Charm physics at LHCb

XV International Conference on Beauty, Charm,
Hyperons in Hadronic Interactions
Charleston, SC

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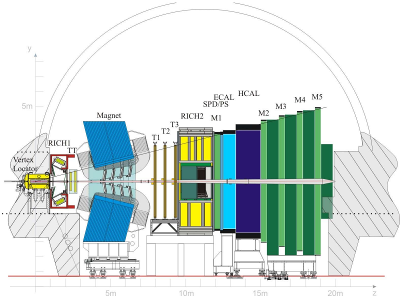
on behalf of the LHCb collaboration

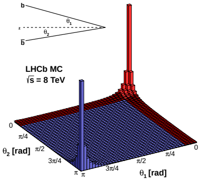
05.06.2024

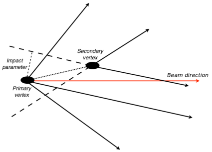
The University of Manchester

The LHCb detector at the LHC

- single-arm forward spectrometer covering $2 < \eta < 5$







[JINST 3 (2008) S08005] [IJMP A 30, 1530022 (2015)]

Excellent impact parameter resolution

- vital to distinguish displaced heavy flavor decays from background

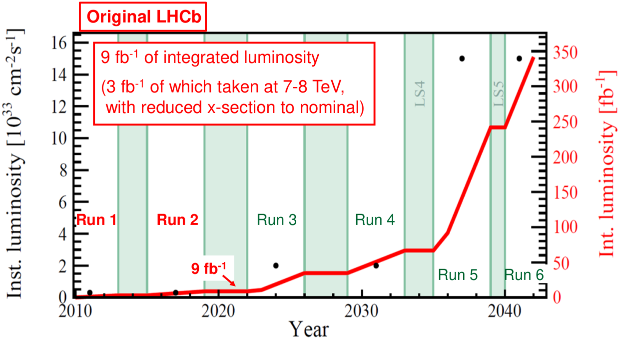
Excellent particle identification

- vital for signal purity

World largest sample of charm hadrons collected by LHCb

- $\mathcal{O}(10^{13}) c\bar{c}$ pairs in Run 1+2 [Nucl. Phys. B 871 (2013)] [JHEP 2016, 159 (2016)]

LHCb collected sample of integrated luminosity of 9 fb^{-1} during LHC Run 1+2



98 papers published by the Charm working group

Broad charm program at LHCb

- search for rare charm decays
- search for new charm hadrons
- decay and production properties
- measurements of D^0-$\overline{D}^0$ mixing
- search for CP violation in mixing
- search for CPV in decays

Charm@LHCb

Charming highlights at LHCb including many 'firsts'

2013 — first observation of charm mixing by single experiment [PRL 110, 101802]

2017 — first observation doubly charmed baryon Ξ_{cc} [PRL 119, 112001]

2019 — first observation of CPV in charm decays [PRL 122, 211803]

2019 — observation of new charmonium state $\psi_3(3842)$ [JHEP 2019, 35]

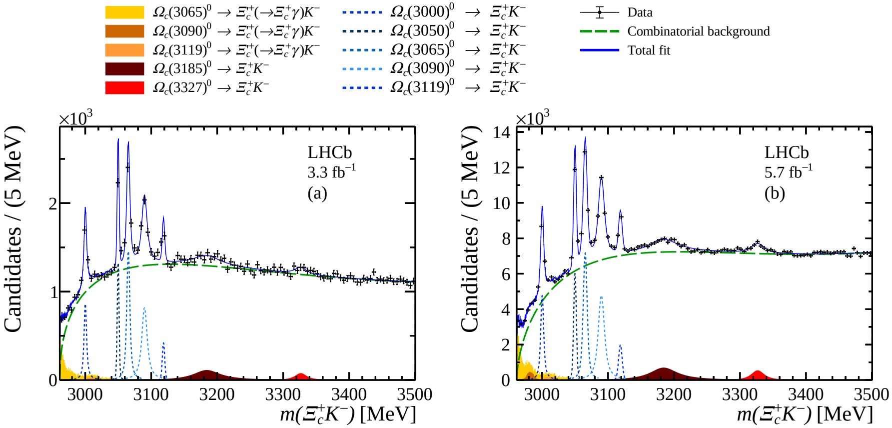
2021 — first observation of non-zero mass difference [PRL 127, 111801]

2023 — first evidence of direct CPV in a specific decay [PRL 131, 091802]

Charm baryons

[PRL 131, 131902 (2023)]

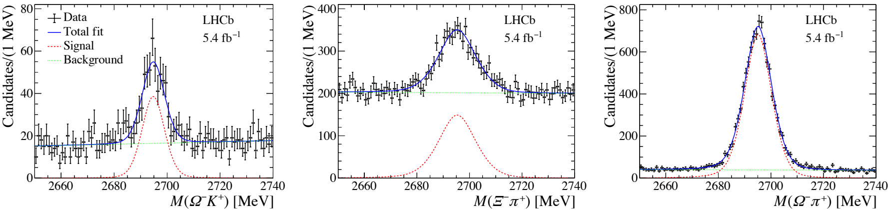
"Observation of new Ω_c^0 states decaying to the $\Xi_c^+ K^-$ final state" ($9\,\mathrm{fb}^{-1}$)



