Measurement of the charm-mixing parameter y_{CP}

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CP violation and mixing in charm

Mass eigenstates of the neutral charm mesons:

$$|D_L\rangle = p\,|D^0\rangle + q\,|\overline{D^0}\rangle$$

$$|D_H\rangle = p\,|D^0\rangle - q\,|\overline{D^0}\rangle$$

Mixing parameters:

$$x = 2\frac{m_H - m_L}{\Gamma_H + \Gamma_L}$$

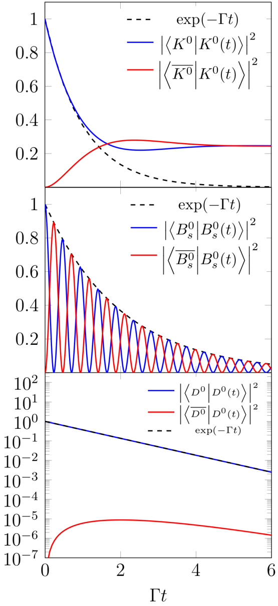
$$y = \frac{\Gamma_H - \Gamma_L}{\Gamma_H + \Gamma_L}$$

So that the time evolution looks like:

$$\langle D^0|D^0(t)\rangle = \frac{e^{-\Gamma t}}{2}\left[\cosh(y\Gamma t) + \cos(x\Gamma t)\right]$$

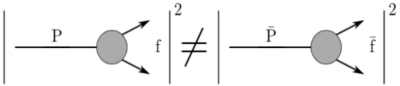
$$\langle \overline{D^0}|D^0(t)\rangle = \left|\frac{q}{p}\right|^2 \frac{e^{-\Gamma t}}{2}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

In the charm system: $x, y \sim \mathcal{O}(0.01)$
$\rightarrow$ enormous oscillation period



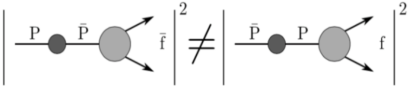
CP violation and mixing in charm

Direct CP violation



- Occurring when $|A_f|^2 \neq |\bar{A}_{\bar{f}}|^2$
- $|A_f|^2$ decay amplitude to state f
- In charm is measured via CP asymmetries of two-body decays
- $\Delta A_{CP} = A_{CP}^{KK} - A_{CP}^{\pi\pi}$
- LHCb reported nonzero ΔA_{CP} at 5.3σ in 2019

Indirect CP violation



- Occurring when $|p| \neq |q|$
- Also by interference between direct and mixing diagrams
- Accessible through time-dependent studies
- No evidence of mixing-induced CP violation in charm yet

[PRL 122 211803 (2019)]

CP violation and mixing in charm

Because of mixing, for CP-even final states the effective decay width $\hat{\Gamma}$ differs from the average Γ

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

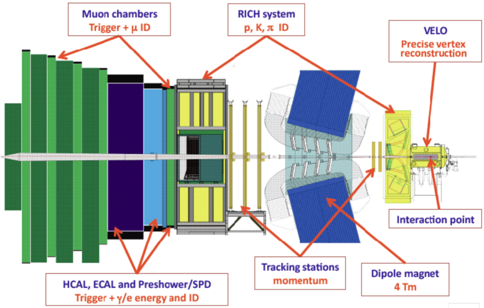
where $\phi_D = \arg(\frac{q\bar{A}_f}{pA_f})$.

