Status of Direct CPV searches in Charm at LHCb

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11th International Workshop on the CKM Unitarity Triangle - **CKM 2021**

22-26 November 2021

Outline

- Introduction
- Charm *CP* violation observation in ΔA_{CP}
- Search for *CP* violation in $D_{(s)}^+ \to h^+\pi^0$ and $D_{(s)}^+ \to h^+\eta$ decays
- Search for *CP* violation in $D^0 \to K_S^0 K_S^0$ decays
- Search for *CP* violation in $D^0 \to h^+h^-\mu^+\mu^-$ decays

Introduction

Introduction to CPV in charm

- *Up*-type quark: unique probe of NP in the flavour sector, complementary to studies in *K* and *B* systems (precision CKM physics in the *B* sectors needs input from charm)
- New Physics may be hidden in the loops, but these are very suppressed in charm. *CPV* is expected to be small: $O(10^{-3} - 10^{-4})$
- Moreover, long-distance contributions are non-negligible and precise theoretical predictions are difficult
- CPV classification:

DIRECT CPV	CPV IN MIXING	CPV IN INTERFERENCE
Different decay amplitudes for D and $\bar{D}$	Different mixing rates $D^0 \to \bar{D}^0$ and $\bar{D}^0 \to D^0$	between mixing and decay

Only CPV possible for charged hadrons

TIME DEPENDENT CPV

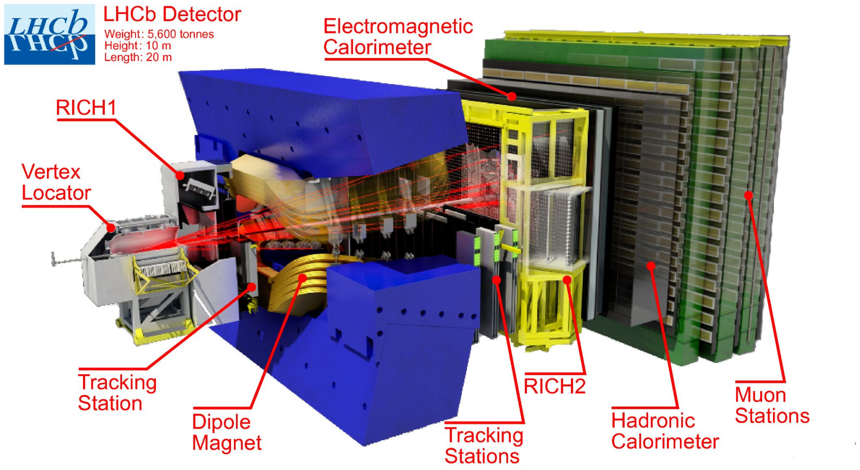
Charm production at LHCb

- LHCb detector: excellent particle identification, IP and momentum resolution (~13 μm on the transverse plane and Δp/p ~ 0.5% – 0.8%, respectively.)
- Huge charm production $\sigma(pp \to c\bar{c}X)_{p_T < 8\ \mathrm{GeV}/c,\, 2.0 < y < 4.5} = 2369 \pm 3 \pm 152 \pm 118\,\mu\mathrm{b}.$

$$\sigma(pp \to D^0 X) = 2072 \pm 2 \pm 124\,\mu\mathrm{b},$$
$$\sigma(pp \to D^+ X) = 834 \pm 2 \pm 78\,\mu\mathrm{b},$$
$$\sigma(pp \to D_s^+ X) = 353 \pm 9 \pm 76\,\mu\mathrm{b},$$
$$\sigma(pp \to D^{*+} X) = 784 \pm 4 \pm 87\,\mu\mathrm{b},$$

[JHEP 05 (2017) 074]

>10^{12} $c\bar{c}$ pairs per year!



