CPV and mixing in charm decays: experimental status at LHCb

Giulia Tuci[1], on behalf of the LHCb collaboration
[1]Università di Pisa and INFN-Pisa

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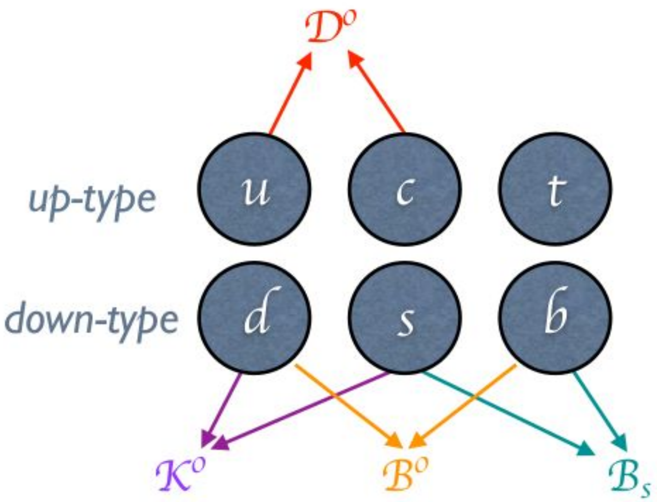
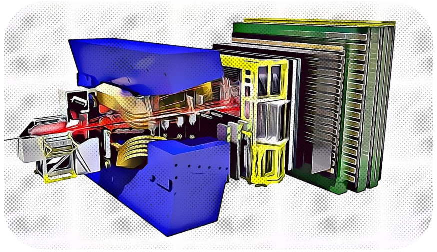
Introduction

- Charm transitions are a unique portal for obtaining a novel access to flavor dynamics
  - ➢ there might exist some New Physics coupling only to up-type quarks
  - ➢ expected CPV in charm $\lesssim 10^{-3} \rightarrow$ difficult to observe it experimentally

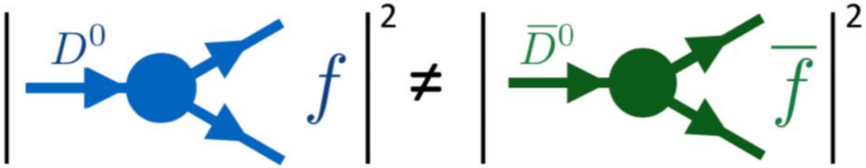


- **Finally CPV in charm has been observed!** PRL122. 211803
- Now it's the moment to start a systematic exploration of all the charm hadrons decay channels to do a quantitative study of CPV
- Large samples of charm hadrons decays needed → **LHCb**
  - ➢ collected ~ 1 billion of D^0 decays up to now



CPV in charm

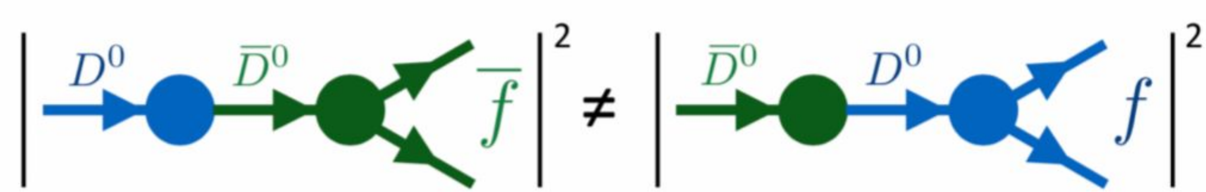
5.3 σ observation by LHCb



CPV in decay

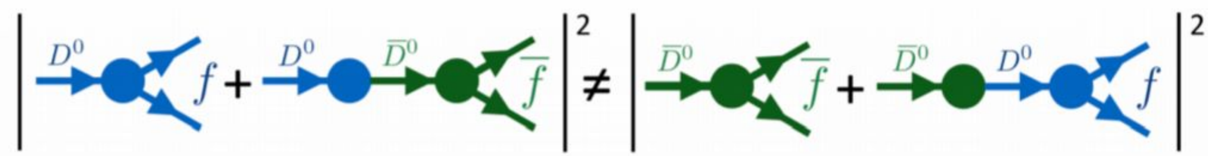
$|A_f| \neq |\overline{A}_{\overline{f}}|$

Still no evidence of mixing-induced CPV



CPV in mixing

$|q/p| \neq 1$



CPV in interference between decay and mixing

$$\arg\left(\frac{q\bar{A}_f}{pA_f}\right) \neq 0$$

CPV in mixing and interference expected to be very small: $O(10^{-5})$

→ still room for New-Physics

Time-integrated CPV (≈CPV in the decay)