- For $|p| = |q|$ and $\phi_D = 0$ (no CP violation), then $y_{CP} = y$
- Any difference between y_{CP} and y would indicate CP violation in mixing
- Sensitive to a broad class of non-SM processes that would enhance the oscillation rate or the CP violation strength
- World average $y_{CP} = (0.715 \pm 0.111)\%$, dominated by LHCb (Run 1)
- Compatible with $y = (0.651^{+0.063}_{-0.069})\%$
- In this presentation: update of the LHCb Run 1 measurement using Run 2 data

[HFLAV website], [PRL 122 011802 (2019)]

The LHCb experiment at CERN

- Single-arm spectrometer designed for high precision flavour physics measurements
- Pseudorapidity range $\eta \in [2, 5]$
- Highly efficient particle identification
- Very good momentum and IP resolution
- Excellent primary and secondary vertex reconstruction



Analysis strategy

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Measurement of y_{CP} by taking the ratio of $D^0 \to K^+K^-$ or $D^0 \to \pi^+\pi^-$ to $D^0 \to K^-\pi^+$ yields in order to extract $\Delta\Gamma^{hh} = \Gamma^{hh} - \Gamma^{K\pi} = \hat{\Gamma} - \Gamma$:

$$R^{hh} = \frac{N(D^0 \to h^+h^-)}{N(D^0 \to K^-\pi^+)} \propto e^{-\Delta\Gamma^{hh}} \frac{\epsilon(D^0 \to h^+h^-)}{\epsilon(D^0 \to K^-\pi^+)}.$$

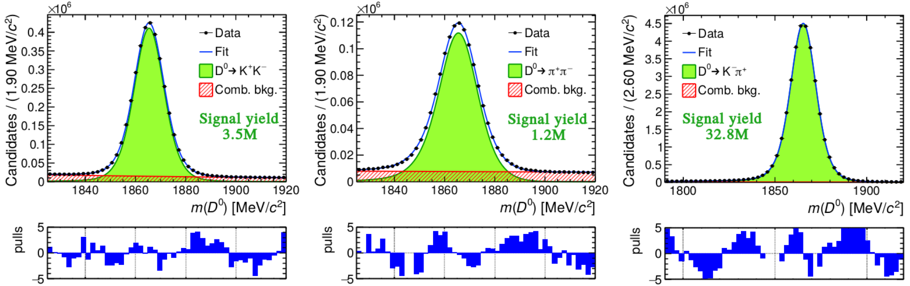
Then, using the known average D^0 lifetime: $y_{CP} = \Delta\Gamma^{hh}\tau_{D^0}$

- 5.53 fb^{-1} of pp collisions collected by LHCb in 2016-2018 at $\sqrt{s} = 13$ TeV
- Analysis ongoing: all plots are preliminary and results are blind (central value)
- D^0 candidates are reconstructed via semimuonic inclusive B decays, using a dedicated trigger-level selection and a multivariate offline selection

Decay-time binning and mass fits

Candidates from each channel are divided into 18 exclusive decay-time bins

- The decay time is calculated as $t_D = m_D \frac{\vec{L}\cdot\vec{p}_D}{|p_D^2|}$, where $\vec{L} = \vec{V}_D - \vec{V}_B$
- The signal model is a sum of 4 Gaussians with power law tail to account for radiative loss of energy
- They share the same power tail parameter but different mean and width, and the model has been validated using high-statistics simulated samples
- Combinatorial background parametrised with an exponential function
- For each decay-time bin, signal yields for the three channels are extracted with a mass fit



Decay-time acceptance

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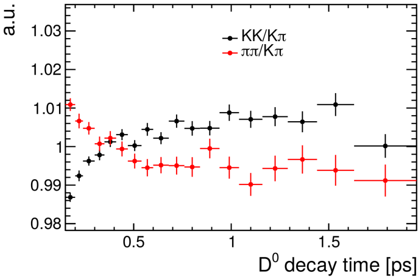
Trigger, reconstruction and selection can distort the decay-time acceptance

- Mostly due to time resolution and kinematic cuts
- This effect needs to be disentangled in order to be able to access $\Delta\Gamma^{hh}$
- Use the same decay-time binning as above
- Get the relative acceptance variation from simulated events, by comparing a sample with the same selection as data with another one without any selection
- Take the two ratios $\epsilon^{KK}/\epsilon^{K\pi}$ and $\epsilon^{\pi\pi}/\epsilon^{K\pi}$