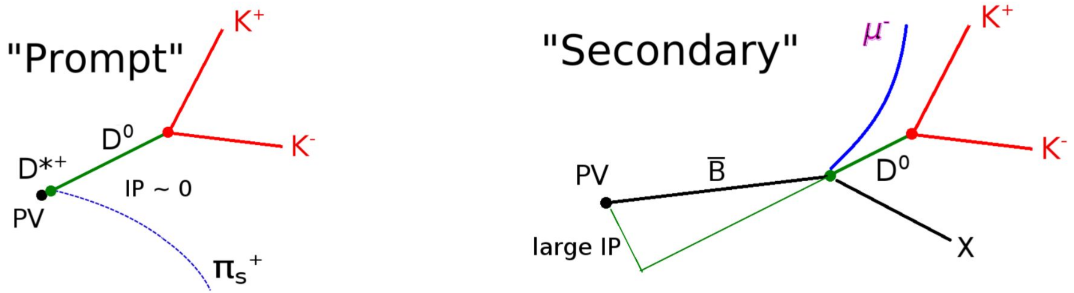
[JINST 3 S08005 (2008)]

Flavour tagging

- Whether the decaying D meson is produced as D^0 or $\bar{D}^0$ needs to be determined to perform mixing and CPV measurements
- There are two possible tagging methods

$D^{*\pm}$-tag

Semileptonic-tag



- Both samples used by LHCb, independent and complementary in lifetime coverage

Measuring the CP asymmetry

- We want to measure the time integrated asymmetries

$$A_{CP}(f) = \frac{\Gamma(M \to f) - \Gamma(\overline{M} \to \overline{f})}{\Gamma(M \to f) + \Gamma(\overline{M} \to \overline{f})} = \frac{1 - |\overline{A}_{\overline{f}}/A_f|^2}{1 + |\overline{A}_{\overline{f}}/A_f|^2}$$

In general for D^0 SCS decays $A_{CP}(f) = A_{CP}^{dir}(f) + A_{CP}^{mix} + A_{CP}^{int}$

In the studies presented today, time dependent CPV is negligible

- However the observable is the yield asymmetry, which must be corrected to extract the physical asymmetry

$$A_{raw} = \frac{N(D \to f) - N(\bar{D} \to \bar{f})}{N(D \to f) + N(\bar{D} \to \bar{f})} = A_{CP} + A_P + A_D$$

- A_P is the production asymmetry in pp collisions
- A_D is the detection asymmetry due to the detector
- A_P and A_D Are determined and corrected for using calibration samples

Observation of CPV in charm

[PRL 122 (2019) 211803]

Observation of CPV in charm with ΔA_{CP}

- Full Run1 + Run2 dataset , D* and semileptonic tag
- Observable is mainly sensitive to direct CPV

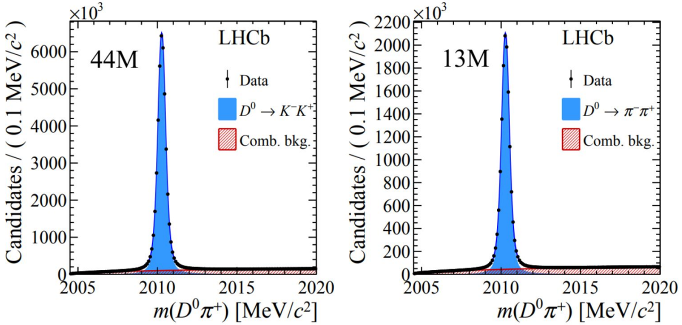
$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$

assuming universal a_{cp}^{ind}

$$\simeq \Delta a_{CP}^{dir} + \frac{\Delta\langle t\rangle}{\tau_{D^0}} a_{CP}^{ind} \qquad \Delta\langle t\rangle = \langle t\rangle_{KK} - \langle t\rangle_{\pi\pi}$$

- Experimentally robust as production and detection asymmetries cancel to first order
- Not clear is NP or not, additional measurements are needed!

D* tag sample



$\Delta a_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$

CP violation observed at 5.3σ!

