Search for CP violation in two-body charm decays at LHCb

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on behalf of LHCb Collaboration

Today results

- Measurement of CP asymmetry in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ [LHCB-PAPER-2014-013, submitted to JHEP]
- Search for CP violation in $D^\pm \rightarrow K^0_s K^\pm$ and $D^\pm_s \rightarrow K^0_s \pi^\pm$ [LHCB-PAPER-2014-018, submitted to JHEP]

Charm physics at LHCb

LHCb is designed for beauty physics, but it offers a great opportunity to perform charm physics as well

$$\sigma_{c\bar{c}} = (1419 \pm 133)\ \mu b \quad (1)$$

$$\sigma_{b\bar{b}} = (75.3 \pm 14.1)\ \mu b \quad (2)$$

$$\Rightarrow \frac{\sigma_{c\bar{c}}}{\sigma_{b\bar{b}}} \approx 20$$

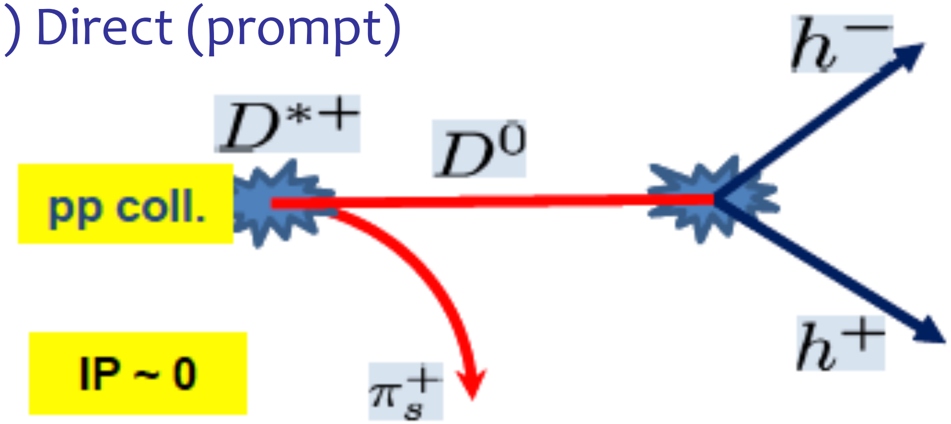
~350M reconstructed charm decays in 2011 data ($1 fb^{-1}$, $s^{1/2} = 7$ TeV).

A dedicated trigger allows to collect a huge amount of D and Λ_c decays

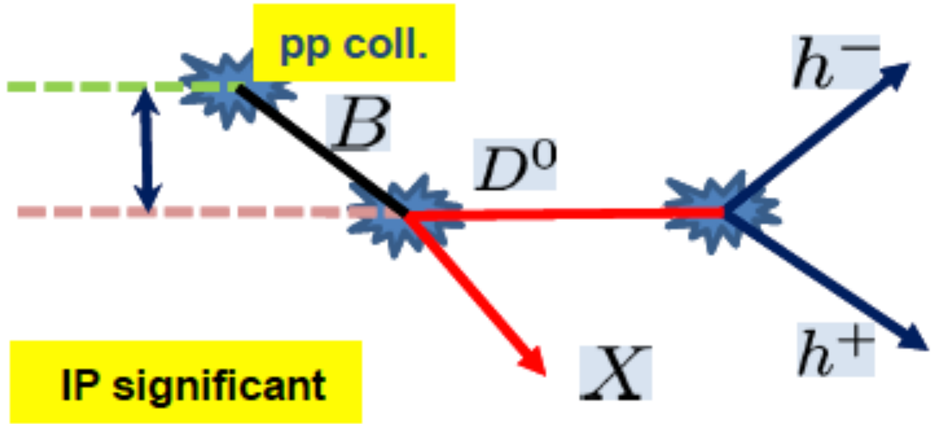
(1) Nucl.Phys.B 871(2013), 1
(2) Phys. Lett. B 694 (2010), 209

Two mechanism of production

1) Direct (prompt)



2) Indirect (from b-hadron decays)



Measurement of CP asymmetry in $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$

The method (I): D^0 from semileptonic B decay

CP asymmetry is defined as

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

with $f=K^-K^+$ and $f=\pi^-\pi^+$

The flavour of the initial state (D^0 or $\overline{D}^0$) is tagged by the charge of the muon in the semileptonic decay, $B \to D^0 \mu^- \bar{\upsilon}_\mu X$

The raw asymmetry for tagged D^0 decays to a final state f is given by

$$A_{raw}(f) = \frac{N(B \to D^0(f)\mu^-\bar{\upsilon}_\mu X) - N(B \to \overline{D}^0(f)\mu^+\upsilon_\mu X)}{N(B \to D^0(f)\mu^-\bar{\upsilon}_\mu X) + N(B \to \overline{D}^0(f)\mu^+\upsilon_\mu X)}$$

where N refers to the number of reconstructed events of decay after background subtraction

The method (II): D⁰ from semileptonic B decay

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

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

CP asymmetry

Any charge-dependent asymmetry in muon reconstruction

B production asymmetry

- No detection asymmetry for D^0 decays to K^-K^+ or $\pi^-\pi^+$
- … if we take the raw asymmetry difference