Methodology

- We want to measure

$$\mathcal{A}_{CP}(f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

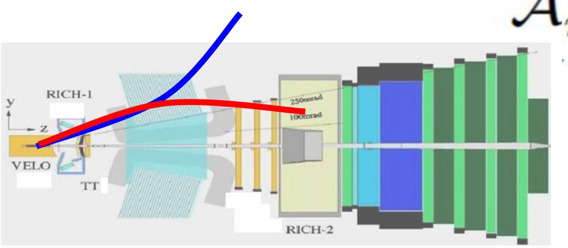
- Quantity measured in LHCb

$$\mathcal{A}_{raw} \equiv \frac{N_D - N_{\bar{D}}}{N_D + N_{\bar{D}}}$$

Production asymmetry: initial state pp is not CP symmetric

$$\mathcal{A}_{raw} \approx \mathcal{A}_{CP} + \mathcal{A}_{prod} + \mathcal{A}_{det}$$

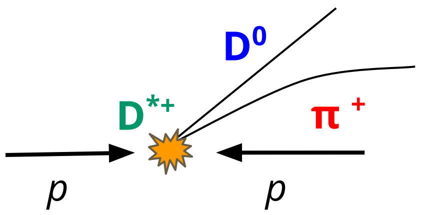
Asymmetric detector acceptance + material interaction different for particles/antiparticles



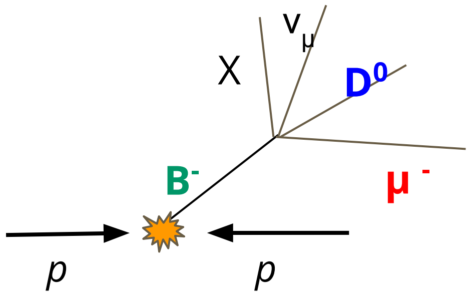
- A_{prod} and A_{det} are O(1%)

Ingredients

- ***D^0 flavour tagging:***
  - ➢ $D^{*+} \to D^0 \pi^+$ (largest yield)



  - ➢ $B^- \to D^0 \mu^- X$



- ***Taking into account for production and detection asymmetries***
  - ➢ Use of Cabibbo-Favoured calibration channels
  - ➢ $\to A_{prod}$ and A_{det} cancel out in the difference between raw asymmetries if the kinematic distributions are equal in the different decay channels

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

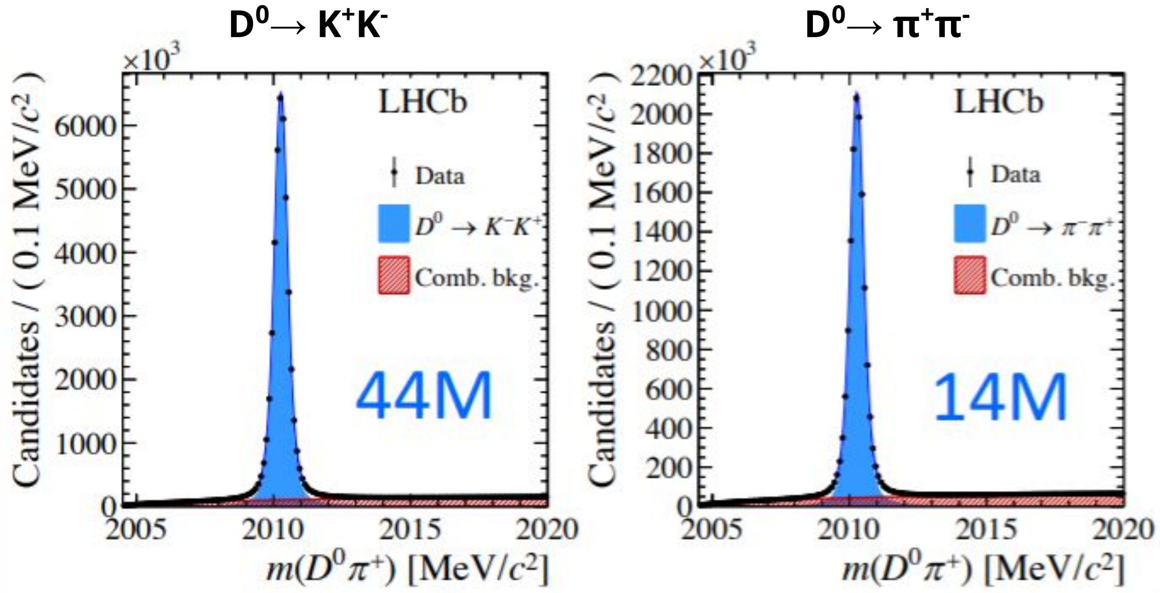
PRL122. 211803

- Analysed data collected in 2015-2018 and combined with Run1 measurement (total of $9 fb^{-1}$)