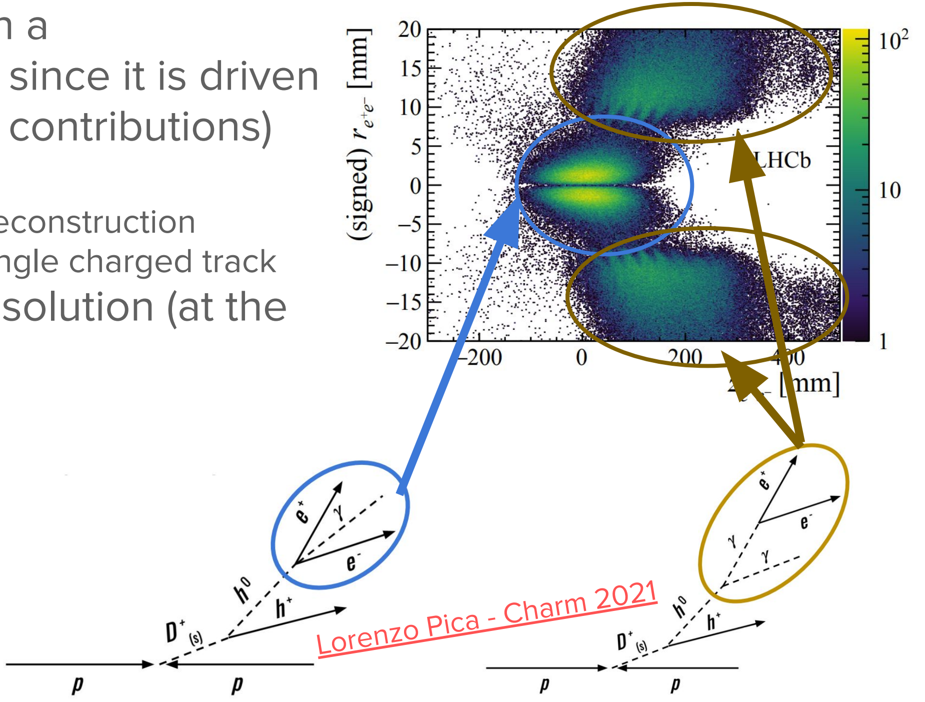
Search for CP violation in $D_{(s)}^{+} \rightarrow h^{+}\pi^{0}$ and $D_{(s)}^{+} \rightarrow h^{+}\eta$ decays

[JHEP 06 (2021) 019]

Overview

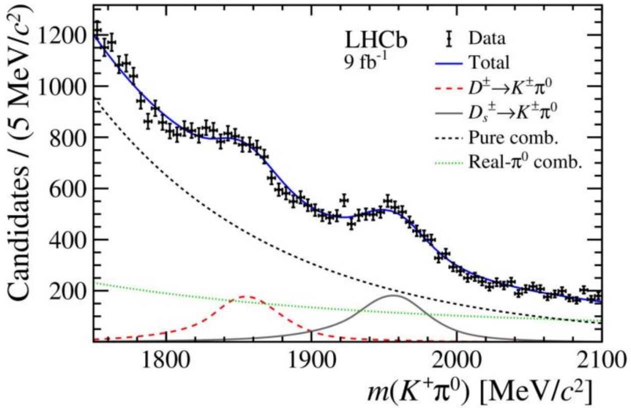
Decay	Branching fraction
$\pi^0 \to \gamma\gamma$	$98.8 \pm 0.03\%$
$\pi^0 \to e^+e^-\gamma$	$1.17 \pm 0.04\%$
$\eta \to \gamma\gamma$	$39.41 \pm 0.20\%$
$\eta \to e^+e^-\gamma$	$0.68 \pm 0.04\%$