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

- the B production and the muon detection asymmetries will cancel

The method (III): D^0 from semileptonic B decay

- The production and muon detection asymmetry can been determined using the Cabibbo-favoured $D^0 \rightarrow K^- \pi^+$ from semileptonic B
  - CP violation in $D^0 \rightarrow K^- \pi^+$ is expected to significantly suppressed with respect to $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$
- This allows to measure also the single $A_{CP}(KK)$ and $A_{CP}(\pi\pi)$ asymmetries

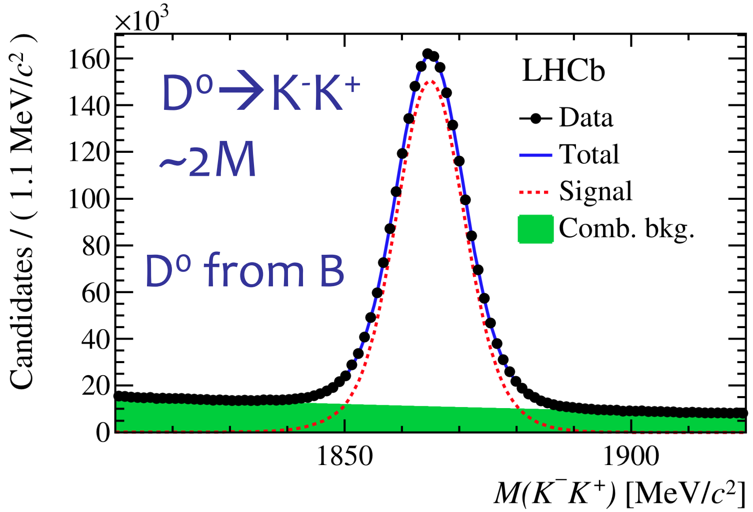
$$A_{CP}(K^-K^+) = A_{\mathrm{raw}}(K^-K^+) - A_{\mathrm{raw}}(K^-\pi^+) + A_D(K^-\pi^+)$$

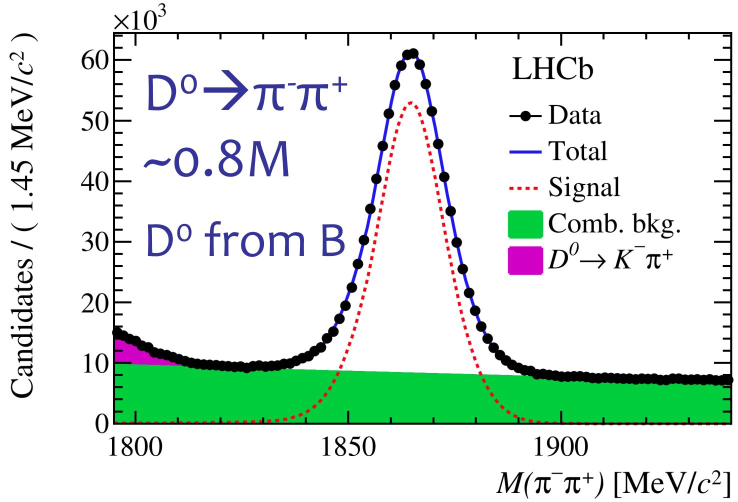
$$A_{CP}(\pi^-\pi^+) = A_{CP}(K^-K^+) - \Delta A_{CP}$$

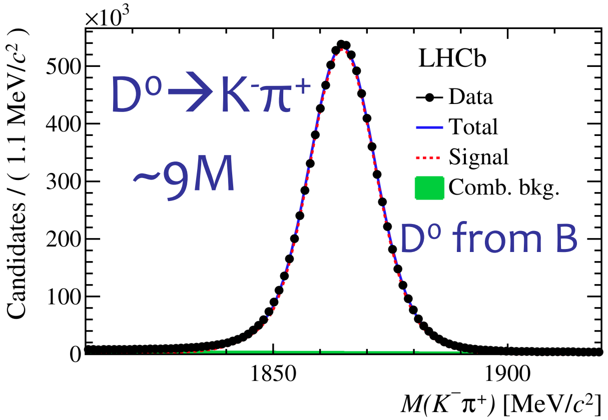
the detection asymmetry $A_D(K\pi)$ is measured exploiting prompt $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^+ \rightarrow K^0_s \pi^+$ decays

