Measurements of direct CPV in two-body charm decays at LHCb

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on behalf of LHCb Collaboration

INFN and University of Bologna

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Charm and New Physics

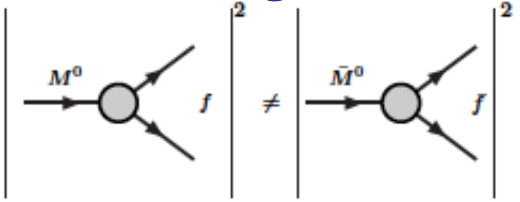
- In indirect searches for new physics, charm furnishes a unique probe of flavour physics in the up-quark sector
  - complementary to strange and bottom physics
- Indirect searches for NP with charm gives complementary constraints to direct searches at the Energy Frontier
- Precision measurements in charm are necessary as inputs for B physics ($B \to DK$, $B \to D\pi$) and the measurement of the CKM angle γ
- Many "null-tests" available, one of them is the search for CP violation, which is expected to be small in SM (but not zero)
  - ... but SM predictions are difficult to be calculated

The direct CPV

Grossman, Kagan, Nir Phys.Rev.D75
Guadagnoli@FPLH

CPV in decay occurs when the absolute value of the decay rate $M \to f$ differs from the decay rate involving the CP-conjugate states

$$|A(M^0 \to f)| \neq \left|A\left(\bar{M}^0 \to \bar{f}\right)\right|$$



CPV can happens if the final state can be reached at least with two different path

The amplitude of a CP eingenstate, i.e. $D^0 \to f$ with $f = K^-K^+$ or $f = \pi^-\pi^+$, it can be written with a leading term and a sub-leading as follows

Sub-leading amplitude: with relative strong (δ_f) and weak (ϕ_f) phases

$$A_f = \boxed{A_f^T}\left(1 + \boxed{r_f e^{i(\delta_f + \phi_f)}}\right)$$

Leading amplitude: its phase is taken to be zero

The direct CPV

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CP violation in the decay can be observed if the asymmetry

$$A_{CP}^{dir}(D^0 \to f) = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

is different from zero

In the limit where $r_f \ll 1$ (which is a good approximation)

$$A_{CP}^{dir}(D^0 \to f) = -2 r_f \sin\delta_f \sin\phi_f$$

Necessary condition to observe direct CP violation is that r_f, δ_f and ϕ_f are all different from zero

The direct CPV

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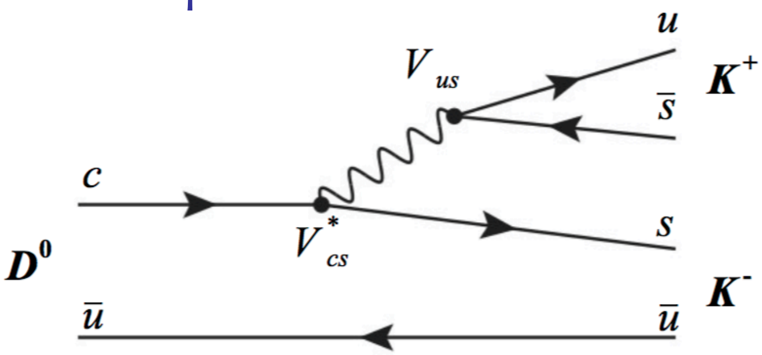
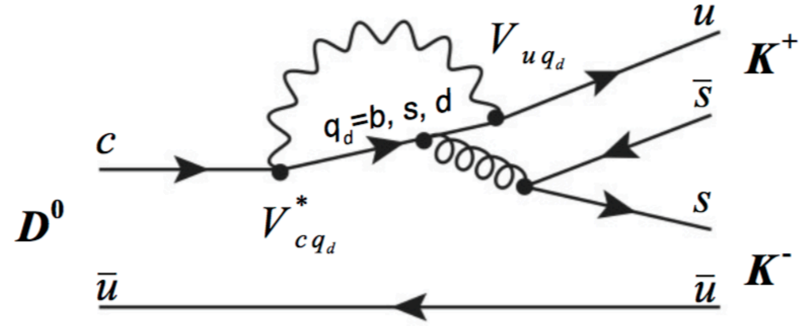
Singly Cabibbo Suppressed (SCS) decay, e.g. $D^0 \to K^- K^+$

Tree amplitude



Penguin amplitude



$$a^T_{KK} \sim \underbrace{V^*_{cs} V_{us}}_{1 \cdot \lambda} T_{KK}$$

$$a^P_{KK} \sim \underbrace{V^*_{cb} V_{ub}}_{\lambda^2 \cdot \lambda^3} P^b_{KK} + \underbrace{V^*_{cs} V_{us}}_{1 \cdot \lambda} P^s_{KK} + \underbrace{V^*_{cd} V_{ud}}_{\lambda \cdot 1} P^d_{KK}$$

Using unitarity on the last term of the penguin amplitude, it follows:

$$A_{KK} = a^T_{KK} + a^P_{KK} = \underbrace{V^*_{cs} V_{us} \left(T_{KK} + P^s_{KK} - P^d_{KK}\right)}_{A^T_{KK} \mathcal{O}(\lambda)} + \underbrace{V^*_{cb} V_{ub} \left(P^b_{KK} - P^d_{KK}\right)}_{A^P_{KK} \mathcal{O}(\lambda^5)}$$