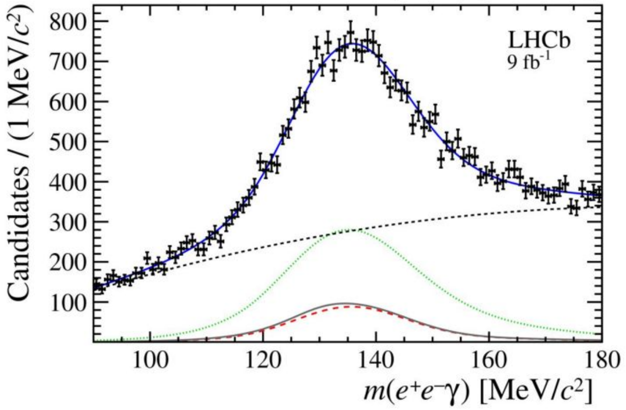
- Measurement of direct CP asymmetries
- $h^+ = \pi^+$ or K^+, these are in fact **8 decays** with a **Golden channel: $A_{CP}(D^+ \to \pi^+\pi^0) = 0$** in SM since it is driven by a single isospin amplitude (no penguin contributions)
- Challenging to reconstruct in LHCb:
  - Large combinatorial background from neutral reconstruction
  - Cannot reconstruct a displaced vertex with a single charged track
- Exploit $e^+e^-\gamma$ final state to recover mass resolution (at the price of a lower BF):
  - $h^0 \to \gamma(\to e^+e^-)\,\gamma$, with converted photon (86%)
  - $h^0 \to \gamma\, e^+e^-$ (14%)
- $D_{(s)}^+ \to h^+\pi^0$ Run 1 and Run 2 (9 fb-1)
- $D_{(s)}^+ \to h^+\eta$ Run 2 (6 fb-1)



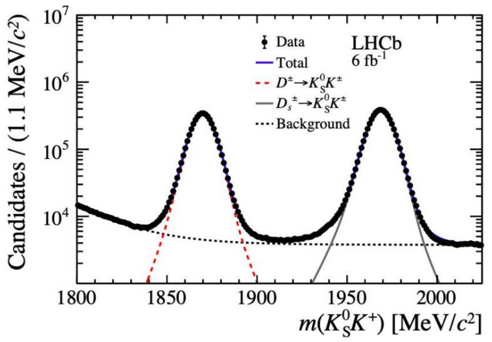
Signal selection and control samples

- Main background is combinatorial: rejected with track/vertex quality and displacement and transverse momentum
- Raw asymmetry and signal yields determined from 2D fits to $m(h^+h^0)$ and $m(\gamma e^+e^-)$





$D_{(s)}^+ \to K_s^0 h^+$ as control samples to subtract production and detection asymmetries, A_{CP} measured with high precision [PRL 122 (2019) 191803]



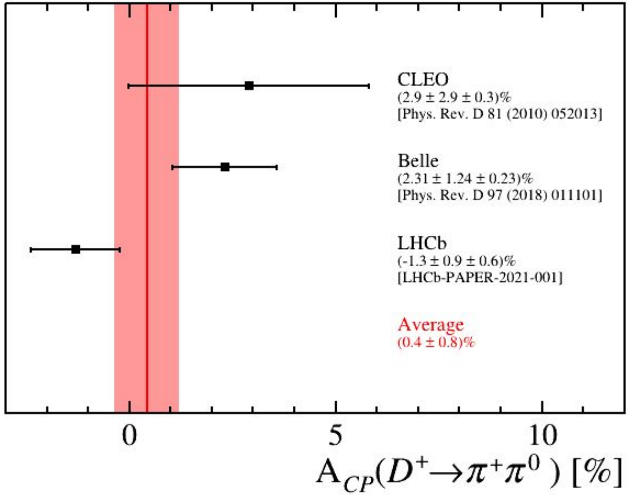
[JHEP 06 (2021) 019]

Results

$$\mathcal{A}_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%$$
$$\mathcal{A}_{CP}(D^+ \to K^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%$$
$$\mathcal{A}_{CP}(D^+ \to \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\%$$
$$\mathcal{A}_{CP}(D^+ \to K^+\eta) = (-6 \pm 10 \pm 4)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to \pi^+\eta) = (0.8 \pm 0.7 \pm 0.5)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\eta) = (0.9 \pm 3.7 \pm 1.1)\%$$

Main systematics:

- Fit model
- Control mode for $D_s^+ \to \pi^+\eta$ ($D_s^+ \to K_s^0 h^+$ has the lowest stat)



First five results are world best, the rest are slightly worse w.r.t. very recent Belle publication [PRD 103, 112005 (2021)]