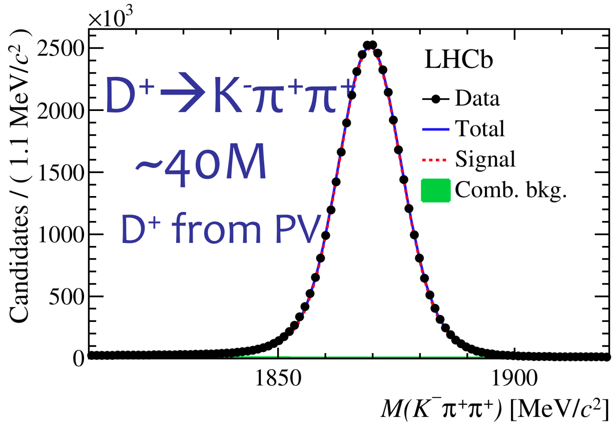
Determination of the raw asymmetries

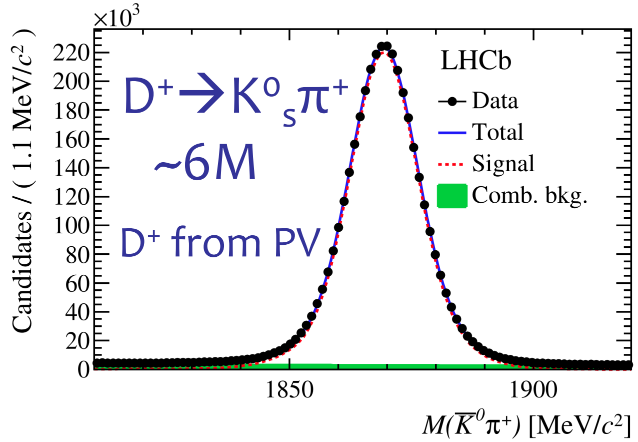
$L = 3\,fb^{-1}$











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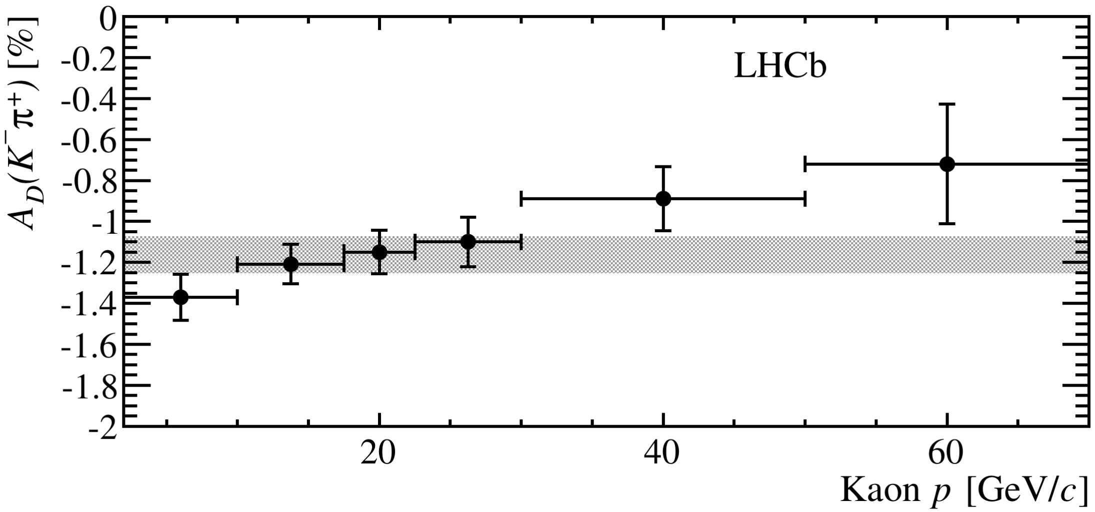
Kπ detection asymmetry

Kπ detection asymmetry is determined using prompt $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^+ \rightarrow K^0_s\pi^+$ raw asymmetries

$A_D(K\pi)$ as function of K momentum



$$A_D(K^-\pi^+) = (-1.17 \pm 0.12)\%$$

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$A_D(K\pi)$ dominated by the different interaction cross section of K^- and K^+ mesons in the matter
As expected, the kaon interaction asymmetry decreases with the kaon momentum

Final results

$$\Delta A_{CP} = (+0.14 \pm 0.16\,(\text{stat}) \pm 0.08\,(\text{syst}))\%$$
$$A_{CP}(K^-K^+) = (-0.06 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

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

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 modelling	0.03%	0.03%
Quadratic sum	0.08%	0.10%

$\rho(\Delta A_{CP}, A_{CP}(KK))=0.28$

No significant CP violation observed at the level of 10^{-3}

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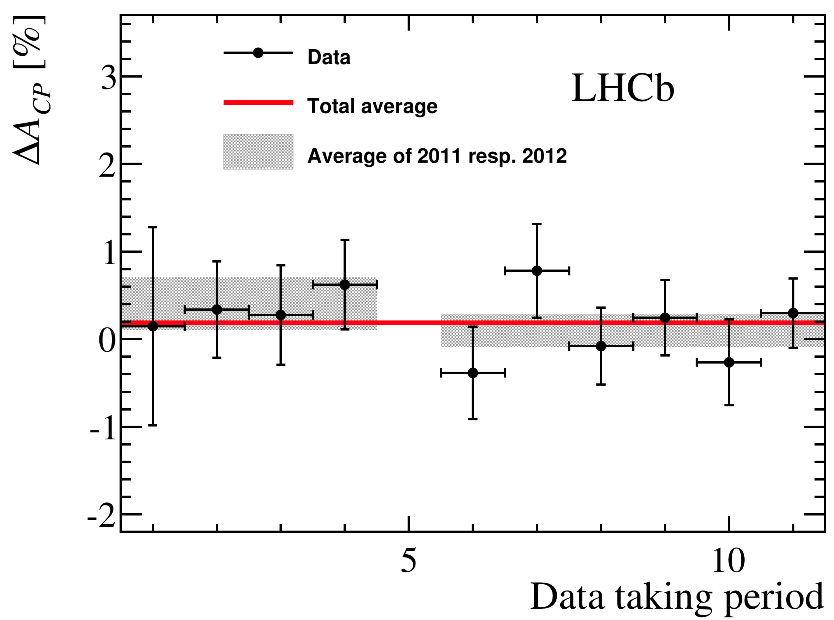
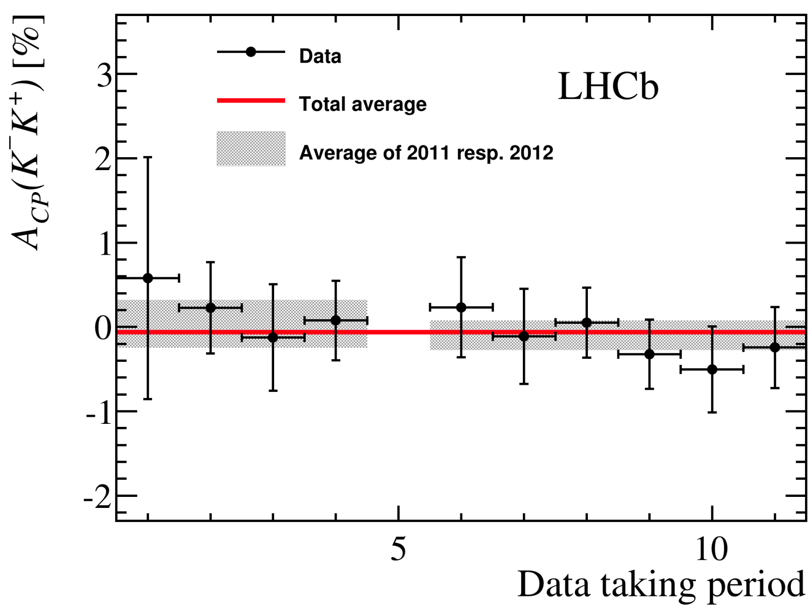
Consistency checks