The direct CPV

Grossman, Kagan, Nir Phys.Rev.D75
Bucella F. et al. Phys.Lett. B302 (1993) 319-325
Petrov, A. J.Phys.Conf.Ser. 556 (2014)
Santorelli, P. See talk@CHARM2016
Giudice, Isidori, Paradisi JHEP 1204 (2012) 060

In the Standard Model direct CP violation is naively estimated to be

$$A_{CP}^{dir}(D^0 \to KK) \sim 10^{-3} - 10^{-4}$$

Non-perturbative QCD as well as New Physics effects can contribute to enhance CPV → but we already know that these effects can not be large

In the U-spin symmetric limit ($d \leftrightarrow s$), the same calculations holds for the $\pi\pi$ final state, with

$$A_{CP}^{dir}(D^0 \to KK) = -A_{CP}^{dir}(D^0 \to \pi\pi)$$

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Direct CP violation is not yet observed

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Charm and D⁰ production at LHC

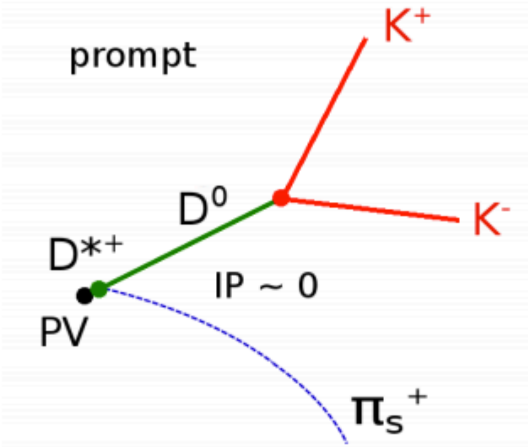
LHCb is designed for beauty physics, but it offers a great opportunity to perform charm physics as well

$$\sigma(pp \to c\bar{c}) = \begin{array}{lll} (1419 \pm 134)\mu b & @ \;\; 7\text{TeV} & \text{Nucl.Phys.B871(2013)1} \\ (2940 \pm 240)\mu b & @ \; 13\text{TeV} & \text{JHEP03(2016)159} \end{array}$$

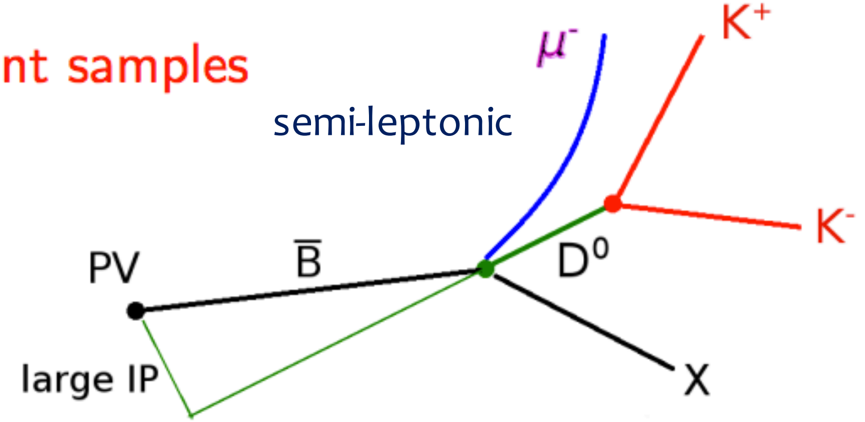
About 20 times more $b\bar{b}$

$p_T < 8$ GeV/c, $2.0 < y < 4.5$

Two mechanisms of D^0 production



Independent samples



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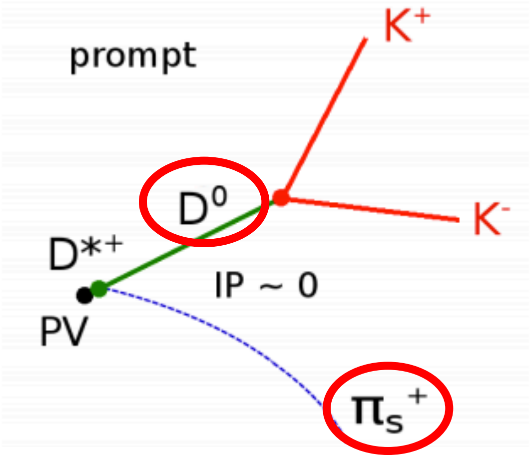
Experimentally we can tag D^0 flavour at production by means of the charge of the muon and the soft pion