Update for $D_{(s)}^+ \to \eta'\pi^+$ [PLB771 (2017) 21] is in the pipeline

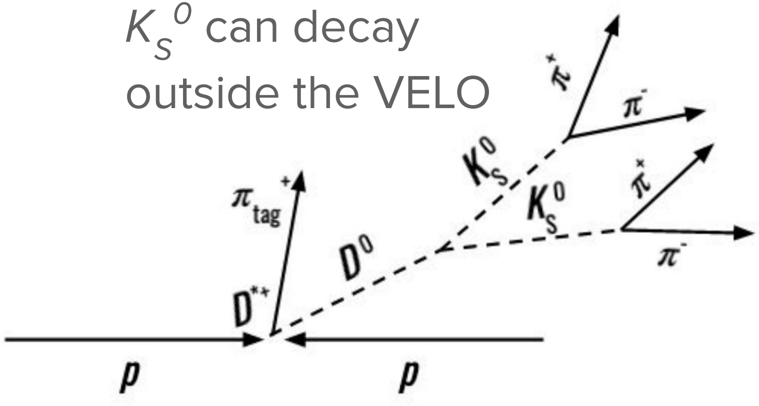
Search for CP asymmetry in $D^0 \rightarrow K_S^0 K_S^0$

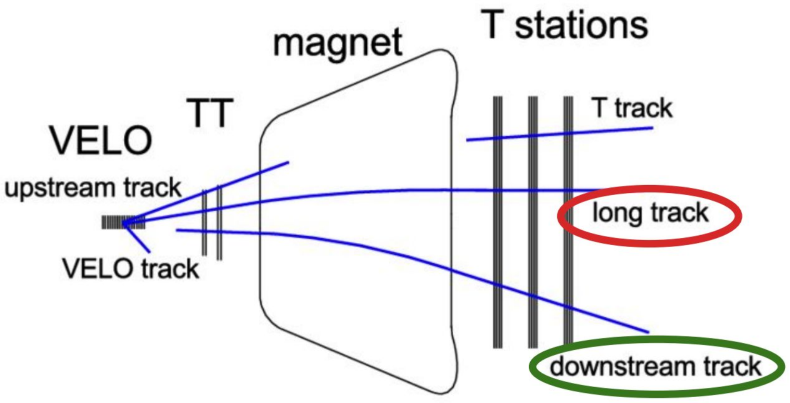
[PRD 99, 113001 (2019)]

Overview

- **A_{CP} in $D^0 \to K_S^0 K_S^0$ is SM is predicted to sizeable** [PRD 92, 054036 (2015)], [PRD 86, 036012 (2012)], [PRD 100, 093002 (2019)], [PRD 99, 113001 (2019)]
- Challenging at LHCb, due to the long K_S^0 lifetime
- **Three samples are analysed separately**:
  - **LL** → both K_S^0 are reconstructed with **long tracks**
  - **LD** → one K_S^0 is reconstructed with **long** and the other with **downstream** tracks
  - **DD** → both K_S^0 are reconstructed with **downstream** tracks
- This analysis exploits the full run 2 sample (6 fb^{-1})

K_S^0 can decay outside the VELO





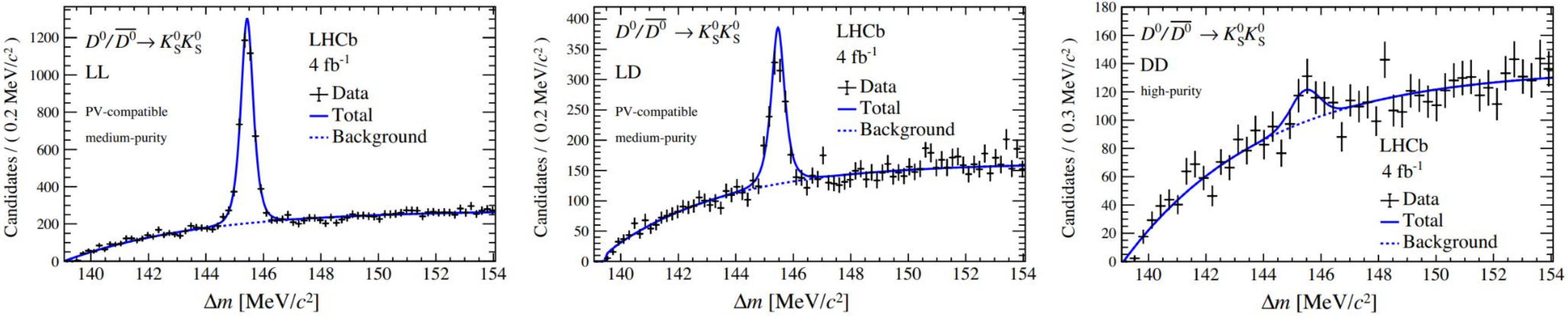
[PRD 99, 113001 (2019)]

