Mixing & Time-Dependent CPV In Charm

17 OCTOBER 2018

NATHAN JURIK

UNIVERSITY OF OXFORD

ON BEHALF OF THE LHCB COLLABORATION

Outline

Introduction of mixing & time-dependent CPV in Charm.

What's new since a year ago?

1) "Updated determination of $D^0 - \overline{D}^0$ mixing and CP violation parameters with $D^0 \to K^+\pi^-$":arxiv:1712.03220
2) "Measurement of the charm-mixing parameter y_{CP}":arxiv:1810.06874

What's to come in the near/distant future.

Introduction

Mixing

- Mass eigenstates of neutral D mesons are not the flavour eigenstates: $\left| D_{1,2} \right\rangle = p\left| D^0 \right\rangle \pm q\left| \overline{D}^0 \right\rangle$

➢ Mesons produced as one flavour eigenstate will oscillate while propagating through spacetime.

Mixing governed by $x = \frac{m_2 - m_1}{\Gamma}$ and y$= \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$, with $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$

➢ The x,y parameters are expected to be small in the standard model $\leq 10^{-2}$

CP Violation

- CP-Violation in charm sector is very small in the SM: $\mathcal{O}(10^{-3})$.

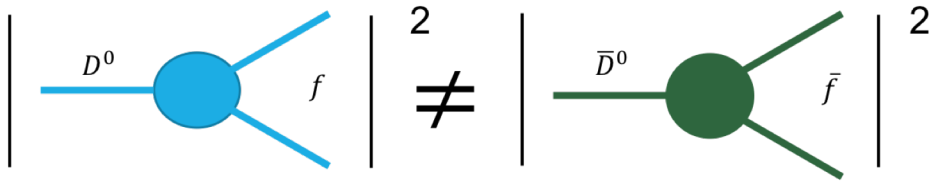
➢ A promising place to look for new physics

➢ Charm is only laboratory for studying some of these effects in the up-type quarks

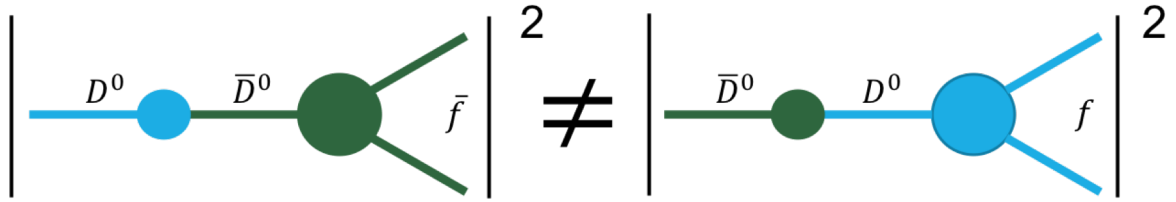
Very challenging: requires huge samples and control of systematic uncertainties below the $\mathcal{O}(10^{-3})$ level

Types of CPV

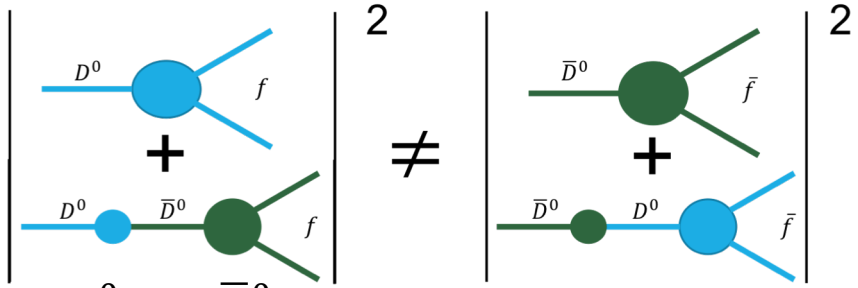
- **Direct CPV**
  - Occurs if $\left|\bar{A}_{\bar{f}}/A_f\right| \neq 1$
  - Discussed in the next talk by Federico [link]



- **CPV in mixing**
  - Occurs if $\left|\frac{q}{p}\right| \neq 1$



- **CPV in interference between mixing and decay**
  - Occurs if $\phi \equiv \arg\left(\frac{q\bar{A}_{\bar{f}}}{pA_f}\right) \neq 0$