ΔA_{CP} is also studied as function of several kinematic variables
No significant dependence is observed

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Search for CP violation in $D^{\pm} \rightarrow K^0_s K^{\pm}$ and $D^{\pm}_s \rightarrow K^0_s \pi^{\pm}$

The method (I): prompt $D^{\pm} \rightarrow K^0_s K^{\pm}$ and $D^{\pm}_s \rightarrow K^0_s \pi^{\pm}$

CP asymmetries are defined as

$$\mathcal{A}_{CP}^{D^{\pm}_{(s)} \to K^0_S h^{\pm}} \equiv \frac{\Gamma(D^+_{(s)} \to K^0_S h^+) - \Gamma(D^-_{(s)} \to K^0_S h^-)}{\Gamma(D^+_{(s)} \to K^0_S h^+) + \Gamma(D^-_{(s)} \to K^0_S h^-)}$$

Measured asymmetries are

$$\mathcal{A}_{\rm meas}^{D^{\pm}_{(s)} \to K^0_S h^{\pm}} = \frac{N_{\rm sig}^{D^+_{(s)} \to K^0_S h^+} - N_{\rm sig}^{D^-_{(s)} \to K^0_S h^-}}{N_{\rm sig}^{D^+_{(s)} \to K^0_S h^+} + N_{\rm sig}^{D^-_{(s)} \to K^0_S h^-}}$$

We measure CP asymmetry plus asymmetries due both to production and detector effects

$$\mathcal{A}_{\rm meas}^{D^{\pm}_{(s)} \to K^0_S h^{\pm}} \approx \mathcal{A}_{CP}^{D^{\pm}_{(s)} \to K^0_S h^{\pm}} + \mathcal{A}_{\rm prod}^{D^{\pm}_{(s)}} + \mathcal{A}_{\rm det}^{h^{\pm}} + \mathcal{A}_{K^0/\overline{K}^0}$$

CP asymmetry

Any charge-dependent asymmetry in pion/kaon reconstruction

$D^{\pm}_{(s)}$ production asymmetry

detection + CP violation asymmetry $K^0/\overline{K}^0$

The method (II): prompt $D^{\pm} \to K^0_s K^{\pm}$ and $D^{\pm}_s \to K^0_s \pi^{\pm}$

Assuming negligible CP violation in Cabibbo favoured decay,
we can define the double difference

$$\mathcal{A}_{CP}^{\mathcal{DD}} = \left[\mathcal{A}_{\rm meas}^{D_s^{\pm}\to K_S^0\pi^{\pm}} - \mathcal{A}_{\rm meas}^{D_s^{\pm}\to K_S^0 K^{\pm}}\right] - \left[\mathcal{A}_{\rm meas}^{D^{\pm}\to K_S^0\pi^{\pm}} - \mathcal{A}_{\rm meas}^{D^{\pm}\to K_S^0 K^{\pm}}\right] - 2\mathcal{A}_{K^0}$$

where pion/kaon detection and D production asymmetry cancel
and A_{K^0} is measured by LHCb [LHCb-PAPER-2014-013]

The double difference is the related to the CP asymmetry

$$\mathcal{A}_{CP}^{D^{\pm}\to K_S^0 K^{\pm}} + \mathcal{A}_{CP}^{D_s^{\pm}\to K_S^0\pi^{\pm}} = \mathcal{A}_{CP}^{\mathcal{DD}}$$

