Quantum-Correlated $D^0\overline{D}^0$ systems in LHCb Run 3 data

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08 April 2026

Introduction

- From neutral meson oscillations, we know that neutral D mesons exist in CP eigenstates which are a superposition of flavour eigenstates (neglecting CPV):

$$|D_+\rangle = \frac{1}{\sqrt{2}}(|D^0\rangle + |\overline{D}^0\rangle)$$
$$|D_-\rangle = \frac{1}{\sqrt{2}}(|D^0\rangle - |\overline{D}^0\rangle)$$

- Quantum-correlated $D^0\overline{D}^0$ systems refer to pairs of neutral D mesons which exist in eigenstates of C and P defined by (in absence of charm mixing):

$$C\text{-even}: \ \frac{|D^0\overline{D}^0\rangle + |\overline{D}^0 D^0\rangle}{\sqrt{2}} = \frac{|D_+D_+\rangle - |D_-D_-\rangle}{\sqrt{2}}$$

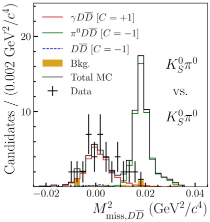
and

$$C\text{-odd}: \ \frac{|D^0\overline{D}^0\rangle - |\overline{D}^0 D^0\rangle}{\sqrt{2}} = \frac{|D_-D_+\rangle - |D_+D_-\rangle}{\sqrt{2}}$$

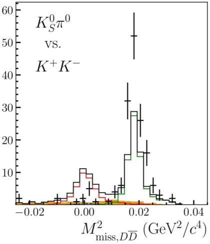
- Produced in decays of particles with definite J^{PC} quantum numbers to certain final states...e.g. $\psi(3770)$, $\chi_{c1}(3872)$...etc
- Reconstructing both neutral D mesons in CP-definite final states, e.g. K^+K^-, $\pi^+\pi^-$ enhances/suppresses contributions depending on the parent particle J^{PC}

Physics Motivation

- To date, QC $D^0\overline{D}^0$ systems have been studied at e^+e^- experiments to obtain:
  - Time-integrated measurements of charm mixing parameters
  - D^0 decay strong phases (input to charm mixing and CKM γ measurement)
- May also be able to exploit them for other measurements (JHEP 03 (2023) 038):
  - Ruling out quantum numbers in hadron spectroscopy
  - T/CPT symmetry measurements in neutral charm
- Need a large sample of correlated $D^0\overline{D}^0$ pairs — charmonia(-like) states such as $\chi_{c1}(3872)$ provide an opportunity to do so at LHCb



C-even final state



C-odd final state

Figure from BESIII: Phys. Rev. D 112 (2025), 072006

Quantum Correlations in $\chi_{c1}(3872)$ decays

- $\chi_{c1}(3872)$ quantum numbers were measured to be $J^{PC} = 1^{++}$ in Phys. Rev. Lett. 1101, 222001
- $\chi_{c1}(3872)$ can decay to both the $(D^0\overline{D}^0)_{C+}\pi^0$ and $(D^0\overline{D}^0)_{C-}\gamma$ final states
- This analysis focuses mainly on $D^0\overline{D}^0$ pairs produced by the decay $\chi_{c1}(3872) \to D^0\overline{D}^0\pi^0/\gamma$ where the neutral particle is not reconstructed
- $\mathcal{O}(10^3)$ partially reconstructed $\chi_{c1}(3872) \to D^0\overline{D}^0X$ decays were seen by LHCb during run 1+2 (JHEP 1907 (2019) 035 ($9\,\text{fb}^{-1}$))
- Expect enhancement of $D^0\overline{D}^0\pi^0$, suppression of $D^0\overline{D}^0\gamma$ components when both D mesons are reconstructed in the CP-even $K^-K^+/\pi^-\pi^+$ final states