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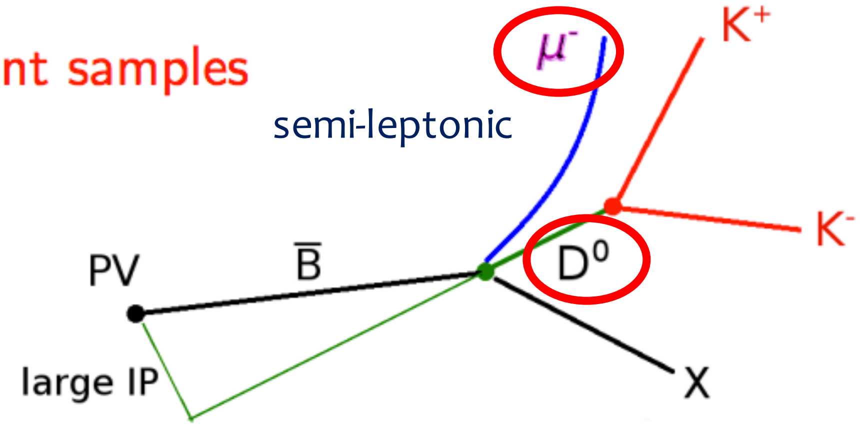

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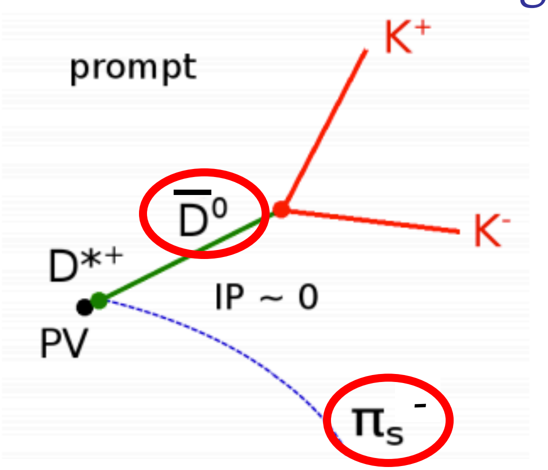

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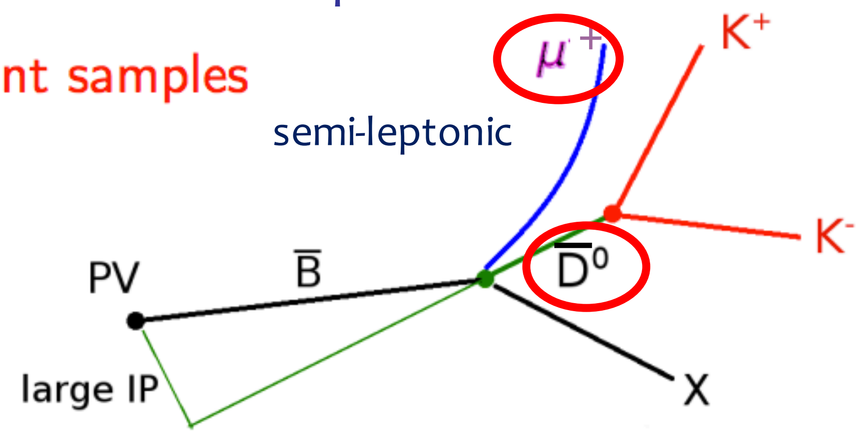


Charm physics at LHCb

- Unprecedented charm yields at LHC produced world best measurements:
  - Mixing and CPV in $D^0 \rightarrow K\pi$ [PRL 111 (2013) 251801, LHCb-PAPER-2016-033 submitted to PRD, Phys. Rev. Lett. 116 (2016)]
  - Direct CPV with ΔA_{CP} [JHEP 07 (2014) 041, LHCb-CONF-2013-003]
  - Indirect CPV in A_Γ [LHCb-CONF-2016-009, LHCb-CONF-2016-010, PRL 112 (2014) 041801]
  - CP violation searches in multibody decays [LHCb-CONF-2016-008, PLB 726 (2013) 623, PLB 728 (2014) 585, JHEP 10 (2014) 005 …]
- Still statistically dominated in core measurements

TODAY:

- Measurement of direct CP asymmetry in $D^0 \rightarrow K^- K^+$[LHCb-PAPER-2016-033, submitted to PLB]
- Measurement of the difference of time-integrated CP asymmetries in $D^0 \rightarrow K^- K^+$and $D^0 \rightarrow \pi^- \pi^+$ [arXiv:1602.03160, Phys. Rev. Lett. 116 (2016) 191601]

Measurement of the difference of time-integrated CP asymmetry in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decay

LHCb-PAPER-2015-055
Phys. Rev. Lett. 116 (2016) 191601

Time-integrated CP asymmetry

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 slow pion from, $D^{*\pm}\to D^0\pi^\pm$

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

$$A_{raw}(f)=\frac{N(D^{*+}\to D^0\pi^+)-N(D^{*-}\to \overline{D}^0\pi^-)}{N(D^{*+}\to D^0\pi^+)+N(D^{*-}\to \overline{D}^0\pi^-)}$$