Using asymmetry measured from Cabibbo-favoured $D_s^{\pm} \to \phi\pi^{\pm}$ is
possible to measure the single CP asymmetries

$$\mathcal{A}_{CP}^{D^{\pm}\to K_S^0 K^{\pm}} = \left[\mathcal{A}_{\rm meas}^{D^{\pm}\to K_S^0 K^{\pm}} - \mathcal{A}_{\rm meas}^{D_s^{\pm}\to K_S^0 K^{\pm}}\right] - \left[\mathcal{A}_{\rm meas}^{D^{\pm}\to K_S^0\pi^{\pm}} - \mathcal{A}_{\rm meas}^{D_s^{\pm}\to \phi\pi^{\pm}}\right] - \mathcal{A}_{K^0}$$

$$\mathcal{A}_{CP}^{D_s^{\pm}\to K_S^0\pi^{\pm}} = \mathcal{A}_{\rm meas}^{D_s^{\pm}\to K_S^0\pi^{\pm}} - \mathcal{A}_{\rm meas}^{D_s^{\pm}\to \phi\pi^{\pm}} - \mathcal{A}_{K^0}$$

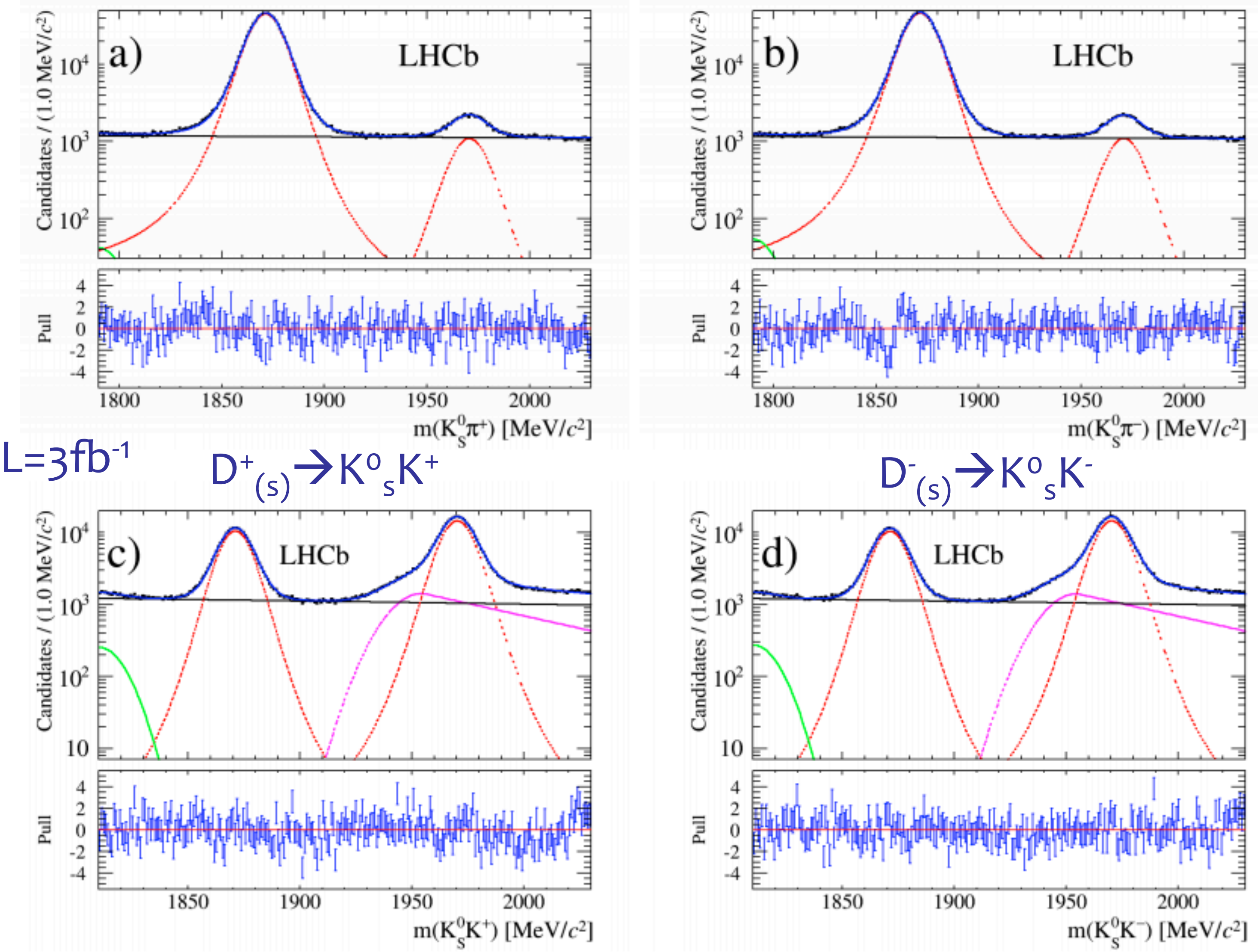
Determination of the raw asymmetries: $D^{\pm}_{s} \rightarrow K^{0}_{s} h^{\pm}$

Example fits

$D^{+}_{(s)} \rightarrow K^{0}_{s}\pi^{+}$ $D^{-}_{(s)} \rightarrow K^{0}_{s}\pi^{-}$

L=3fb^{-1}

$D^{+}_{(s)} \rightarrow K^{0}_{s}K^{+}$ $D^{-}_{(s)} \rightarrow K^{0}_{s}K^{-}$



Simultaneous fit performed for each final state to four independent data sample divided by magnet polarity and candidate charge