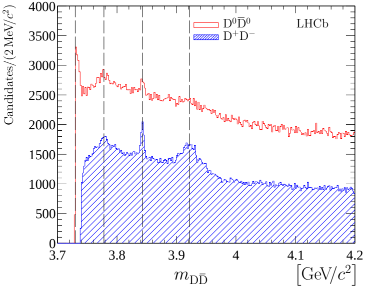
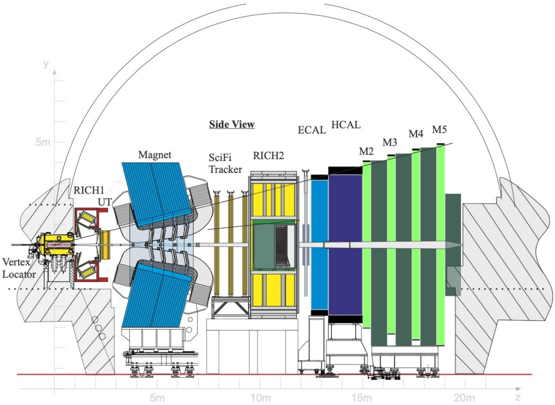


Figure from JHEP 1907 (2019) 035

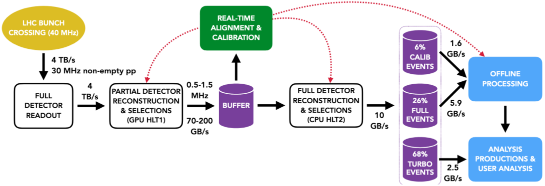
The LHCb Detector

- Single-arm forward spectrometer built to study decays of b and c hadrons produced in the forward region
- Fully instrumented within pseudorapidity range of $2 < \eta < 5$
- This analysis looks at $5.4\,\text{fb}^{-1}$ and $11.4\,\text{fb}^{-1}$ of pp collision data taken in 2024 and 2025 respectively



LHCb in Run 3

- During LS2, LHCb underwent a major upgrade, allowing it to run at five times the luminosity of previous runs
- Key features of the upgrade include:
  - Overhaul of tracking and PID systems and associated readout electronics to accommodate full detector readout at 40 MHz
  - Replacement of hardware trigger with a software-based trigger $\implies$ Improved efficiency especially for fully hadronic final states



- Changes in online selections for *DD* pair reconstruction in 2025 also brings a factor of 2 improvement in signal yield per lumi compared to 2024
- Makes it viable to study Cabibbo-suppressed *CP* double-tagged *DD* pairs despite low branching fraction ($\mathcal{B}(D^0 \to K^-K^+) \sim 1/10$ of $\mathcal{B}(D^0 \to K^-\pi^+)$)

Analysis Outline

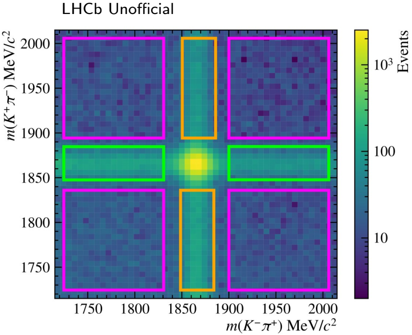
- Measure the efficiency-corrected yield relative to the number of $D\overline{D} \to K^-\pi^+$ vs $K^+\pi^-$ decays:

$$\kappa_{ij} = \frac{\text{Yield in channel } ij}{\text{Yield in channel } ij \text{ without correlations}}$$
$$= \frac{N_{X\to D^0\overline{D}^0, D^0\to i, \overline{D}^0\to j}}{N_{X\to D^0\overline{D}^0, D^0\to K^-\pi^+, \overline{D}^0\to K^+\pi^-}} \frac{\mathcal{B}(D^0\to K^-\pi^+)\times\mathcal{B}(\overline{D}^0\to K^+\pi^-)}{\mathcal{B}(D^0\to i)\times\mathcal{B}(\overline{D}^0\to j)} \frac{\epsilon_{K^-\pi^+/K^+\pi^-}}{\epsilon_{ij}}$$

  where i, j correspond to CP-even final states (i.e. $K^-K^+, \pi^-\pi^+$)
- Perform measurements over the known DD resonances in the near-threshold region: $\chi_{c1}(3872)$, $\psi(3770)$, $X(3842)$, $\chi_{c2}(3930)$
- Expect to see $\kappa \approx 2$ and $\kappa = 0$ for C-even and C-odd resonances respectively
- Measurement of relative enhancement in $D\overline{D} \to K^-\pi^+$ vs $K^-K^+/\pi^-\pi^+$ also provides sensitivity to $D^0 \to K^-\pi^+$ strong phase $r^D_{K\pi}\cos\delta^D_{K\pi}$
- This talk covers some of the work done so far on the $K^-\pi^+$ vs $K^+\pi^-$ channel