Signal selection and control samples

- Main backgrounds are:
  - ***$D^0 \rightarrow K_S^0 \pi^+\pi^-$*:** reduced with a cut on the D^0 - K_S^0 vertices distance and then statistically separated with a simultaneous fit to the distributions of $\Delta m = m(D^*) - m(D^0)$ and $m(K_S^0)$
  - **Combinatorial:** reduced with a multivariate discriminant and accounted for in the fit
- $\boldsymbol{A_P}$ **and** $\boldsymbol{A_D}$ are corrected for using a $\boldsymbol{D^0 \rightarrow K^+K^-}$ calibration sample, $A_{CP}(KK)$ is taken from [PLB 767 (2017) 177-187]. Selections equalized between signal and calibration sample
- Separate measurements are performed by splitting in:
  - LL, LD and DD categories:
  - 2015-2016, 2017-2018 (different trigger selections)
  - purity level (determined using a kNN classifier)
  - compatibility for D * to come from PV

[PRD 99, 113001 (2019)]

Results



Competitive with Belle, aim to improve significantly in Run3 with better KS reconstruction

Combining all categories:

$A_{CP}(D^0 \to K_S^0 K_S^0) = $ (**-3.1** ± 1.2 (stat.) ± 0.4 (syst.) ± 0.2 ($A_{CP}(D^0 \to KK)$))%

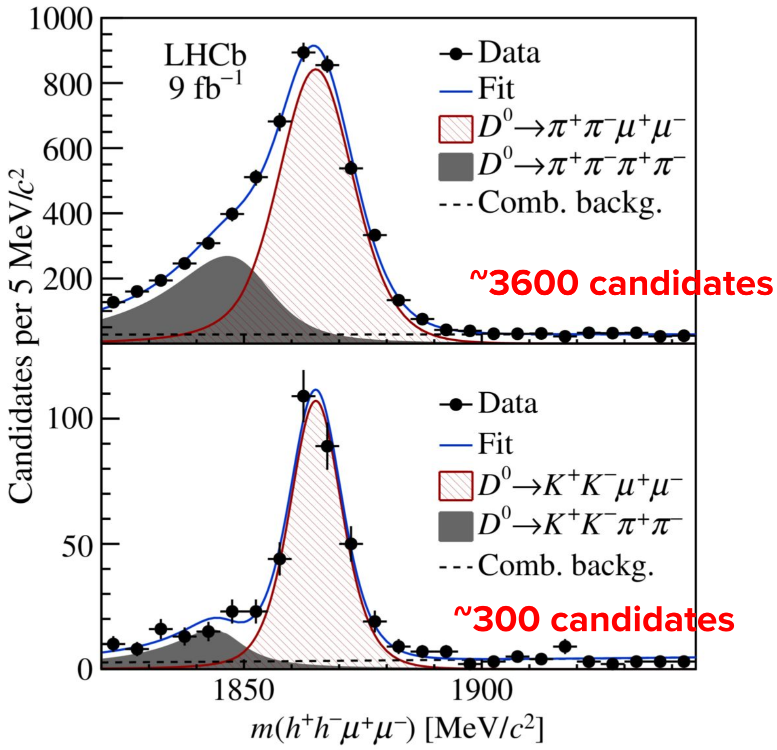
Most precise to date, compatible with no CPV at 2.4σ