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

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

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



- **First observation of charm CPV at 5.3 σ!**
- Still statistically limited (syst. < 0.3 x stat. in D*-tagged sample)

- **How to interpret this result? SM or BSM?** JHEP 1907 (2019) 161, JHEP 07 (2019) 020, JHEP 1907 (2019) 020, PRD 99 (2019) 113001, 1903.10638, 1905.00907, PRD100(2019)093002

From ΔA_{CP} to $A_{CP}(K^+K^-)$

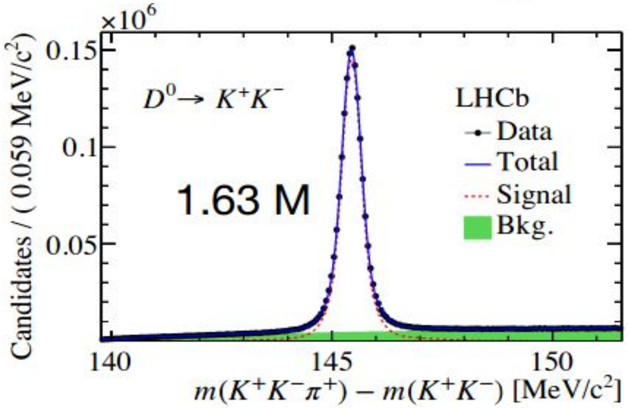
- Separate measurement of $A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$ is needed to understand the nature of CPV
- Assuming $SU(3)_F \rightarrow A_{CP}(K^+K^-) = -A_{CP}(\pi^+\pi^-) \rightarrow$ naively expected $|A_{CP}(K^+K^-)| \approx 8 \times 10^{-4}$
- Measurement performed with $3fb^{-1}$ of data collected in Run1, using $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^+ \rightarrow K_S^0\pi^+$ decays

$$A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\pi^+_{soft}) + A(D^+ \to K^-\pi^+\pi^+) - \left[A(D^+ \to K^0_S\,\pi^+) - A_D(\overline{K}^0)\right]$$

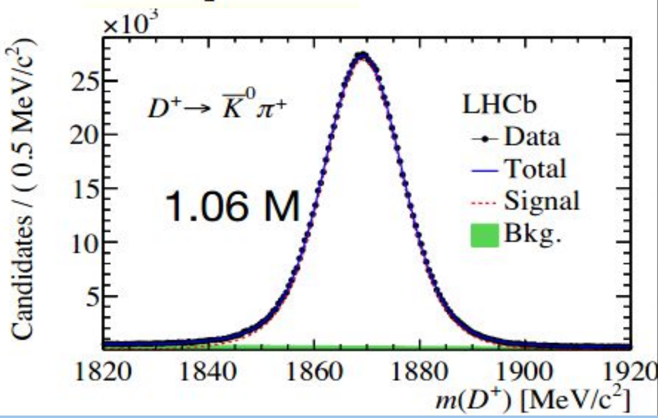
detection asymmetry of neutral kaons, which includes mixing and CPV effects

- Particles with same colour must have same kinematic distributions: loss of statistical power after the weighting

$$A_{CP}(D^0 \to K^-K^+) = \left[14 \pm 15\,(\text{stat}) \pm 10\,(\text{syst})\right] \cdot 10^{-4}$$



Run1 result
JHEP 07 (2014) 041



Prospects on $A_{CP}(K^+K^-)$ with Run 2 data

- Extrapolating from Run1, expected uncertainty on Run2: $\sigma_{stat} = 8.5 \times 10^{-4}$

CERN-PUB-LHCC-2018-027

- Improvements in offline analysis: using also D_s^+ decays as control channel

$$A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+_{soft}) + A(D^+ \to K^-\pi^+\pi^+) - \left[A(D^+ \to K^0_S\,\pi^+) - A_D(\overline{K}^0)\right]$$

+

$$A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+_{soft}) + A(D_s^+ \to \phi\pi^+) - \left[A(D_s^+ \to K^0_S\,K^+) - A_D(\overline{K}^0)\right]$$