Backgrounds

- Combinatoric backgrounds forming fake D^0 candidates:
  - Real D^0 + Fake $\overline{D}^0$
  - Fake D^0 + Real $\overline{D}^0$
  - Fake D^0 + Fake $\overline{D}^0$
- Real D^0 faking prompt $D^0\overline{D}^0$ candidates:
  - D^0 from different PV
  - D^0 from PV + D^0 from B-decay
  - $B \to D^0\overline{D}^0 X$ decays
- Partially reconstructed D^+, D_s^+ decays
- D^0 decays with misidentified daughters
- Peaking backgrounds:
  - Partially reconstructed $T_{cc}^+ \to D^0 D^0 \pi^+$ in suppressed D^0 decay modes
  - D^0 from prompt $D^{*+} \to D^0\pi^+$

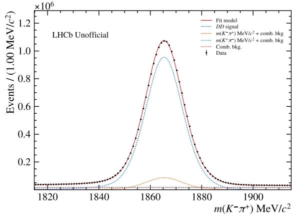


$m(D^0)$ Mass Fits

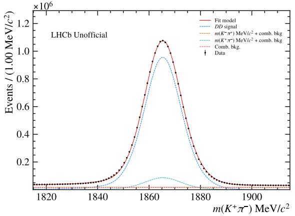
- Signal component is sum of a Double-sided Crystal Ball and Gaussian
- Combinatoric background components $B_{1,2}(x)$ consists of a product of an exponential and a 2nd order polynomial
- For channels where both D^0 final states are identical or charge conjugates of each other, require PDF to be symmetric

The fitted PDF can be written as:

$$
\begin{aligned}
PDF(x,y) = {} & N_{D,\overline{D}} G(x)G(y) \\
& + N_{D,bkg} G(x)B(y) + N_{\overline{D},bkg} B(x)G(y) \\
& + N_{bkg,bkg} B(x)B(y)
\end{aligned}
$$



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

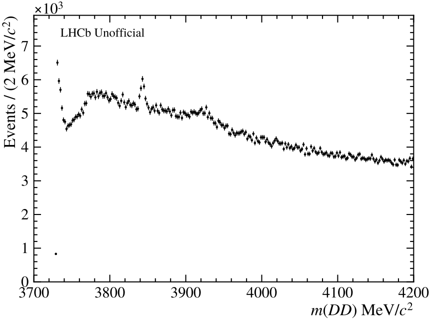


$D^0 \to K^+\pi^-$

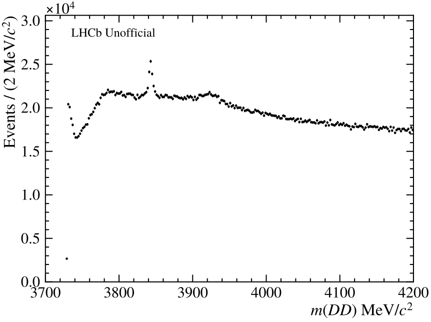
Partial 2025 dataset ($5.7\,\text{fb}^{-1}$)

$m(DD)$ Mass Spectrum

- Using results of the D^0 mass fit, we calculate per-event *sWeights* to subtract the $D^0 \to hh$ combinatoric background
- Substantial difference between 2024, 2025 $m(DD)$ spectrum at open charm threshold — due to changes in trigger selections at start of 2025
- Clear peaking structures seen for the $\chi_{c1}(3872)$, $X(3842)$ and $\chi_{c2}(3930)$
- $\psi(3770)$ less clear; wide resonance lying on top of $D\overline{D}$ threshold