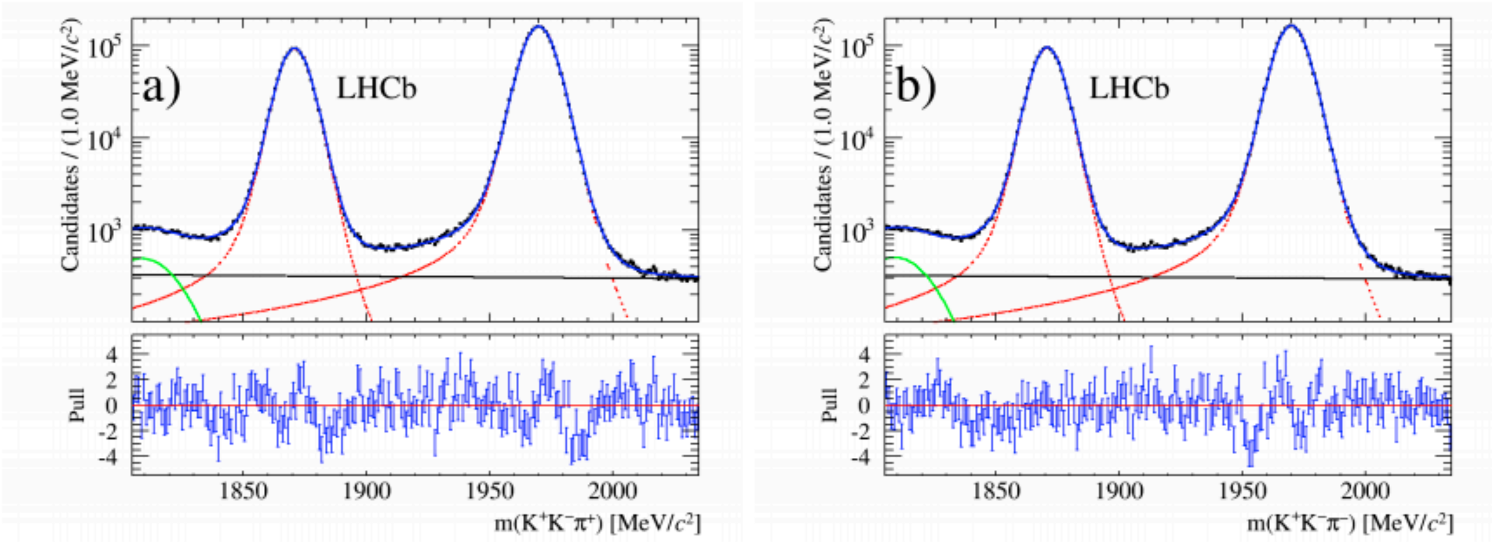
– signal
– combinatorial bkg
– cross feeds
– partially reco bkg

LHCB-PAPER-2014-018 submitted to JHEP

Determination of the raw asymmetries: $D^{\pm} \to \phi\pi^{\pm}$

L=3fb[-1]

$D^{+} \to \phi\pi^{+}$ $D^{-} \to \phi\pi^{-}$



– signal
– combinatorial bkg
– partially reco bkg

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Decay Mode	Yield
$D^{\pm} \to K^0_S\pi^{\pm}$	$4\,834\,440 \pm 2\,555$
$D_s^{\pm} \to K^0_S\pi^{\pm}$	$120\,976 \pm 692$
$D^{\pm} \to K^0_S K^{\pm}$	$1\,013\,516 \pm 1\,379$
$D_s^{\pm} \to K^0_S K^{\pm}$	$1\,476\,980 \pm 2\,354$
$D^{\pm} \to \phi\pi^{\pm}$	$7\,020\,160 \pm 2\,739$
$D_s^{\pm} \to \phi\pi^{\pm}$	$13\,144\,900 \pm 3\,879$

[%] Asymmetry	Total
$\mathcal{A}_{\rm meas}^{D^{\pm}\to K^0_S\pi^{\pm}}$	-0.95 ± 0.05
$\mathcal{A}_{\rm meas}^{D_s^{\pm}\to K^0_S\pi^{\pm}}$	-0.15 ± 0.46
$\mathcal{A}_{\rm meas}^{D^{\pm}\to K^0_S K^{\pm}}$	$+0.01 \pm 0.19$
$\mathcal{A}_{\rm meas}^{D_s^{\pm}\to K^0_S K^{\pm}}$	$+0.27 \pm 0.11$
$\mathcal{A}_{\rm meas}^{D_s^{\pm}\to \phi\pi^{\pm}}$	-0.41 ± 0.05

Final results

Source	$\sqrt{s} = 7$ TeV			$\sqrt{s} = 8$ TeV		
	$\mathcal{A}_{CP}^{\mathcal{DD}}$	$\mathcal{A}_{CP}^{D^\pm \to K_S^0 K^\pm}$	$\mathcal{A}_{CP}^{D_s^\pm \to K_S^0 \pi^\pm}$	$\mathcal{A}_{CP}^{\mathcal{DD}}$	$\mathcal{A}_{CP}^{D^\pm \to K_S^0 K^\pm}$	$\mathcal{A}_{CP}^{D_s^\pm \to K_S^0 \pi^\pm}$
Fit procedure	0.14	0.09	0.11	0.07	0.05	0.01
Cross-feed bkgd.	0.03	0.01	0.02	0.01	–	0.01
Non-prompt charm	0.01	–	–	0.01	–	–
Kinematic weighting	0.08	0.06	0.13	0.05	0.07	0.12
Kinematic region	0.10	0.06	0.04	0.19	0.02	0.17
Trigger	0.13	0.13	0.07	0.17	0.17	0.09
K^0 asymmetry	0.03	0.02	0.02	0.04	0.02	0.02
Total	0.23	0.18	0.19	0.27	0.19	0.22