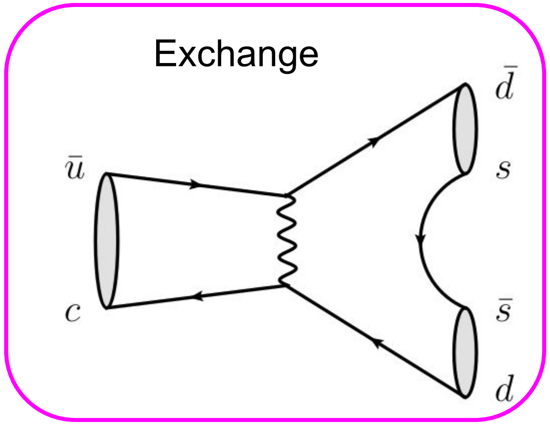
- Combining the two methods → expected **$\sigma_{stat} \sim 5 \times 10^{-4}$**
  - Ongoing work to reduce systematic uncertainty at the level of statistic one
- → We may be able to get an evidence for the single CP asymmetries $D^0 \to K^-K^+$ or $D^0 \to \pi^-\pi^+$ in Run 3 or sooner

A_{CP} in $D^0 \to K_S^0 K_S^0$

- In $D^0 \to K_S^0 K_S^0$ decay channel amplitudes are suppressed
  $\to A_{CP}$ could be enhanced at a level of ~1%   PRD 92 (2015) 054036
- Provides independent information on CPV: sensitive to a different mix of CP-violating amplitudes w.r.t. $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ PRD 85 (2012) 034036

<u>Current experimental status</u>

$\mathcal{A}^{CP}(K_S^0 K_S^0)$ (%)	Yield	Collaboration
$-23. \pm 19.$	65 ± 14	CLEO
$-2.9 \pm 5.2 \pm 2.2$	635 ± 74	LHCb Run 1
$-0.02 \pm 1.53 \pm 0.17$	5399 ± 87	Belle
$4.3 \pm 3.4 \pm 1.0$	1067 ± 41	LHCb 2015+2016