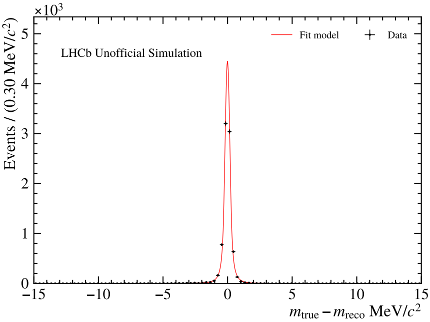
Full 2024 dataset ($5.4\,\mathrm{fb}^{-1}$)

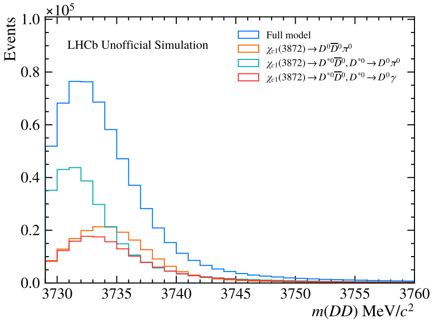


Full 2025 dataset ($11.4\,\mathrm{fb}^{-1}$)

$\chi_{c1}(3872)$ Signal Model

- Threshold peak from partially reconstructed $\chi_{c1}(3872) \to D^0\overline{D}^0\pi^0/\gamma$ decay consists of both C-even and C-odd contributions $\implies$ Needs different treatment from $c\overline{c} \to D^0\overline{D}^0$ peaks
- Generate MC of the various $\chi_{c1}(3872) \to D^0\overline{D}^0 X$ components:
  - $\chi_{c1}(3872) \to D^0\overline{D}^0\pi^0$
  - $\chi_{c1}(3872) \to D^{*0}\overline{D}^0, D^{*0} \to D^0\pi^0$
  - $\chi_{c1}(3872) \to D^{*0}\overline{D}^0, D^{*0} \to D^0\gamma$
- Fix ratio of D^*D components using known branching fractions
- Convolve with resolution function obtained from fit to $m(DD)_{\text{true}} - m(DD)_{\text{reco}}$ in simulation

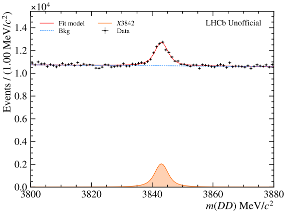




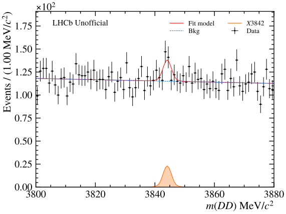
Uncorrelated Normalisation

$$\kappa_{ij} = \frac{\text{Yield in channel } ij}{\text{Yield in channel } ij \text{ without correlations}}$$

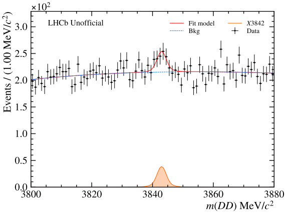
- Obtain uncorrelated normalisation for each $m(DD)$ peak from the $K^-\pi^+/K^+\pi^-$ channel
- Perform fit to $m(DD)$ and generate toys with statistics scaled by branching fraction and efficiency ratios
- Based on toy fits, expect to observe $X(3842)$ with a significance $> 5\sigma$ under the no-correlation hypothesis only when including All 3 CP double-tag $D \to hh$ channels (K^-K^+ vs K^-K^+, $\pi^-\pi^+$ vs $\pi^-\pi^+$ and K^-K^+ vs $\pi^-\pi^+$)



2025 $K^-\pi^+/K^+\pi^-$ Data



Expected 2025 toy (K^-K^+/K^-K^+)



Expected 2025 toy (All CP double-tag channels)