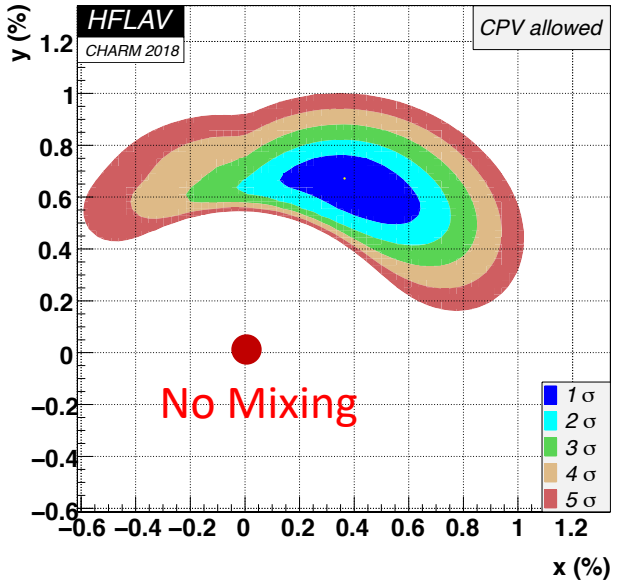


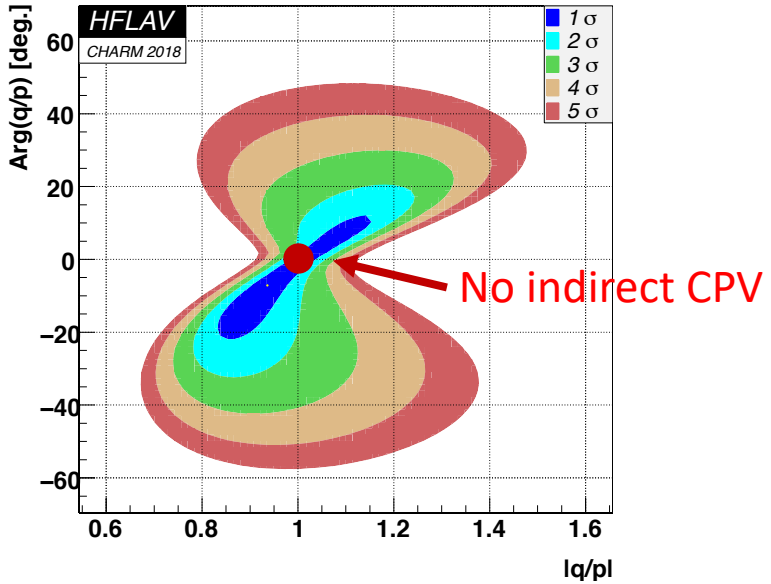
N.B. In presence of CP violation, the mixing rates for mesons produced as D^0 and $\bar{D}^0$ differ.
  - The two are intimately intertwined.

“Current” Picture

- Taken from the CPV allowed Charm 2018 HFLAV fit
- Non-mixing hypothesis rejected at overwhelming significance

…. but x is still consistent with zero, and there is no indication of indirect CPV

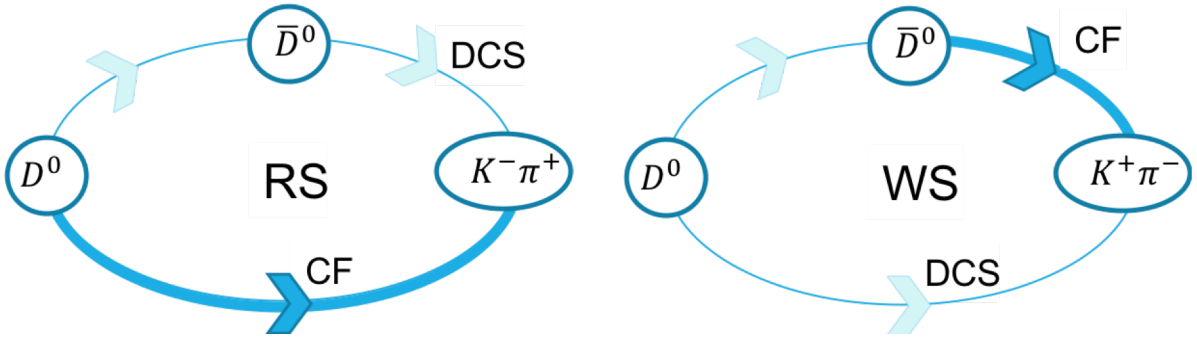




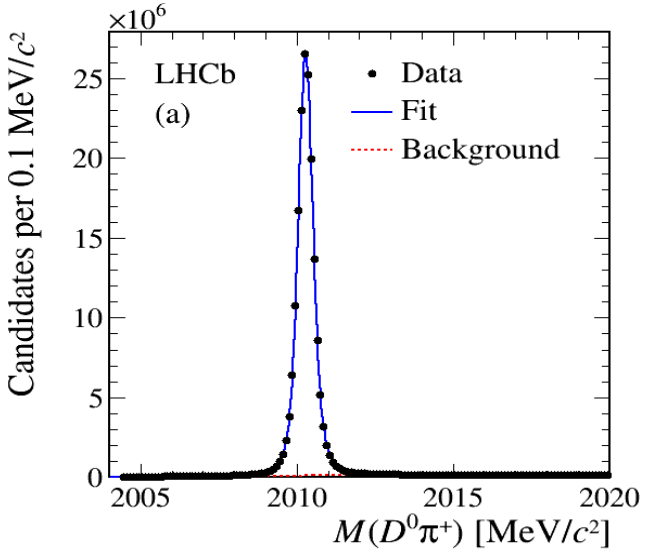
Updated determination of $D^0 - \bar{D}^0$ mixing and CP violation parameters with $D^0 \to K^+\pi^-$

