5} \equiv p_{\text{other}}$





The strategy for $A_{K\pi}$

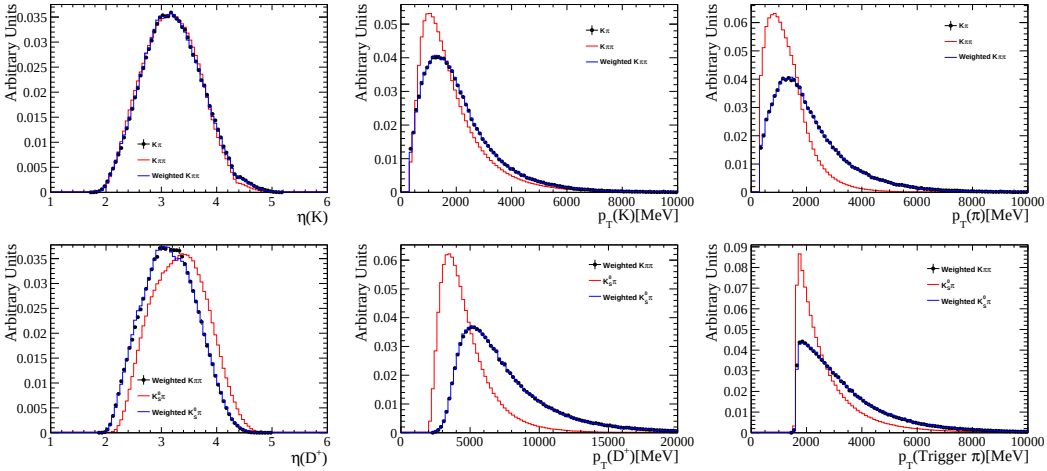
- Calculate Instrumental $K\pi$ asymmetry as

$$A_{K\pi} = \frac{\epsilon(K^+\pi^-) - \epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-) + \epsilon(K^-\pi^+)}$$
$$\approx A(K^0_S\pi) - A(K\pi\pi) - A(\overline{K}^0) + A_{L0\ \mathrm{Muon}} + \mathcal{O}(10^{-6})$$

- $A(\overline{K}^0) = -(0.05 \pm 0.01)\%$ from previous measurements
- Use $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K^0_S\pi^+$ to extract $A(K\pi\pi)$ and $A(K^0_S\pi)$
- Calculate $A_{L0\ \mathrm{Muon}}$ directly from DT data
- Extract asymmetry of each sample from simultaneous fit to $D^\pm$ mass
- To cancel $D^\pm$ production asymmetry, must reweight

Reweighting Plots

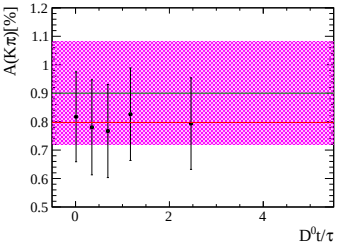
MD 2012, LHCb Preliminary



$A(K\pi)$ Results

Sample	$A(K\pi\pi)[\%]$	$A(K^0_S\pi)[\%]$	$A_{L0muon}[\%]$	$A(K\pi)[\%]$
2011 Mag Down	-1.31 ± 0.27	-0.85 ± 0.31	-0.01 ± 0.01	0.50 ± 0.41
2011 Mag Up	-1.43 ± 0.28	-0.794 ± 0.36	0.02 ± 0.01	0.71 ± 0.45
2012 Mag Down	-1.81 ± 0.17	-0.647 ± 0.27	0.00 ± 0.01	1.22 ± 0.32
2012 Mag Up	-1.79 ± 0.21	-0.929 ± 0.25	0.00 ± 0.01	0.91 ± 0.33
Total	-1.67 ± 0.11	-0.81 ± 0.14	0.00 ± 0.01	0.90 ± 0.18

- Search for decay time variation by splitting DT sample by decay time, reweight in each of 5 bins
- See no variation with respect to decay time, take offset as systematic



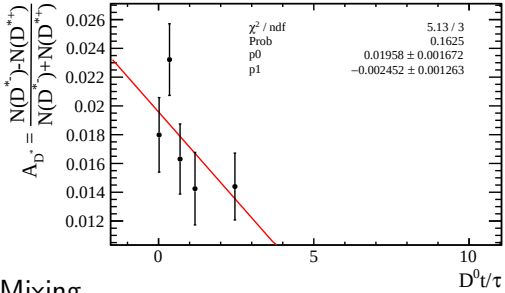
$$A(K\pi) = [0.90 \pm 0.18 \pm 0.10]\%$$

Cross checks and Systematic Uncertainties

- Cross Checks
  - Split by magnet polarity
  - Split by data-taking year
  - Split by polarity and year
  - Split by kaon momentum
  - Split by slow pion p_T
  - Split by muon p_T
  - All consistent with statistical fluctuations
- Systematic Uncertainties
  - No scaling of the SS background,
  - Allowing the RS fit model to be different for each decay time bin.
  - Variation of the $K\pi$ asymmetry as a function of decay time,
  - Fit coverage using 2σ possible bands of x and y from HFAG
  - Differences from nominal taken as systematic uncertainty, correlations taken into account
  - All cross-checks performed on blinded data, systematic uncertainties calculated before unblinding.

Time dependence of $K\pi$ asymmetry

- Know that $A(K\pi)$ does not depend on decay time
- Know we have a time dependent charge asymmetry
- Vary $A(K\pi) \to A(K\pi)(t) = A(K\pi) + \delta(A_{K\pi}) + \alpha + \beta t$.
- α, β terms taken from fit to the asymmetry of the RS$D^{*\pm}$
- $\delta(A_{K\pi}) = -0.0110$ chosen such that $\int dt\ A(K\pi)(t) = A(K\pi)$



Mixing

Parameter	$R_D[10^{-3}]$	$y'[10^{-3}]$	$x'^2[10^{-3}]$
Systematic Uncertainty	0.01	0.07	0.04

No DCPV

Parameter	$R_D[10^{-3}]$	$y'^+[10^{-3}]$	$x'^{2+}[10^{-4}]$	$y'^-[10^{-3}]$	$x'^{2-}[10^{-4}]$
Systematic Uncertainty	0.01	1.17	0.98	1.64	1.67

All CPV

Parameter	$R_D^+[10^{-3}]$	$y'^+[10^{-3}]$	$x'^{2+}[10^{-4}]$	$R_D^-[10^{-3}]$	$y'^-[10^{-3}]$	$x'^{2-}[10^{-4}]$
Systematic Uncertainty	0.06	0.25	0.03	0.07	0.28	0.03

No Mixing Fit for DT alone

- In fit, set $x'^2 = y' = 0$
- Result: $R_D = (3.76 \pm 0.05) \times 10^{-3}$
- $\chi^2/\text{ndf} = 31.953/9$
- $\Delta\chi^2 = 22.66$, NDF $= 2$, $p = 2.68 \times 10^{-6}$
- Inconsistent with no mixing at 4.6σ