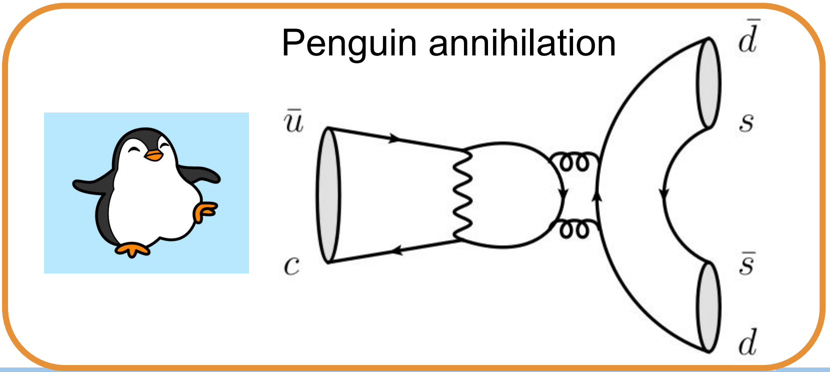


CLEO PRD 63 (2001) 071101

LHCb (Run1) JHEP 10 (2015) 055

Belle PRL 119 (2017) 171801

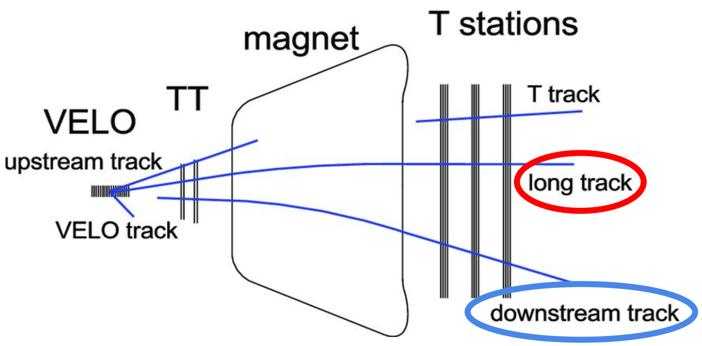
LHCb (2015+2016) JHEP 11 (2018) 048



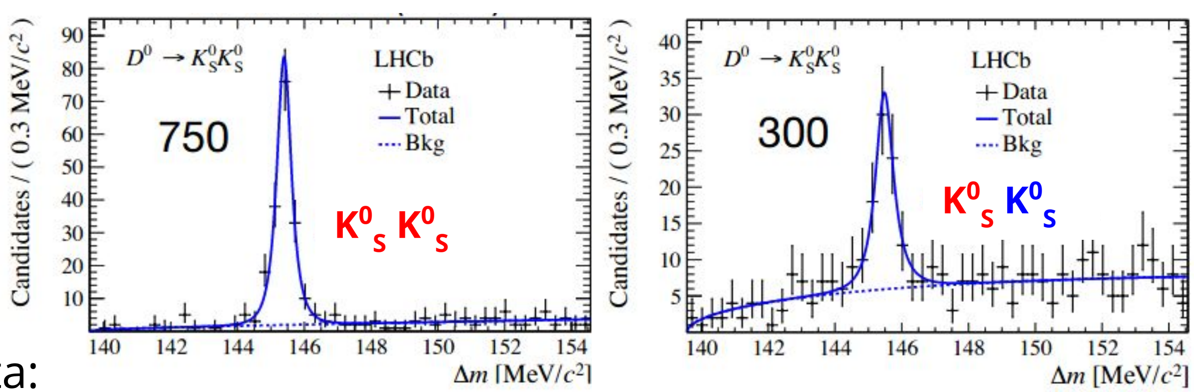
A_{CP} in $D^0 \rightarrow K_S^0 K_S^0$ with Run2 data

Full Run 2 measurement will be ready soon!

- Challenges at LHCb:
  - $\tau(K^0_S) = 0.9 \times 10^{-10}$ s , $\langle\beta\gamma\rangle \sim 80 \rightarrow \beta\gamma c\tau \sim 216$ cm
  - K_S^0 decays often outside vertex detector acceptance → difficult to select at trigger level



2015+2016 data ($2fb^{-1}$)



- Now analysing full Run2 data:
  - Improvements in both trigger and offline selections
  - → expected **$\sigma_{stat+syst}$ ~ 1.3 x 10^{-2}** (while extrapolating from published 2015+2016 measurement: $\sigma_{stat+syst} \sim 2.1 \times 10^{-2}$)
- Ongoing effort to introduce a specialised K_S^0 Hlt1-trigger in Run 3
  - Large room for improvement!

Mixing and time-dependent CPV

Status

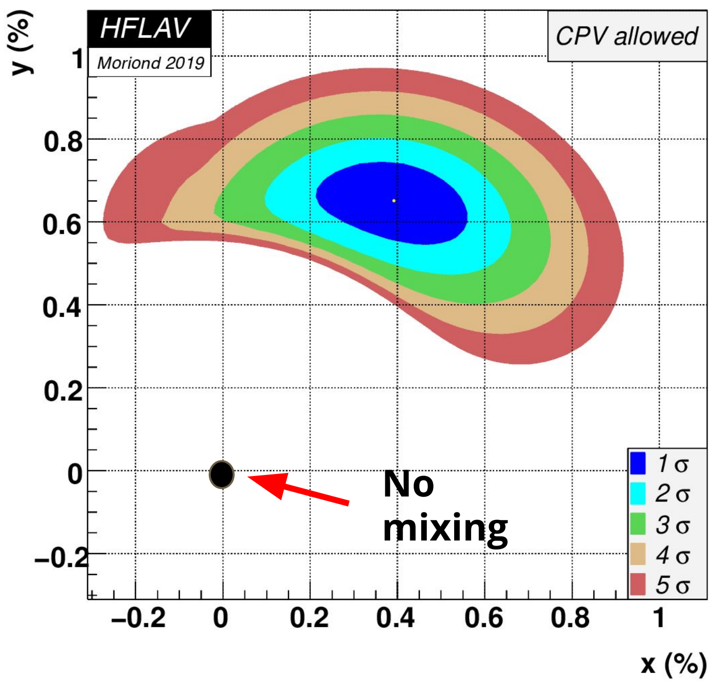
- Mass eigenstates linear combination of flavor eigenstates

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

$$x \equiv \Delta m/\Gamma$$
$$y \equiv \Delta\Gamma/2\Gamma$$

Experimental status

Mixing well established



Reminder:

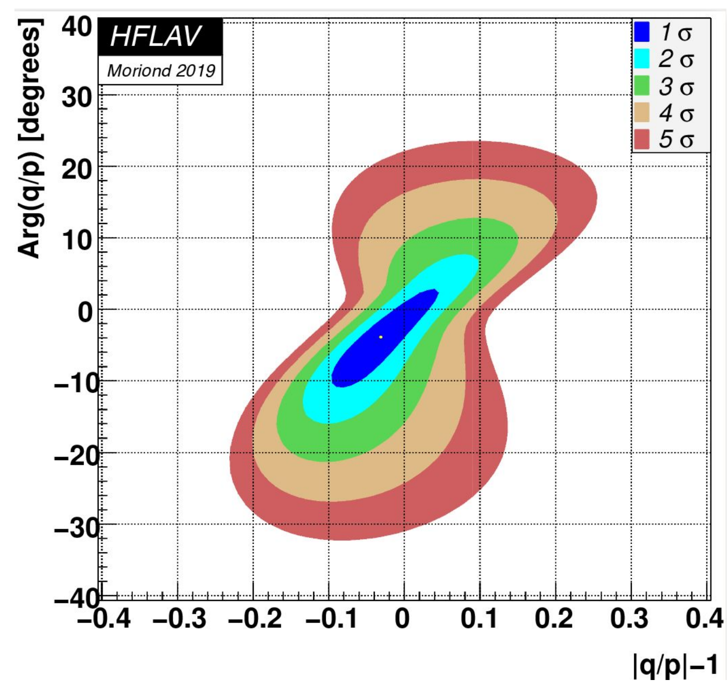
Mixing-induced CPV

→ |q/p|≠1

and

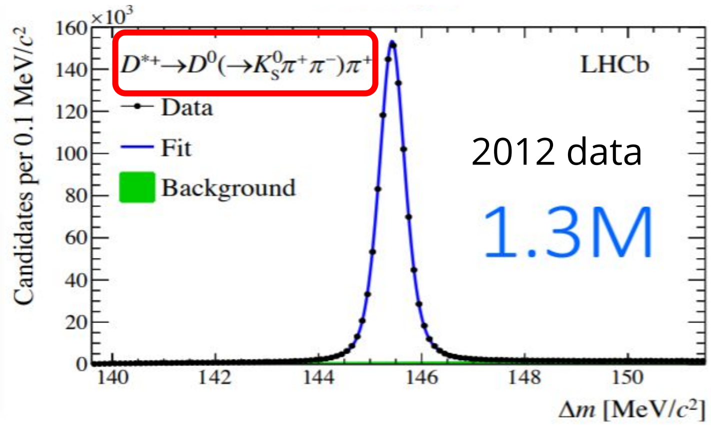
$$\arg\left(\frac{q\bar{A}_f}{pA_f}\right) \neq 0$$

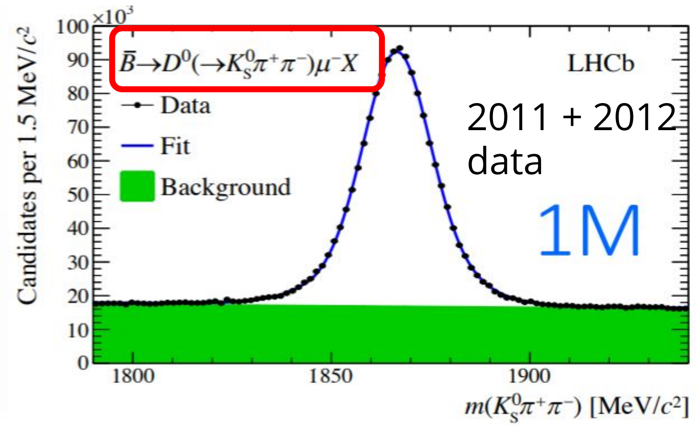
No evidence for CP violation in mixing or interference



Mixing parameters using $D^0 \to K_S^0 \pi^+ \pi^-$ decays

- Most recent measurement uses Run1 data PRL122.231802



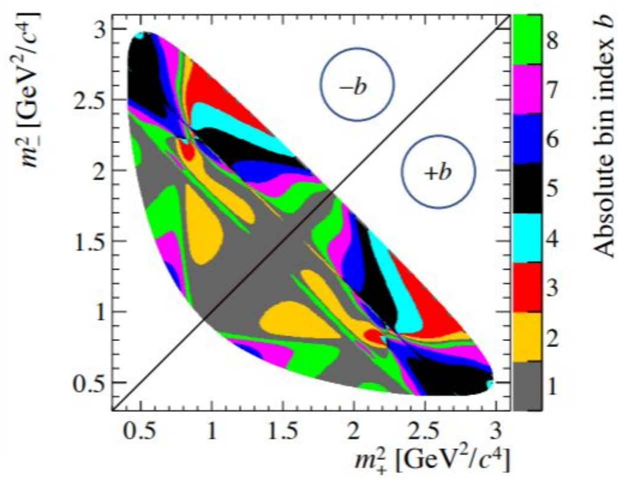


30x more data in 2015-2018!
Analysis ongoing

- Bin-flip method → model-independent and data-driven approach PRD99.012007
- Combining with the world average value

$$x = 3.9^{+1.1}_{-1.2} \times 10^{-3}$$

Evidence of a positive mass difference between the neutral charm meson eigenstates