arxiv:1712.03220

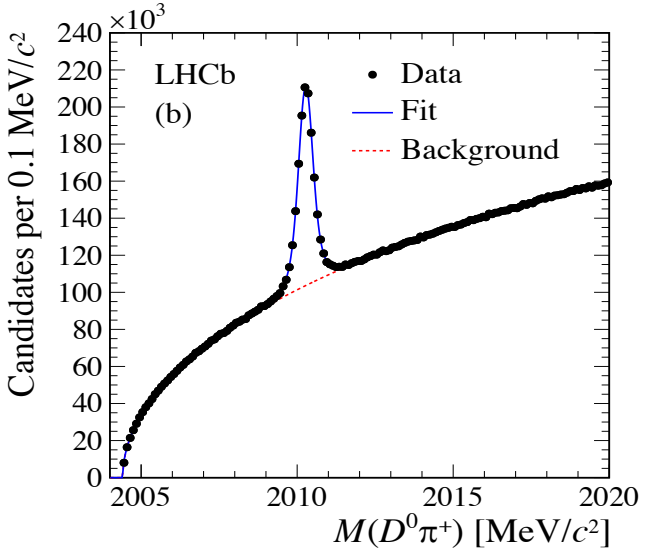
- Data from 2011-2016 (5.0 fb^{-1}): triples the dataset size used in analysis of 2011/2012 data.
- Sample reconstructed via $D^*(2010)^+ \to D^0\pi_s^+$, where π_s^+ tags the flavour at production.
- Method is to measure decay-time-dependent ratio of "Wrong Sign" (WS) to "Right Sign" (RS) decays



1.77×10^8 RS



7.22×10^5 WS



Updated determination of $D^0 - \overline{D}^0$ mixing and CP violation parameters with $D^0 \to K^+\pi^-$

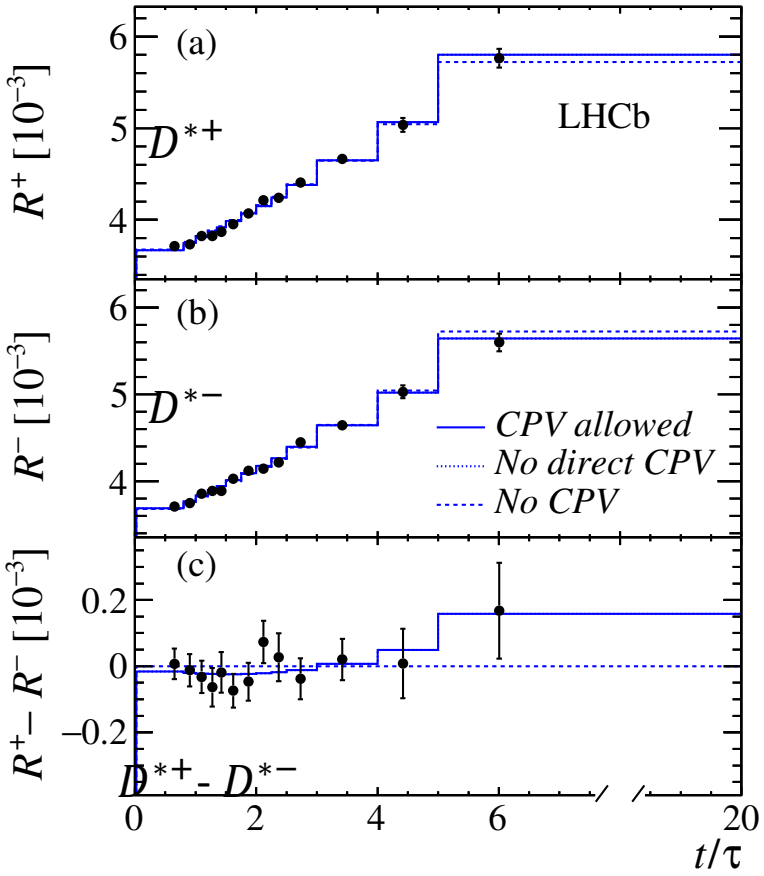
arxiv:1712.03220

- Ratio of yields as a function of decay time is related to mixing parameters via

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

where $\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$ and $\frac{\mathcal{A}(D^0 \to K^+\pi^-)}{\mathcal{A}(D^0 \to K^-\pi^+)} = -\sqrt{R_D}e^{-i\delta}$.