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

Production and detection asymmetries

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

$$A_{\mathrm{raw}}(f) = \boxed{A_{CP}(f)} + A_D\cancel{(f)} + \boxed{A_D(\pi_s^+)} + \boxed{A_P(D^{*+})}$$

$$f = \bar{f}$$

CP asymmetry

Any charge-dependent asymmetry in slow pion reconstruction

$D^{*\pm}$ production asymmetry

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

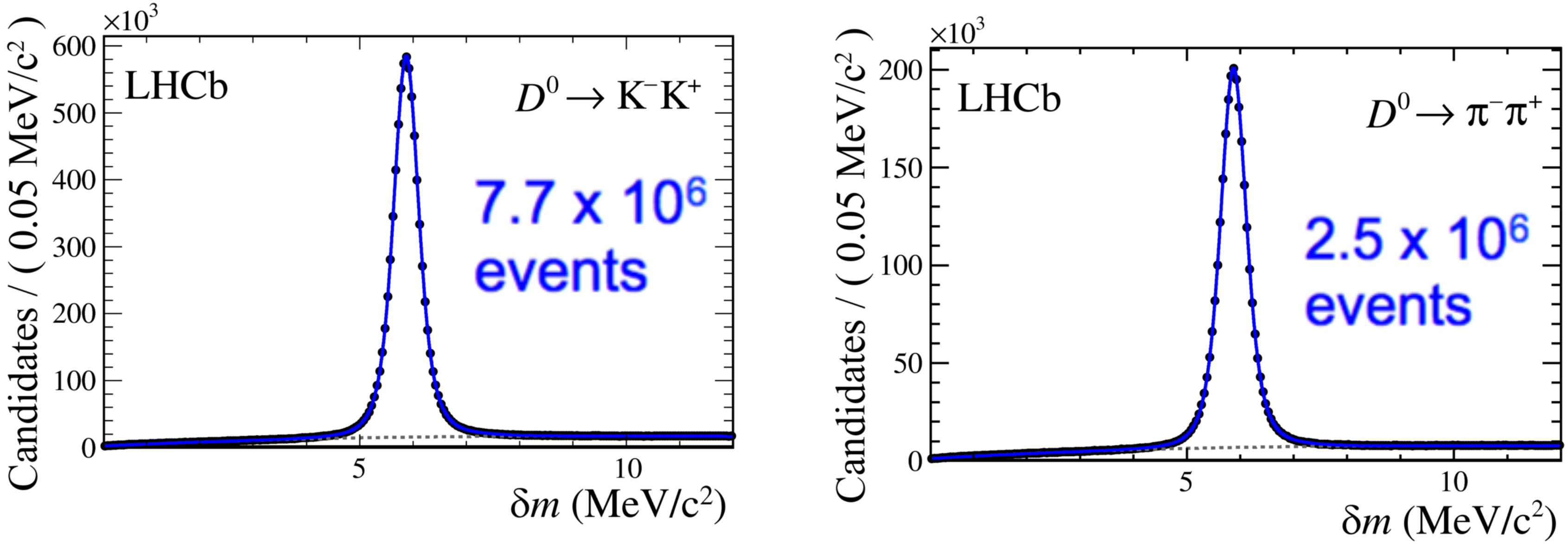
$$\boxed{\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)}$$

- the D^{*+} production and the slow pion detection asymmetries will cancel

Signal yields

LHCb-PAPER-2015-055, PRL 116 (2016) 191601

RUN-1: L = 3/fb



$$\delta m \equiv m(h^+h^-\pi_s^+) - m(h^+h^-) - m(\pi^+)$$

Signal yields and A_{raw} are obtained from minimum χ^2 fits to the binned δ_m distributions of the $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ samples in the D^0 signal regions

Results

LHCb-PAPER-2015-055, PRL 116 (2016) 191601

Source	uncertainty [%]
Fit Model	0.016
Multiple candidates	0.015
Peaking background	0.011
Reweighting	0.004
Fiducial cut	0.017
Secondaries	0.004
Total	0.030

Systematic uncertainties well below statistical error

$$\Delta A_{CP} = (-0.10 \pm 0.08\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst}))\,\%$$

This is the most precise measurement of a time-integrated CP asymmetry in the charm sector from a single experiment.

In agreement with the LHCb muon-tagged measurement: Run-1 3/fb

$$\Delta A_{CP} = 0.14 \pm 0.16^{\mathrm{stat}} \pm 0.08^{\mathrm{syst}}\ \%$$

LHCb-PAPER-2014-069 JHEP 04 (2015) 043

Results

LHCb-PAPER-2015-055, PRL 116 (2016) 191601

The observable ΔA_{CP} is mostly sensitive to direct CP asymmetry, Δa^{dir}_{CP}, but with a small contribution also to indirect CP asymmetry, a^{ind}_{CP}

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$
$$\approx \Delta a^{\rm dir}_{CP}\left(1+\frac{\overline{\langle t\rangle}}{\tau}y_{CP}\right)+\frac{\Delta\langle t\rangle}{\tau}a^{\rm ind}_{CP}$$