These represent the distribution of relative variation of acceptance and must be applied as correction to R^{KK} and $R^{\pi\pi}$ (obtained with the binned mass fits)

Summary of statistical and systematic errors

Evaluation of systematics is still ongoing. Sources include:

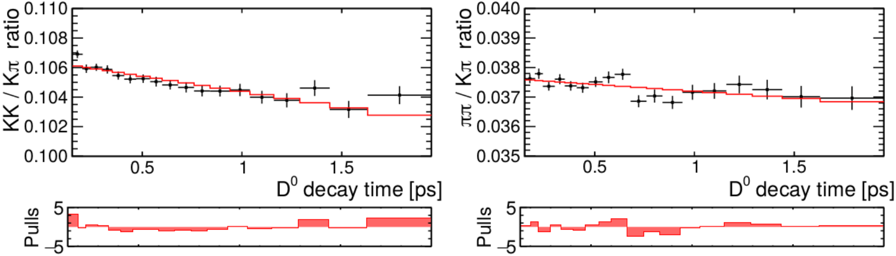
- Limited size of the simulated samples (expected to be dominant)
- Additional sources of background currently unaccounted for
- Decay model and composition of simulated samples
- Biases from the fit model and the decay-time resolution
- External D^0 average lifetime (checked to be negligible up to $\mathcal{O}(10^{-5})$)

	$\sigma(\Delta_\Gamma^{KK})$ [ps^{-1}]	$\sigma(\Delta_\Gamma^{\pi\pi})$ [ps^{-1}]	$\sigma(y_{CP}^{KK})$ [%]	$\sigma(y_{CP}^{\pi\pi})$ [%]
Simulated sample size	0.0011	0.0014	0.06	0.05
Total systematic	0.0011	0.0014	0.06	0.05
Statistical only	0.0018	0.0033	0.07	0.14

Results

$\Delta\Gamma^{hh}$ is obtained by fitting R^{KK} and $R^{\pi\pi}$ after the decay-time acceptance correction, minimising

$$\chi^2 = \sum_{i=1}^{18} \frac{(N_i^{hh} - R_i^{hh} N_i^{K\pi})^2}{(\sigma_{N_i^{hh}})^2 + (R_i^{hh}\sigma_{N_i^{K\pi}})^2}, \text{ where } R_i^{hh} = \mathcal{N}_i \frac{\epsilon_i(hh)}{\epsilon_i(K\pi)} \frac{\int_{\Delta t_i} e^{-(\Gamma^{K\pi}+\Delta\Gamma^{hh})t} dt}{\int_{\Delta t_i} e^{-\Gamma^{K\pi} t} dt}$$



$\Delta\Gamma^{KK} = -1.8527 \pm 0.021 \pm 0.0011 \text{ ps}^{-1}$ $\qquad$ $\Delta\Gamma^{\pi\pi} = -1.8603 \pm 0.036 \pm 0.0014 \text{ ps}^{-1}$

Reminder: central values are randomised and only used to check compatibility

Conclusions

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- Measurement of the charm-mixing parameter y_{CP} using LHCb Run 2 data
- Using the CP-even decays $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ to measure $\Delta\Gamma$ with respect to $D^0 \to K^-\pi^+$ decays
- $\Delta\Gamma^{KK} = -1.8527 \pm 0.021 \pm 0.0011$ ps^{-1}
- $\Delta\Gamma^{\pi\pi} = -1.8603 \pm 0.036 \pm 0.0014$ ps^{-1}

Using the average D^0 lifetime $\tau_{D^0} = 0.4101 \pm 0.0015$ ps as external input:

$$y_{CP}^{KK} = (75.98 \pm 0.07 \pm 0.06)\%$$

$$y_{CP}^{\pi\pi} = (76.29 \pm 0.14 \pm 0.05)\%$$

Compatible within 1.8σ, and their combination:

$$y_{CP} = (76.08 \pm 0.06 \pm 0.04)\%$$

Most precise measurement of y_{CP} from a single experiment and a factor of two better than the current world average