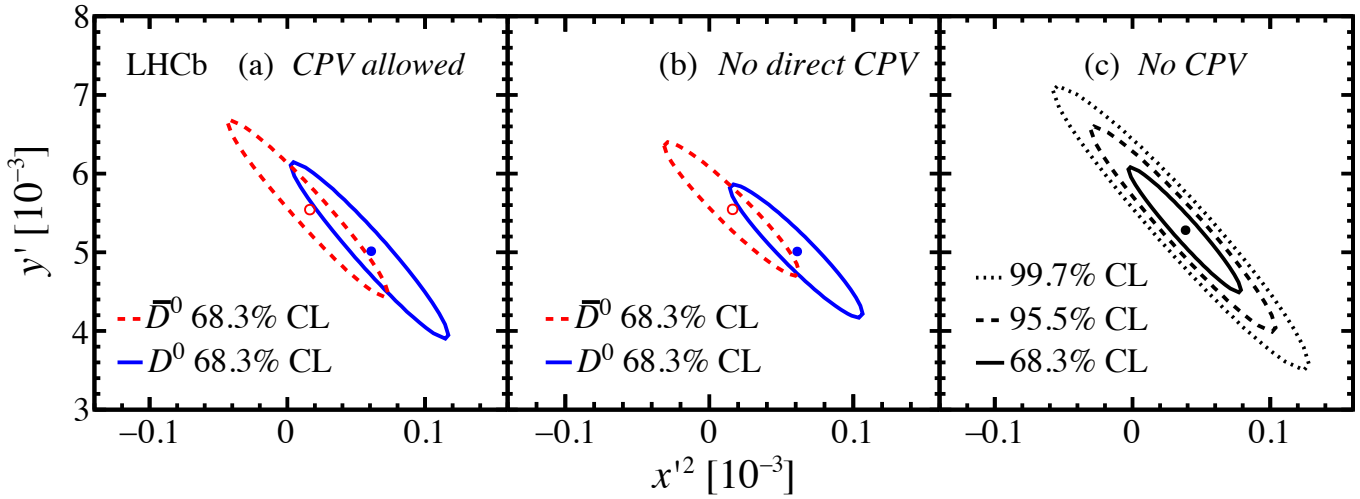
- In presence of CPV, need independent sets of parameters ($R^{\pm}(t)$) to describe data.
- Three fits are performed:
  1) Allow for direct and indirect CPV
  2) Allow only indirect CPV ($R_D^+ = R_D^-$)
  3) CP-conservation hypothesis (all parameters shared)



Updated determination of $D^0 - \overline{D}^0$ mixing and CP violation parameters with $D^0 \to K^+\pi^-$

arxiv:1712.03220

- Twice as precise as previous LHCb results!



- However fitting the D^0 and $\overline{D}^0$ decays separately shows no evidence for CP violation.

- The analysis places stringent bounds on the CPV parameters:
  $A_D \equiv (R_D^+ - R_D^-)/(R_D^+ + R_D^-)$= (−0.1 ± 9.1) × 10^{-3} and
  $1.00 < |q/p| < 1.35$ at the 68.3% confidence level.

"Measurement of the charm-mixing parameter y_{CP}"

arxiv:1810.06874

- Analysis compares decay width of D^0 to CP-even final states (Γ_{CP}) to the decay width to CP-mixed states (Γ), denoted as $\Delta_\Gamma \equiv \Gamma_{CP} - \Gamma$

- These quantities are related to the y_{CP} parameter via $y_{CP} \equiv \frac{\Gamma_{CP}}{\Gamma} - 1$, which can also be written as

$$y_{CP} \equiv \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

CPV in mixing

CPV in interference

- In the limit of CP symmetry, the quantity y_{CP} is identical to the mixing parameter y

Thus a significant deviation from known y value would indicate CP violation in $D^0 - \bar{D}^0$ mixing.

"Measurement of the charm-mixing parameter y_{CP}"