Summary

- LHCb Run 3 opens up a unique opportunity to study quantum-correlated $D\overline{D}$ mesons at hadron colliders for the first time
- Ongoing analysis to demonstrate quantum correlations in $D^0\overline{D}^0$ system produced at LHCb using run 3 dataset
- Procedures for event selection and mass fits are currently being finalised, and work on fitting the uncorrelated $K^-\pi^+/K^+\pi^-$ channel near the open charm threshold is underway
- To-do: Apply selections to and fit mass spectrum in other $D^0 \to hh$ channels, systematic uncertainties, measure yield ratios and $r^D_{K\pi}\cos\delta^D_{K\pi}$

Backup

T/CPT symmetry measurements

- Can make direct measurements of T/CPT symmetry using flavour-CP transitions (e.g. $D_+ \to D^0$ with a CPT conjugate decay of $\overline{D}^0 \to D_+$) by reconstructing D_1 at time t_1 in a CP state (e.g. K^-K^+) and D_2 in a CF final state

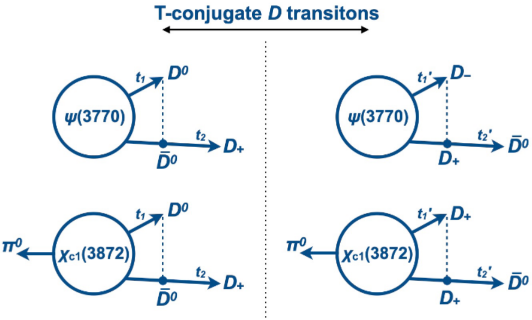


Figure from JHEP 03 (2023) 038

Strong phase measurements

- The decay rate for $D\overline{D} \to Y_1$ vs Y_2 is given by:

$$
\begin{aligned}
\frac{\Gamma(D\bar{D} \to Y_1 \text{ vs. } Y_2)}{A_1^2 A_2^2} = & \left[r_1^2 + r_2^2 + 2CR_1R_2r_1r_2\cos(\delta_1 - \delta_2)\right] \\
& - (1+C)y\left[R_1r_1\cos\delta_1(1+r_2^2) + R_2r_2\cos\delta_2(1+r_1^2)\right] \\
& - (1+C)x\left[R_1r_1\sin\delta_1(1-r_2^2) + R_2r_2\sin\delta_2(1-r_1^2)\right] \\
& + \mathcal{O}(x^2, y^2),
\end{aligned}
$$

  where Y_1, Y_2 denotes the final state of the D, C the even/odd correlation of the $D\overline{D}$ pair and x, y are charm mixing parameters

- For a correlated $D\overline{D}$ pair decaying to a $D\overline{D} \to K^-\pi^+$ vs $K^-K^+/\pi^-\pi^+$ final state, the relative enhancement wrt the uncorrelated case is given by:

$$
1 + \frac{2Cr^D_{K\pi}\cos\delta^D_{K\pi} - (1+C)y}{1 + (r^D_{K\pi})^2}
$$

  where λ is $+1$ and -1 for C-even and odd correlated $D\overline{D}$ pairs respectively

Fitted $m(D^0\overline{D}^0)$ spectrum — Run 1+2 analysis

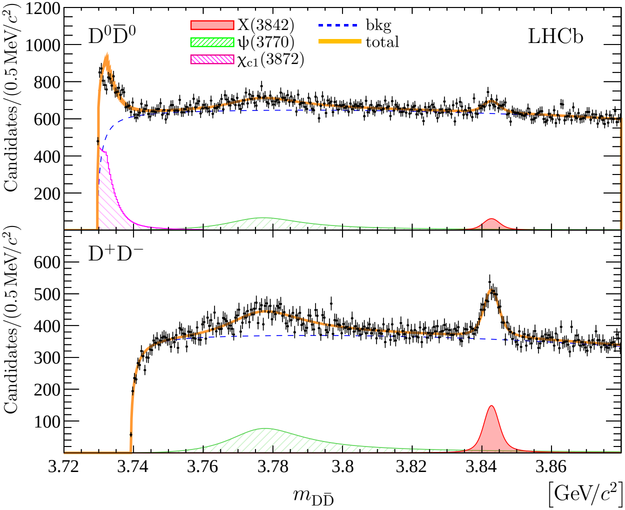


Figure from JHEP 1907 (2019) 035 (9 fb^{-1})