~2 x 10^{-4}

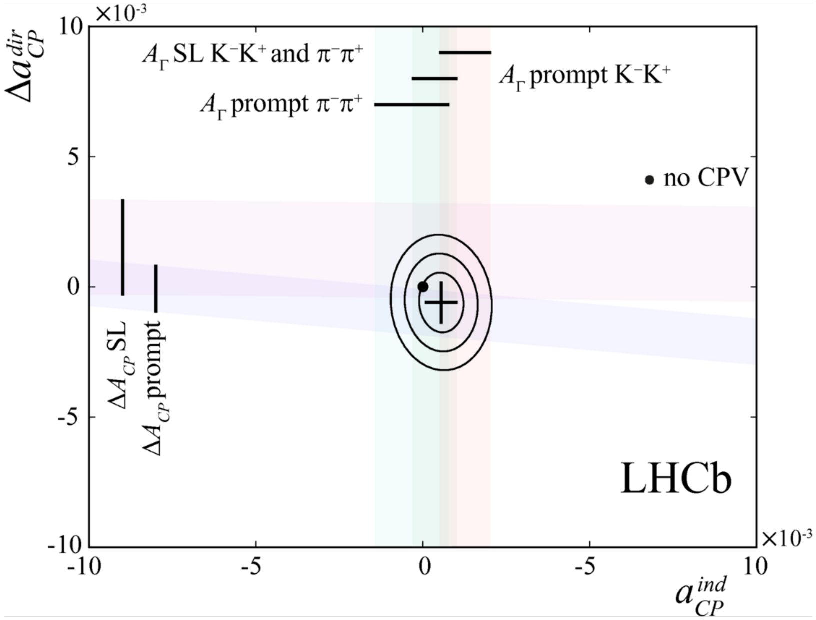
~0.12

Combination with LHCb measurements

$$\Delta a^{dir}_{CP}\,(-0.061 \pm 0.076)\%$$

$$a^{ind}_{CP}\,(0.058 \pm 0.044)\%$$

The result is consistent with the hypothesis of CP symmetry with a p-value of 0.32



Measurement of CP asymmetry in $D^0 \to K^- K^+$ decay

LHCb-PAPER-2016-035
Submitted to PLB

The single asymmetry $A_{CP}(KK)$

In order to measure the single asymmetry it is necessary to know the pion detection asymmetry $A_D(\pi_s^+)$ and the D^{*+} production asymmetry $A_P(D^{*+})$

$$A_{raw}(KK) = A_{CP}(KK) + A_P(D^{*+}) + A_D(\pi_s^+)$$

The raw asymmetry for $D^{*+} \to D^0(K^-\pi^+)\pi^+$, $A_D(\pi_s^+)$ cancel

$$A^*_{raw}(K\pi) = A_{CP}(K\pi) + A_D(K\pi) + A_P(D^{*+}) + A_D(\pi_s^+)$$

In the difference between the two A_{raw}, $A_P(D^{*+})$ and $A_D(K\pi)$ cancel

$$A_{raw}(KK) - A^*_{raw}(K\pi) = A_{CP}(KK) - A_D(K\pi)$$

It is still necessary to measure $A_D(K\pi)$

$A_D(K\pi)$ measurement

It is measured using the $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K_S^0\pi^+$ decay

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

$$A_{raw}(K_S^0\pi) = A_D(K_S^0) + A_P(D^+) + A_D(\pi^+)$$

from the difference of the above asymmetries, $A_P(D^+)$ and $A_D(\pi^+)$ cancel out

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

$A_D(K_S^0)$ include CP violation, mixing and interaction with the material, all the effects are known and found to be small