Search for CP asymmetry in $D^0 \rightarrow h^+h^-\mu^+\mu^-$

[arXiv:2111.03327]

Overview

- Rarest observed charm meson decay [PRL 119, 181805 (2017)], dominated by vector meson intermediate resonances
- A_{CP} is predicted to be **up to $O(1\%)$ in NP models** [PRD101 (2020) 115006] ...
- First LHCb measurements (which includes angular observables) available at [PRL 121, 091801 (2018)]
- **Now:** update with the full Run1+Run2 dataset (more details and full angular analysis shown in D. Brundu's talk (WP3))
- $D^0 \to K^+K^-$ used as control sample

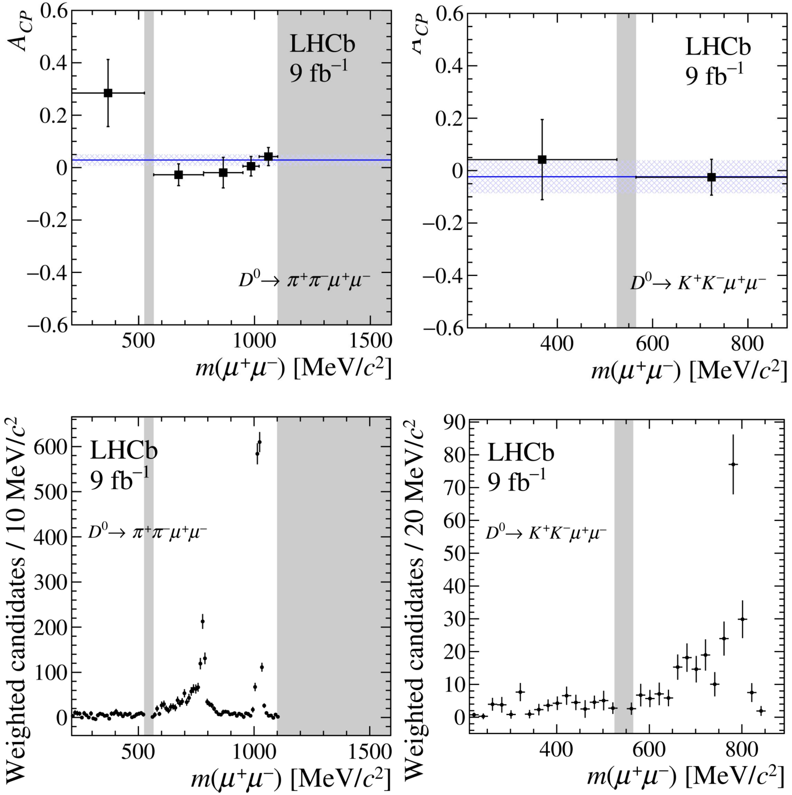


[arXiv:2111.03327]

Results

Measurement in the full phase space and in bins of $m(\mu\mu)$

No CPV observed (yet)



$m(\mu^+\mu^-)$ [MeV/c^2]	A_{CP} [%]
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	
< 525	$28 \pm 13 \pm 1$
525–565	–
565–780	$-2.7 \pm 4.1 \pm 0.4$
780–950	$-1.9 \pm 5.8 \pm 0.4$
950–1020	$0.5 \pm 3.7 \pm 0.4$
1020–1100	$4.2 \pm 3.4 \pm 0.4$
> 1100	–
Full range	$2.9 \pm 2.1 \pm 0.4$
$D^0 \to K^+K^-\mu^+\mu^-$	
< 525	$4 \pm 15 \pm 1$
525–565	–
> 565	$-2.5 \pm 6.8 \pm 0.6$
Full range	$-2.3 \pm 6.3 \pm 0.6$

Conclusion

- LHCb collected the largest charm sample to date
- After the observation of non-zero direct CPV, the hunt continues in other channels (even in rare decays!)
- Significant improvements may come in the upgrade, not only for the additional luminosity, but from higher efficiency thanks to our fully software trigger

STAY TUNED