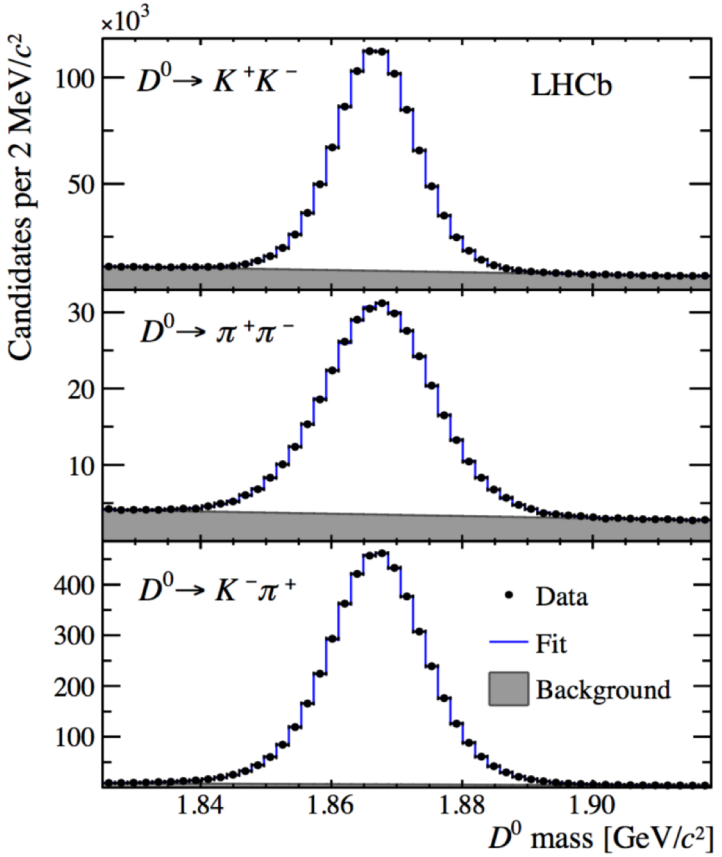
arxiv:1810.06874

- Current world average y_{CP} is dominated by B factories.
- ➢ Previous LHCb measurement used a 29pb^{-1} sample.

- New analysis has been performed with 3fb^{-1} of Run 1 data, using D^0mesons coming from semimuonic B^- and $\bar{B}^0$ decays

- Decays to the CP eigenstates: $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ are reconstructed along with the CP mixed $D^0 \to K^-\pi^+$.

Decay	Signal yield $[10^3]$
$D^0 \to K^+K^-$	878.2 ± 1.2
$D^0 \to \pi^+\pi^-$	311.6 ± 0.9
$D^0 \to K^-\pi^+$	4579.5 ± 3.2

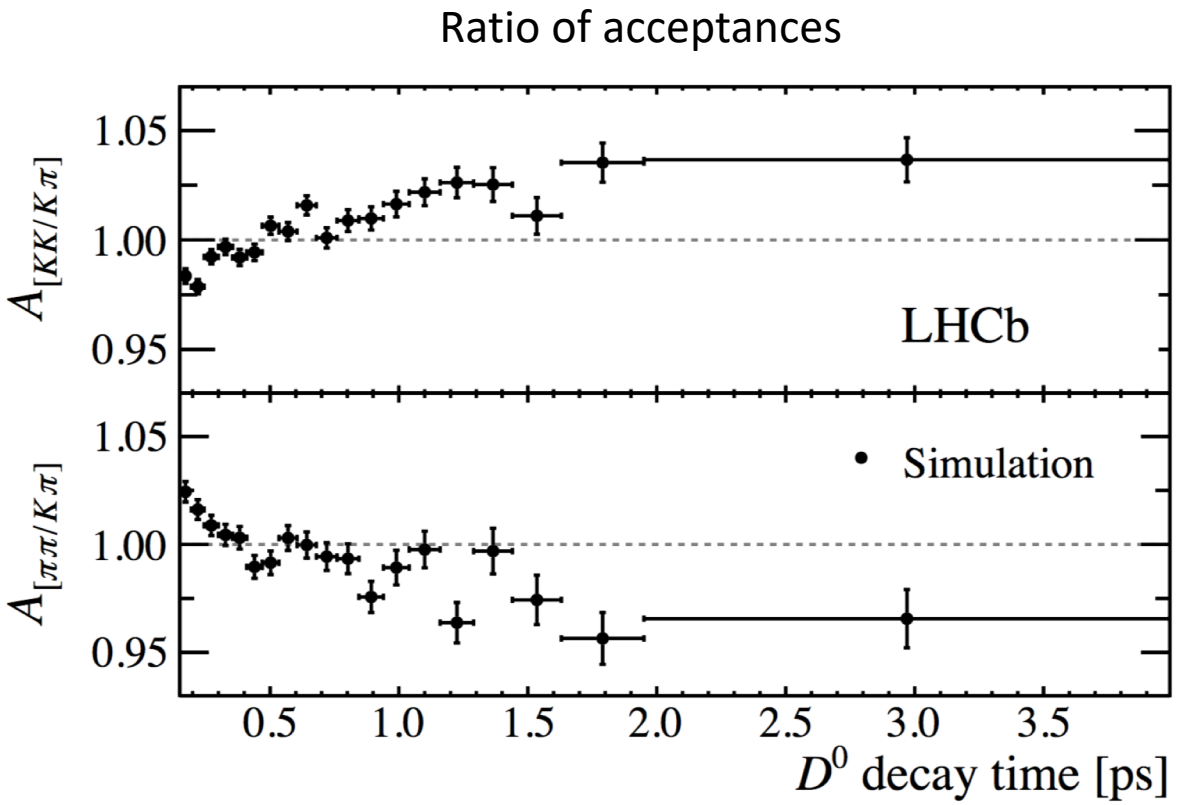


“Measurement of the charm-mixing parameter y_{CP}”

arxiv:1810.06874

- Much of triggering and selection criteria imposed on the muon
- ➢ Differences in acceptance for the different D^0 decay modes are largely suppressed.