$$A_D(K_S^0) = (0.054 \pm 0.014)\%$$

LHCb-PAPER-2014-069 JHEP 04 (2015) 043

The single asymmetry $A_{CP}(KK)$

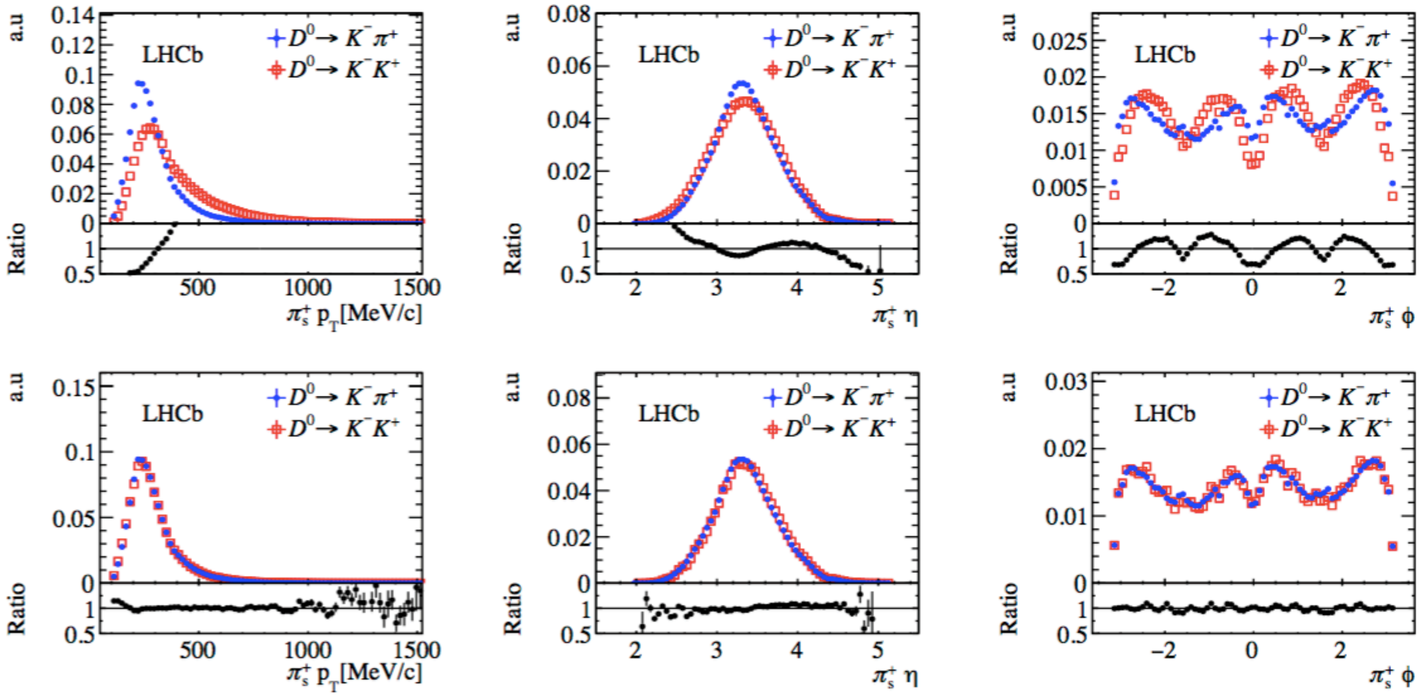
LHCb-PAPER-2016-035, Submited to PLB

All the raw asymmetry differences work if the kinematics of the various decays involved match

Kinematic reweighting is applied, for example between $D^0 \to K^- K^+$ and $D^0 \to K^- \pi^+$