$m_\pm^2 = m^2(K_S^0 \pi^\pm)$

Time-dependent CPV: measure of A_Γ

- Measured asymmetries in bins of decay-time

$$A_{CP}(f,t) \approx A_{CP}^{dec}(f) - A_\Gamma(f)\frac{t}{\tau_{D^0}}$$

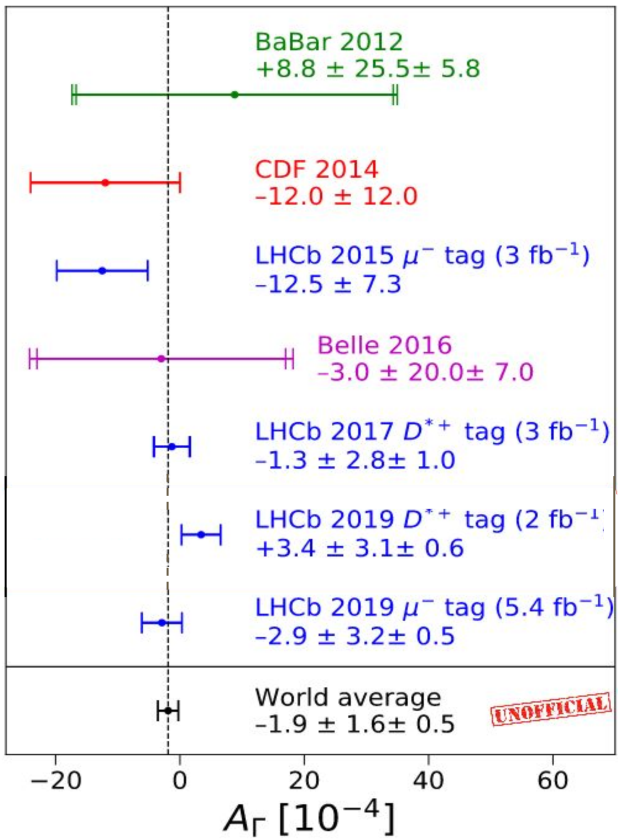
CPV in interference

$$A_\Gamma(f) \approx y\left(\left|\frac{q}{p}\right| - 1\right) - x\Phi_f - yA_{CP}^{dec}(f)$$

CPV in mixing

O(10^{-5})

- Ongoing analysis of full Run2 D*-tagged dataset
  - Expected to halve statistical uncertainty w.r.t Run1
  - $\rightarrow$ reach σ_{stat} ~ 1x 10^{-4} on world average
  - **$\sigma_{stat} \gtrsim 4 \times \sigma_{syst}$**



Full Run 2 measurement will be ready soon!

Much more analysis not covered today (some examples)

- Time-integrated CPV
  - Two-body decays: $D_{(s)}^+ \to K_S^0 h^+$ PRL122(2019)191803 , $D_{(s)}^+ \to \eta' \pi^+$ PLB771(2017)21
  - Multibody decays: $D^0 \to K_S^0 K^\pm \pi^\mp$ PRD 93 (2016) 052018,
    $D^0 \to K^+K^-\pi^+\pi^-$, $D^0 \to \pi^+\pi^-\pi^+\pi^-$ JHEP02(2019)126, $D^0 \to \pi^+\pi^-\pi^0$ PLB 740 (2015) 158,
    $D^+ \to K^+K^-\pi^+$ JHEP 06 (2013) 112 , $D^+ \to \pi^+\pi^-\pi^+$ PLB 728 (2014) 585,
    $\Xi_c^+ \to pK^-\pi^+$ arXiv:2006.03145 (2020), $\Lambda_c^+ \to ph^+h^-$ JHEP 03 (2018) 182
- Time-dependent CPV
  - Two-body decays: $y_{CP}(h^+h^-)$ PRL 122 (2019) 01180 ,
    WS $D^0 \to K^+\pi^-$ PRD 97 (2018) 031101
  - Multibody decays: $D^0 \to K^-\pi^+\pi^-\pi^+$ PRL 116 (2016) 241801

What else can we study?