- Residual differences are of the order of only a few percent
- ➢ Corrected for with simulation.



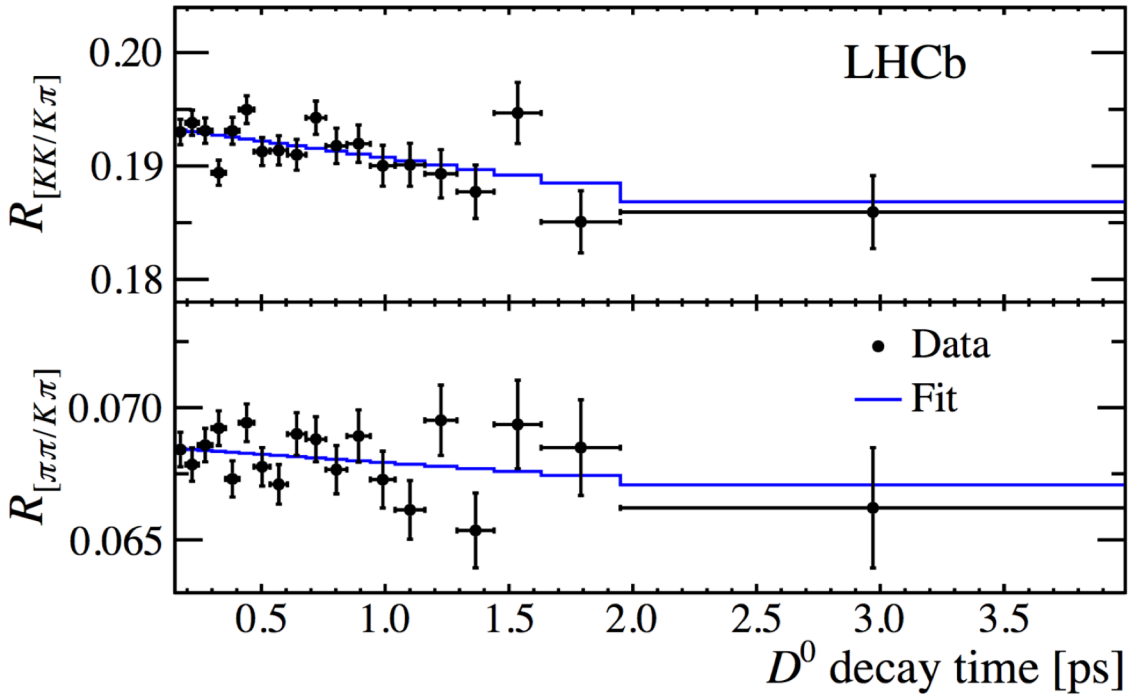
“Measurement of the charm-mixing parameter y_{CP}”

arxiv:1810.06874

- Signal ratio yields between CP-even and $D^0 \to K^-\pi^+$ efficiency corrected as a function of decay time.

- Corrected ratios then fit with ratio of integrals of two exponentials with exponents of $\Gamma_{CP} = \Delta_\Gamma + \Gamma$ and Γ.

➢ Determine the best value of Δ_Γ



"Measurement of the charm-mixing parameter y_{CP}"

arxiv:1810.06874

- The known D^0 lifetime is then used in order to extract $y_{CP} = \Delta_\Gamma \tau$