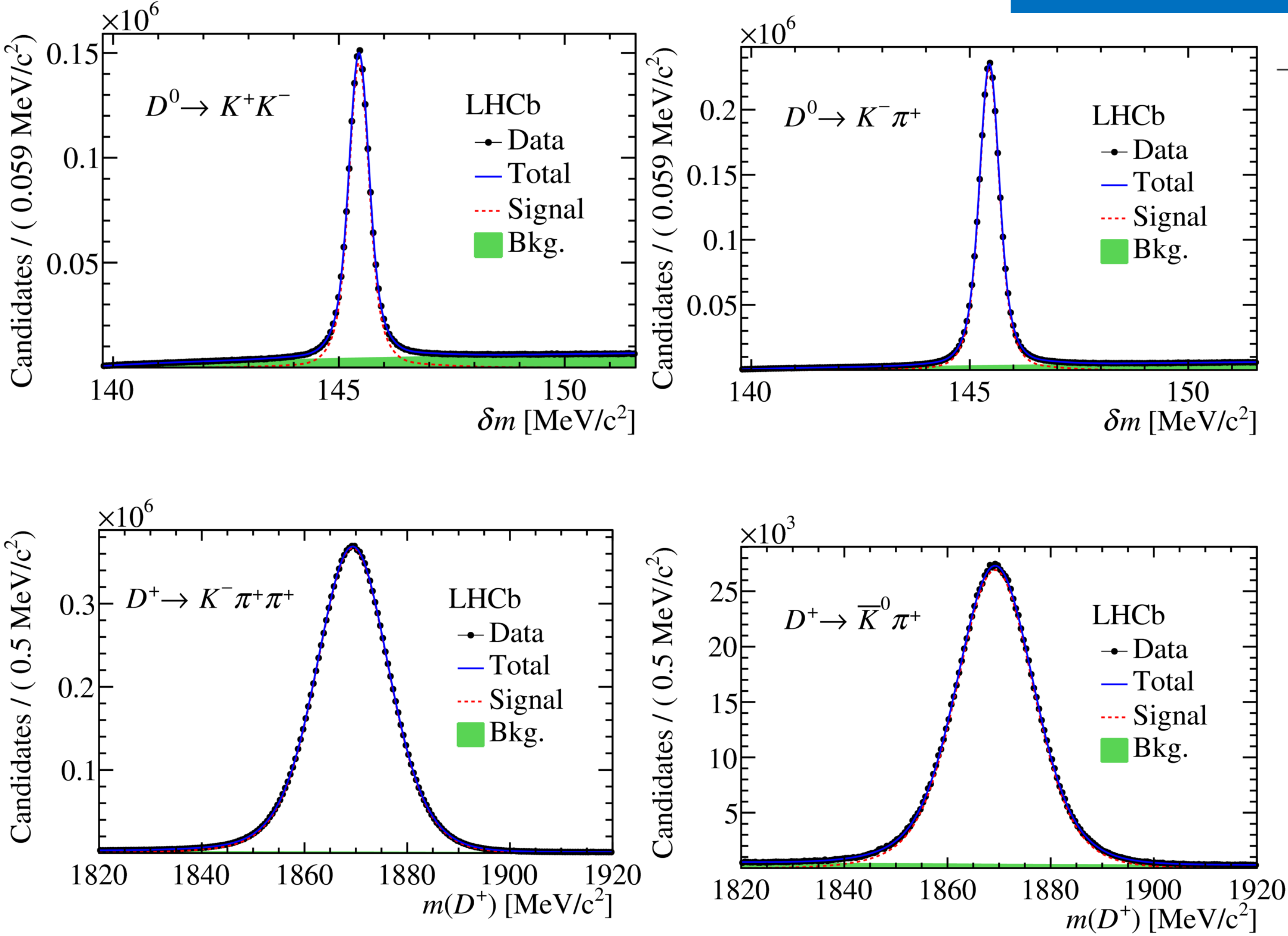
before

after



Signal and control channels yields

LHCb-PAPER-2016-035, Submited to PLB



Channel	After weighting
$D^0 \rightarrow K^-K^+$	1.63 M
$D^0 \rightarrow K^-\pi^+$	2.61 M
$D^+ \rightarrow K^-\pi^+\pi^+$	13.67 M
$D^+ \rightarrow \overline{K}^0\pi^+$	1.06 M

Extract yields with binned maximum Likelihood fit to

- δ_m in D^0 mass region for D^{*+} modes
- $m(K\pi\pi)$ for D^+

The single asymmetry $A_{CP}(KK)$

LHCb-PAPER-2016-035
Submited to PLB

$$A_{CP}(K^-K^+) = (0.14 \pm 0.15\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}))\%$$

Category	Systematic uncertainty[%]
Determination 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
Total	0.10

This result can be combined with the previous LHCb measurement based on a data sample of $D^0 \to K^-K^+$ decays from semi-leptonic B decays

$$A^{\mathrm{sl}}_{CP}(K^-K^+) = (-0.06 \pm 0.15\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}))\%$$

LHCb-PAPER-2013-054 Phys. Rev. Lett. 112 (2014)

$$A^{\mathrm{comb}}_{CP}(K^-K^+) = (0.04 \pm 0.12\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}))\%$$

Combination with previous LHCb measurements

LHCb-PAPER-2016-035, Submited to PLB

From the previous ΔA_{CP} mesurement, is possible to measure $A_{CP}(\pi\pi)$

$$A_{CP}(\pi^+\pi^-) = A_{CP}(K^+K^-) - \Delta A_{CP} = (0.24 \pm 0.15\,(\text{stat}) \pm 0.11\,(\text{syst}))\%$$

with a correlation between the two mesurements

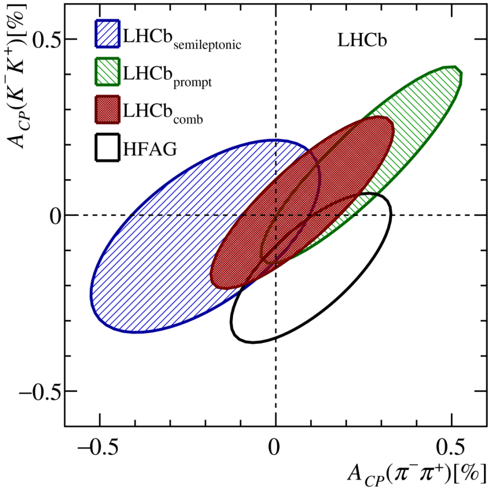
$$\rho\big(A_{CP}(KK), A_{CP}(\pi\pi)\big) = 0.24$$

This result can be combined with the previous LHCb measurement based on a data sample of $D^0 \to \pi^-\pi^+$ decays from semi-leptonic B decays

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

LHCb-PAPER-2013-054 Phys. Rev. Lett. 112 (2014)

$$A^{\text{comb}}_{CP}(\pi^-\pi^+) = (0.07 \pm 0.14\,(\text{stat}) \pm 0.11\,(\text{syst}))\%$$