$$\mathcal{A}_{CP}^{D^\pm \to K_S^0 K^\pm} + \mathcal{A}_{CP}^{D_s^\pm \to K_S^0 \pi^\pm} = (+0.41 \pm 0.49 \pm 0.26)\%$$

$$\mathcal{A}_{CP}^{D^\pm \to K_S^0 K^\pm} = (+0.03 \pm 0.17 \pm 0.14)\%$$

$$\mathcal{A}_{CP}^{D_s^\pm \to K_S^0 \pi^\pm} = (+0.38 \pm 0.46 \pm 0.17)\%$$

LHCB-PAPER-2014-018
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$L = 3 fb^{-1}$

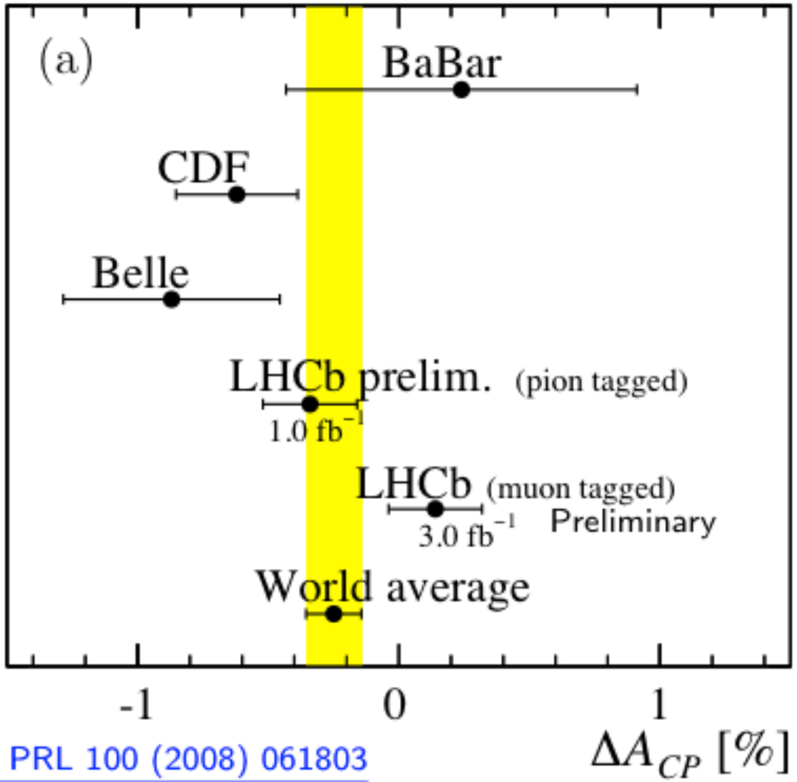
Experimental status: from HFAG

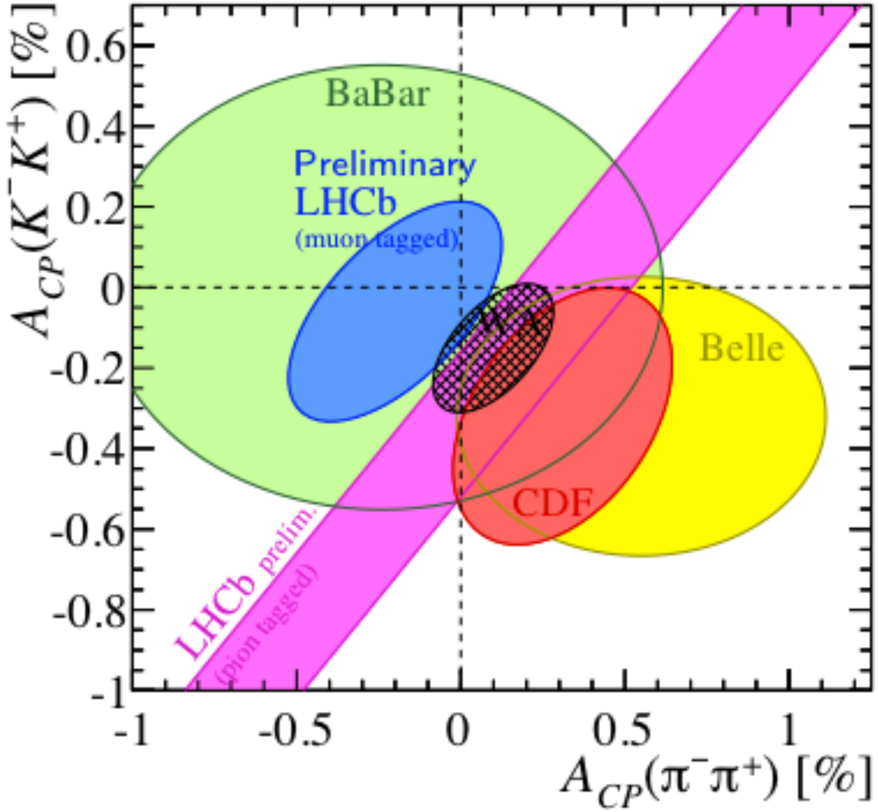
Year	Experiment	CP Asymmetry in the decay mode D+ to K0sK+	[Γ(D+)-Γ(D-)]/[Γ(D+)+Γ(D-)]
2014	LHCb	R. Aaij et al. (LHCb Collab.), arXiv:1406.2624 (2014).	+0.0003 ± 0.0017 ± 0.0014
2013	BABAR	J.P. Lees et al. (BABAR Collab.), Phys. Rev. D 87, 052012 (2013).	+0.0013 ± 0.0036 ± 0.0025
2013	BELLE	B.R. Ko et al. (BELLE Collab.), JHEP 02, 098 (2013).	-0.0025 ± 0.0028 ± 0.0014
2010	CLEO-c	H. Mendez et al. (CLEO Collab.), Phys. Rev. D 81, 052013 (2010).	-0.002 ± 0.015 ± 0.009
2002	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Rev. Lett. 88, 041602 (2002).	+0.071 ± 0.061 ± 0.012
.	.	COMBOS average	-0.0003 ± 0.0017