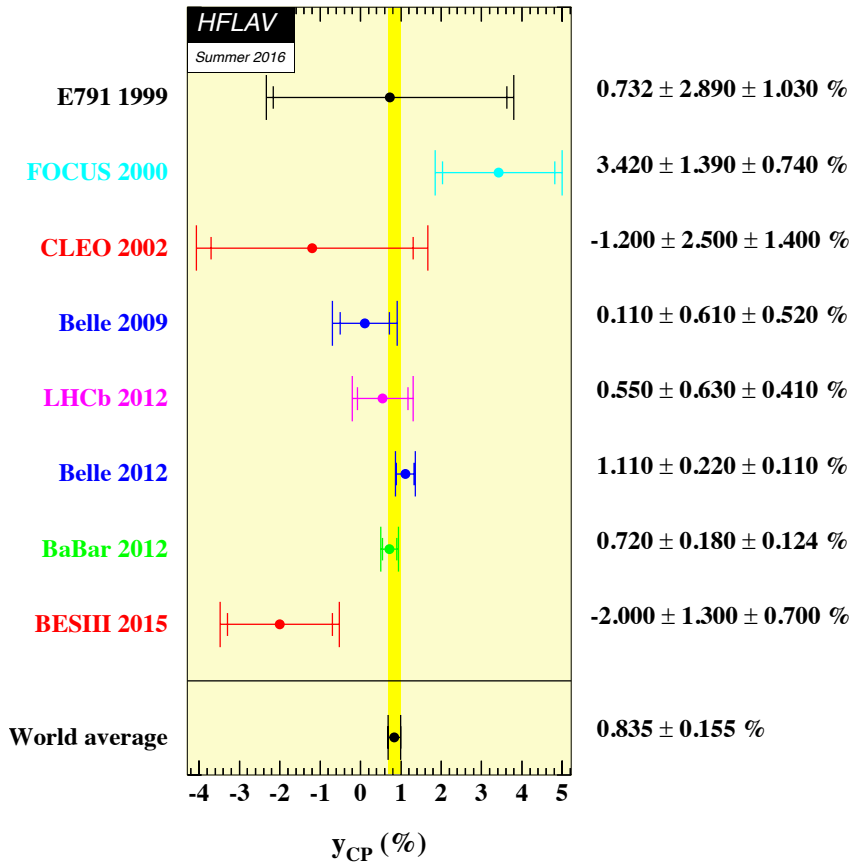
Decay	Δ_Γ [ps^{-1}]	y_{CP} [%]
$D^0 \to K^+K^-$	$0.0153 \pm 0.0036 \pm 0.0027$	$0.63 \pm 0.15 \pm 0.11$
$D^0 \to \pi^+\pi^-$	$0.0093 \pm 0.0067 \pm 0.0038$	$0.38 \pm 0.28 \pm 0.15$

- Results are consistent between modes, and combined give $y_{CP} = (0.57 \pm 0.13(\mathrm{stat}) \pm 0.099(\mathrm{syst}))\%$.

- Consistent with, and as precise, as world average.

- Also consistent with world average value of $y = (0.62 \pm 0.07)\%$. No evidence of CP violation in mixing.

Previous y_{CP} results



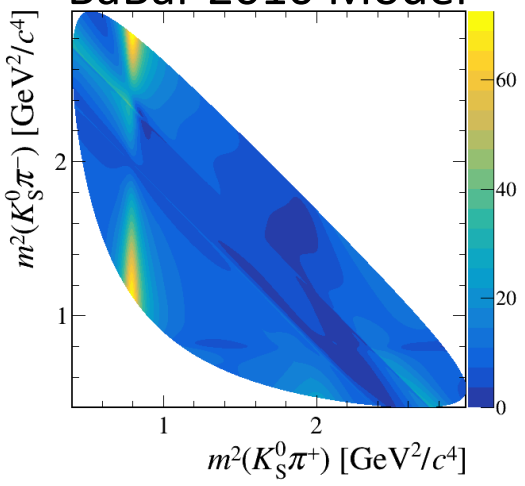
$D^0 \to K_S\pi^+\pi^-$

- Features a rich resonance substructure with varying strong phase across Dalitz plane.
  - Pros: Good for sensitivity to parameters of interests and can allow for direct determination of $x, y, \lfloor q/p \rfloor$ and ϕ.
  - Cons: Requires good understanding of both the decay dynamics and acceptance over the Dalitz plane.

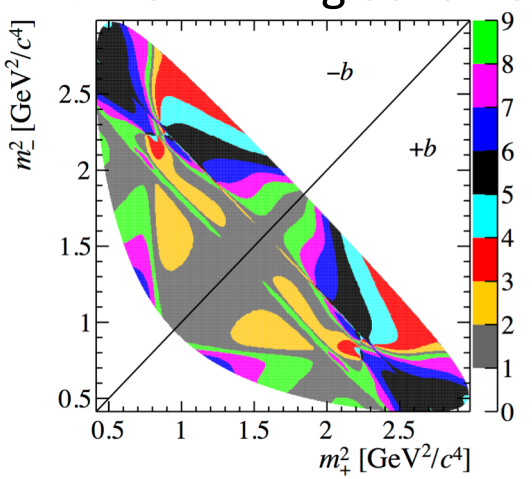
- Hadronic nuisance parameters treated in two ways:
  - Determined from same data with amplitude analysis
  - Use externally measured values of the strong phase difference in bins of the Dalitz plane (CLEO/BESIII).

- A number of interesting options as well for handling acceptance effects.

BaBar 2010 Model



CLEO Binning Scheme



$D^0 \to K_S\pi^+\pi^-$

- LHCb has published a model-independent measurement using 1 fb^{-1} of 2011 data: arxiv:1510.01664

- Analyses utilising larger datasets are being pursued.