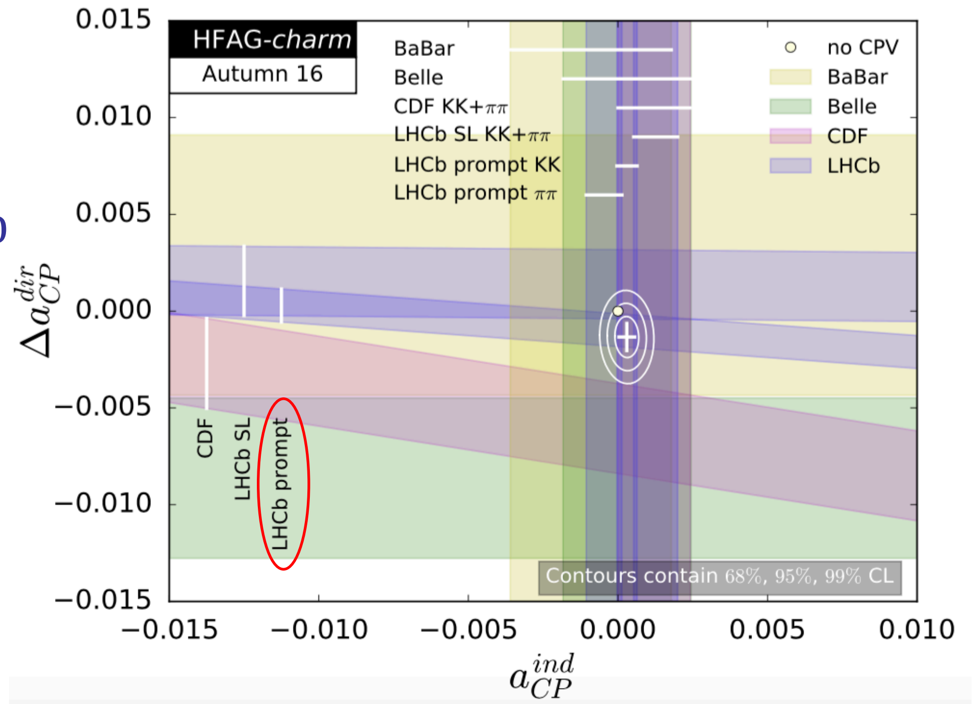


Current experimental status HFAG

$$\Delta a_{CP}^{dir} = (-0.134 \pm 0.070)\%$$

$$a_{CP}^{ind} = (\quad 0.030 \pm 0.026)\%$$

The result is consistent with the hypothesis of CP symmetry with a p-value of 0.09



Current experimental status HFAG

Year	Experiment	CP Asymmetry in the decay mode D0 to π+π-	[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]
2014	LHCb	R. Aaij et al. (LHCb Collab.), JHEP 07, 041 (2014).	-0.0020 ± 0.0019 ± 0.0010
2012	CDF	T. Aaltonen et al. (CDF Collab.), Phys. Rev. D 85, 012009 (2012).	+0.0022 ± 0.0024 ± 0.0011
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	-0.0024 ± 0.0052 ± 0.0022
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett.B 670, 190 (2008).	+0.0043 ± 0.0052 ± 0.0012
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.019 ± 0.032 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	+0.048 ± 0.039 ± 0.025
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.049 ± 0.078 ± 0.030
.	.	COMBOS average	-0.0000 ± 0.0015

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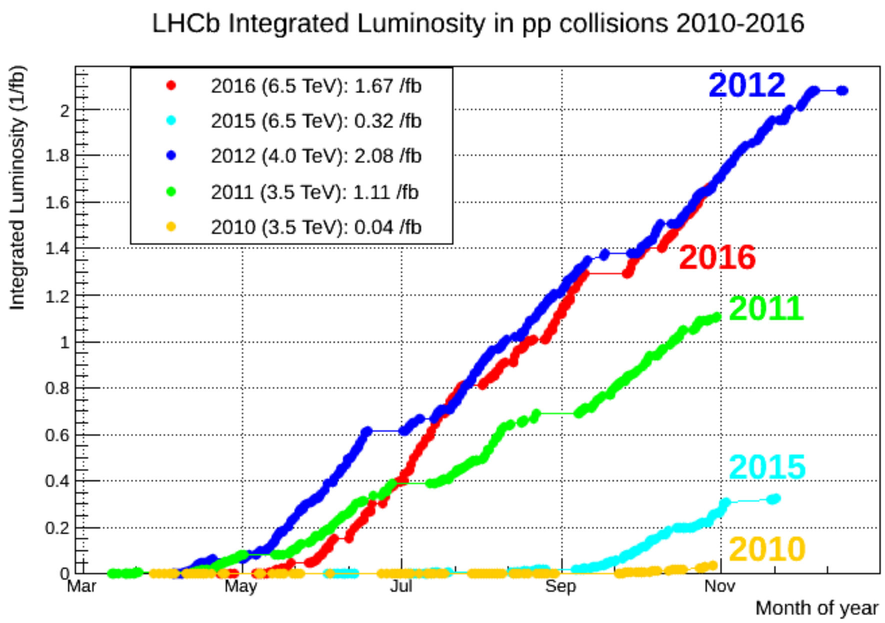
2012	CDF	T. Aaltonen et al. (CDF Collab.), Phys. Rev. D 85, 012009 (2012).	-0.0024 ± 0.0022 ± 0.0009
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	+0.0000 ± 0.0034 ± 0.0013
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett.B 670, 190 (2008).	-0.0043 ± 0.0030 ± 0.0011
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.000 ± 0.022 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	-0.001 ± 0.022 ± 0.015
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.010 ± 0.049 ± 0.012
.	.	COMBOS average	-0.0016 ± 0.0012

Great impact of LHCb on the world averages

Prospects



Run-2: collected about $2fb^{-1}$ @ $\sqrt{s} = 13$ TeV

Net statistics on $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ and control channels increased by a factor 2-3 with respect to the Run-1

Run-1 + Run-2 → $\sigma(\Delta A_{CP}) \sim 5\times10^{-4}$

$\sigma\big(A_{CP}(KK)\big)$ dominated by the precision on $A_D(K\pi)$ → expected to break the wall and go below 10^{-3} with Run-1 + Run-2

New results expected for next winter conferences

Conclusions

Currently LHCb has a leading role in the search for direct CP violation in the charm sector

Two-body charm decays are the more promising decays

Naively SM calculations foresee direct CP violation to be in the range $10^{-3} - 10^{-4}$

With RUN-1 data, LHCb excluded large values of direct CP violation, i.e. $> 10^{-2}$

With RUN-2 data collected so far, LHCb will reach the SM predictions, breaking the wall of 10^{-3} in precision also for a single A_{CP} measurement