Conclusion

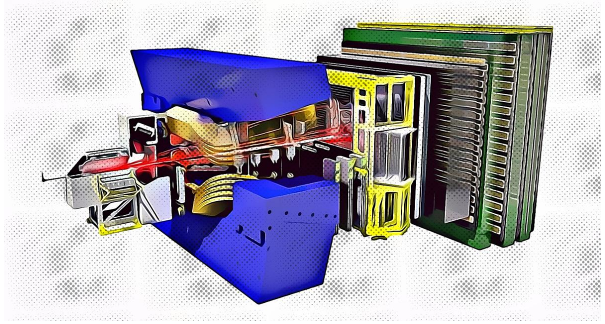
- **CPV observed for the first time by LHCb**
  - Now exploring different decay channels to better clarify the physics picture
- New results on Run2 data are coming!
  - careful study and tuning of analysis strategies to take full advantage of the available statistics
  - **Statistical uncertainty on full Run2 measurements could be better than √L improvement !**
- New data will arrive in 2021/2022 with an almost completely new detector and trigger system
  - Instantaneous luminosity will increase by a factor of 5 (2×10^{33} $cm^{-2}s^{-1}$)
- Current results limited by statistics
  - **We expect significant gains in precision, and sensitivity to CPV effects, in LHCb Run 3**
  - **Stay tuned!**

Backup slides

The main actors

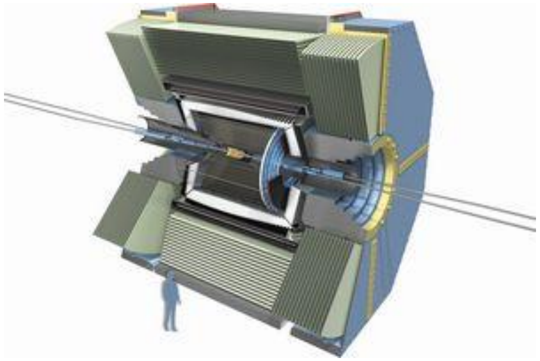
- High production rate
  - ~ 1 billion D^0 decays to be analysed (now) at LHCb
  - $\sigma(pp \rightarrow c\bar{c}X) = (2940 \pm 3 \pm 180 \pm 160)\,\mu b$ @ 13TeV for $p_T < 8$ GeV/c and $2 < \eta < 4.5$ JHEP03(2016)159
- Busy environment
  - Tight selections needed → non-trivial efficiency effects

LHCb



- Clean environment:
  - Easier control of systematic uncertainties
  - Access to absolute asymmetries
- Better efficiency in reconstructions of neutral particles (K_S^0, η, η', π^0, γ)
- Access to decays with neutrinos in the final state

Belle II



Prospects for the future runs

CERN-PUB-LHCC-2018-027
BELLE2-PUB-PH-2018-001

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–3 (23 fb^{-1})	D*	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	D*	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	D*	5.3G	0.0014%	1.6G	0.0025 %

- A_Γ expected to be $O(10^{-5})$ in SM — Kagan & Silvestrini 2020; Li, Umeeda, Xu, Yu 2020
- → with $300 fb^{-1}$ we will reach sensitivity to SM expectations
- With 50 ab^{-1} Belle II will collect about 60M of $D^0 \rightarrow K^+K^-$ decays

Unit of 10^{-3} (in blue unofficial extrapolations)

	Current best measurement (stat.+ syst.)	LHCb 2011-2018 9 fb^{-1}	LHCb U1 50 fb^{-1} (stat.)	LHCb U2 300 fb^{-1} (stat.)	Belle II 50 ab^{-1} (stat.+ syst.)
ΔA_{CP}	LHCb ($9fb^{-1}$) 0.29	0.29 (stat.+ syst.)	0.07	0.03	0.6
$A_{CP}(D^0 \rightarrow K^+K^-)$	LHCb ($3fb^{-1}$) 1.8	0.5 (stat. only)	0.17	0.07	0.3
$A_{CP}(D^0 \rightarrow \pi^+\pi^-)$	LHCb ($3fb^{-1}$) 1.8	0.5 (stat. only)	0.17	0.07	0.5
$A_{CP}(D^0 \rightarrow K^0_S K^0_S)$	Belle (1 ab^{-1}) 15	13 (stat. + syst.)	7	2.8	2.3

CPV in $\Xi_c^+ \rightarrow pK^-\pi^+$

LHCb-PAPER-2019-026

- Actively working also on search of CPV in multibody channels
- Example: perform searches for CPV in $\Xi^+_c \rightarrow pK^-\pi^+$ single-Cabibbo suppressed charm baryon decays using Run 1 data (~3fb^{-1})
- 3-body hadronic decays: make use of the Dalitz plot to look for localized asymmetries
- Search based on two techniques independent from the amplitude modeling in the Dalitz plot
- No evidence of CPV found

$$S^i_{CP} = \frac{n^i_+ - \alpha n^i_-}{\sqrt{\alpha(n^i_+ + n^i_-)}}$$