- Impressive precisions attainable with Run 1+2.
- ➢ Hope for a significant measurement of x!.
- ➢ Model-independent method will also benefit from more precise strong phases from BESIII

From LHCb Upgrade II document: arxiv:1808.08865

Sample (lumi $\mathcal{L}$)	Tag	Yield	$\sigma(x)$	$\sigma(y)$	$\sigma(\lvert q/p\rvert)$	$\sigma(\phi)$
Run 1–2 (9 fb^{-1})	SL	10M	0.07%	0.05%	0.07	4.6°
	Prompt	36M	0.05%	0.05%	0.04	1.8°

- Also hope to give some input on $D \to K_S K^+ K^-$

$D^0 \to K^{\pm}\pi^{\mp}\,\pi^+\,\pi^-$

- Also features rich resonance substructure across its 5 dimensional phase
  - Like the measurement with $D^0 \to K^{\pm}\pi^{\mp}$, a pair of WS/RS decays

- In 2016 LHCb published phase space integrated measurement with 3fb^{-1} of Run 1 data: arxiv:1602.07224
  - First observation of mixing in this channel

- In the past year LHCb has also published studies of the resonance structure: arXiv:1712.08609
  - Instrumental in performing a phase-space resolved analysis

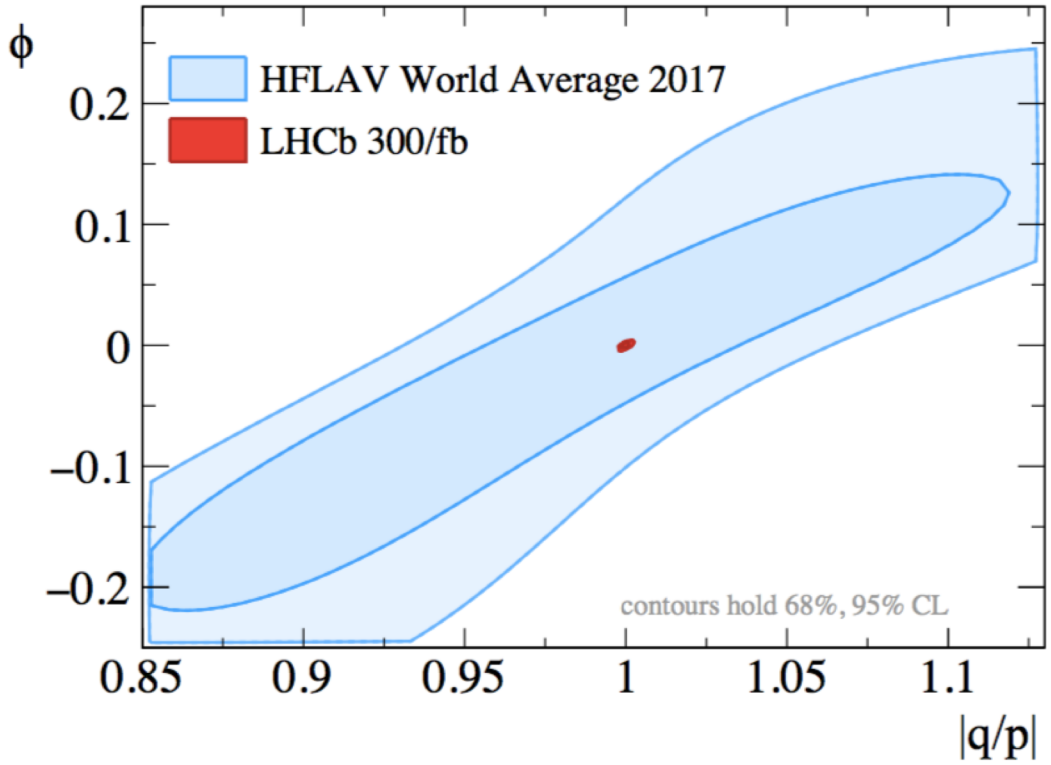
- Will offer very precise measurements!

From LHCb Upgrade II document: arxiv:1808.08865

Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(x'_{K\pi\pi\pi})$	$\sigma(y'_{K\pi\pi\pi})$	$\sigma(\lvert q/p\rvert)$	$\sigma(\phi)$
Run 1–2 ($9\,\mathrm{fb}^{-1}$)	0.22	2.3×10^{-4}	2.3×10^{-4}	0.020	$1.2°$

LHCb Upgrade II Studies

- LHCb has also put together a document presenting the physics case for an LHCb Upgrade II: arxiv:1808.08865
- Includes discussions and projections on what LHCb would be able to do with several modes and analyses, some not discussed today.
- Incredible statistics are on the way, and systematic uncertainties should remain under ultimate statistical uncertainties.
- Will reach frighteningly good precisions!



Summary

- LHCb has continued to establish methods for performing analyses with Run 1 data, and are proceeding with analysing even larger data sets offered in Run 2.
- ➢ The outcome has been multiple single most precise measurements.

- All so far are consistent with CP symmetry, and are not able to rule out $x = 0$ hypothesis.

- However all are limited by statistics, and a large amount of data remains to be analysed, so keep an eye on the results to come!
- ➢ And preparations for the Upgrade (II)!