Year	Experiment	CP Asymmetry in the decay mode Ds+ to K0sπ+	[Γ(Ds+)-Γ(Ds-)]/[Γ(Ds+)+Γ(Ds-)]
2014	LHCb	R. Aaij et al. (LHCb Collab.), arXiv:1406.2624 (2014).	+0.0038 ± 0.0046 ± 0.0017
2013	BABAR	J.P. Lees et al. (BABAR Collab.), Phys. Rev. D 87, 052012 (2013).	+0.006 ± 0.020 ± 0.003
2010	BELLE	B.R. Ko et al. (BELLE Collab.), Phys. Rev. Lett. 104, 181602 (2010).	+0.0545 ± 0.0250 ± 0.0033
2010	CLEO-c	H. Mendez et al. (CLEO Collab.), Phys. Rev. D 81, 052013 (2010).	+0.163 ± 0.073 ± 0.003
.	.	COMBOS average	+0.0063 ± 0.0047

LHCb results represent the most precise to date

Experimental status





[PRL 100 (2008) 061803](#)

[PRL 109 (2012) 111801](#)

[arXiv:1212.1975](#)

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

New world averages:

$$A_{CP}(KK) = (-0.15 \pm 0.11)\%, \qquad A_{CP}(\pi\pi) = (+0.10 \pm 0.12)\%,$$

$$\Delta A_{CP} = (-0.25 \pm 0.11)\%.$$

LHCb results constitute the most precise measurement from a single experiment to date

Conclusions

- LHCb with 3 fb^{-1} measured
  - no significant CP violation in the singly Cabibbo-suppresed $D^0 \to KK$ and $D^0 \to \pi\pi$ decays
  - no evidence of CP violation in the cabibbo suppresed $D^{\pm} \to K^0_s K^{\pm}$ and $D^{\pm}_s \to K^0_s \pi^{\pm}$ decays
  - The results shown today represent the most precise measurements from a single experiment of these quantities to date
- Expected soon an update with 3 fb^{-1} on ΔA_{CP} from an prompt $D^0 \to KK$ and $D^0 \to \pi\pi$ decays
  - with the same precision of the current world average

Backup

From $A_{raw}(K\pi)$ we can measure muon detection and B production asymmetry if we measure

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

Providing a measurement of $A_D(K^0)$, $A_D(K\pi)$ is measured from

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

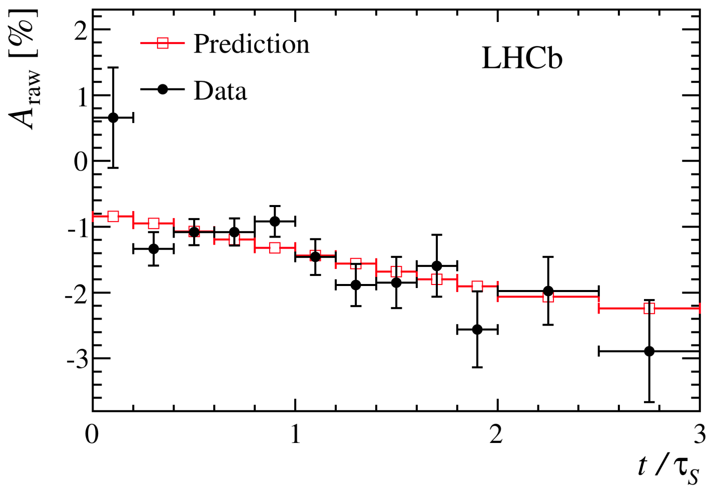
$$A_{\rm raw}(K^-\pi^+\pi^+) = A_P(D^+) + \boxed{A_D(K^-\pi^+)} + A_D(\pi^+)$$

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

K^0 detection asymmetry from $D^+ \to K^0_s\pi^+$

Asymmetry in the detection of K^0 arises from the combination of CP violation and mixing in the neutral kaon system and the difference interaction rates of K^0 and $\bar{K}^0$ in the detector material

$D^+ \to K^0_s\pi^+$ raw asymmetry as function of K^0_s decay time



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

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D^+ production asymmetry and pion detection asymmetry are independent of the K^0_s decay time.
Dependence observed comes from $K^0/\bar{K}^0$ detection asymmetry