- 5× larger sample since previous measurement
- confirm previously found states [PRL 118, 182001 (2017)]

New broad states $\Omega_c^0(3185)^0$ and $\Omega_c^0(3327)^0$ with overwhelming significance

"Observation of Cabibbo-suppressed two-body hadronic decays and precision mass measurement of the Ω_c^0 baryon" ($5.4\,\mathrm{fb}^{-1}$)



- first observation of $\Omega_c^0 \to \Omega^- K^+$ and $\Omega_c^0 \to \Xi^- \pi^+$ decays

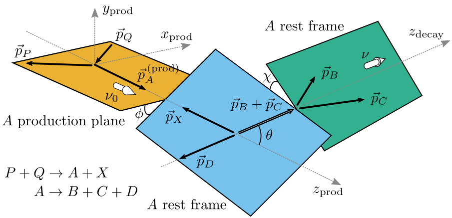
$$M(\Omega_c^0) = \quad 2695.28 \pm 0.07\,(\mathrm{stat}) \pm 0.27\,(\mathrm{syst}) \pm 0.30\,(\mathrm{ext})\,\mathrm{MeV}$$

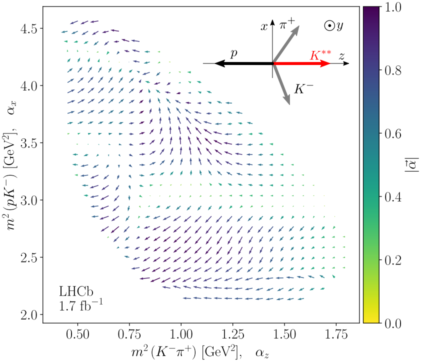
Improving precision of world average on $\mathrm{M}(\Omega_c^0)$ by factor 4 yielding in precision similar to other baryon masses

Perform amplitude analysis using $\Lambda_c^+ \to pK^-\pi^+$ decay and measure Λ_c^+ polarization [PRD 108 012023 (2023)]

- found 6 Λ^*, 3 Δ^*, 3 K^{*0} resonances contributing

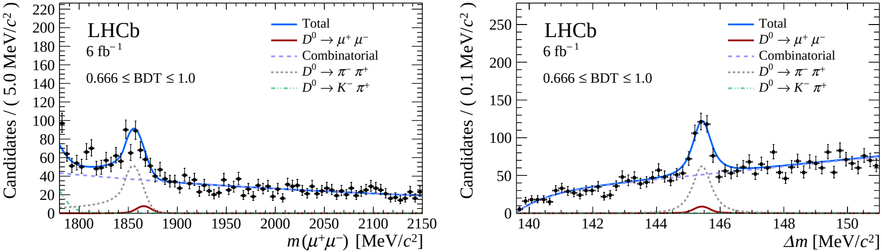
Model-agnostic representation [JHEP 2023, 228 (2023)]





Knowledge of resonant structure opens the way to searches for CP violation in baryon decays

"Search for rare decays of D^0 mesons into two muons" ($9\,\text{fb}^{-1}$)



- using $D^{*+} \to D^0\pi^+$
  - $\Delta m = m(D^{*+}) - m(D^0)$
- suppressed in Standard Model $\mathcal{O}(3 \times 10^{-13})$ [PRD 66, 014009 (2002)]
  - new physics contributions could enhance branching fraction
- background from mis-identified hadrons
- similar search with $\Lambda_c^+ \to p\mu^+\mu^-$ [PRD 97 091101 (2018)]

world's most stringent limit on BF
$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1\,(3.5) \times 10^{-9}$ at 90 (95)% CL

Mixing and CPV

A big part of the charm program at LHCb is mixing and CP violation (CPV)

- measure and characterize direct CPV
- search for CPV in mixing

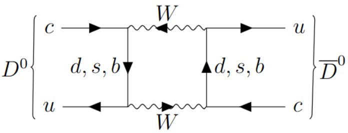
Why is that interesting?

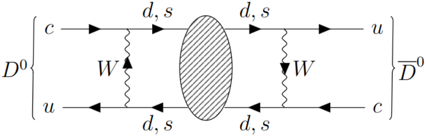
- measured amount of CPV can not account for matter-antimatter asymmetry
- CPV expected to be suppressed in Standard Model (10^{-4} to 10^{-3})
  - GIM mechanism and CKM elements $\mathcal{I}m(V_{cb}V_{ub}^{*}/V_{cs}V_{us}^{*}) \approx -6 \times 10^{-4}$

Precision CPV measurements can test SM at large energies

Mixing and CPV

D^0 flavour not conserved and oscillates to $\overline{D}^0$





$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left[\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}\right]\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

- $|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\overline{D}^0\rangle$
- dispersion $x = \frac{\Delta M}{\Gamma}$
- absorption $y = \frac{\Delta \Gamma}{2\Gamma}$

Expressed in CP conserving x_{12}, y_{12} parameters and CPV mixing phase ϕ_{12} [PRD 103, 053008 (2021)]

- $x_{12} = 2\left|M_{12}\right|/\Gamma$
- $y_{12} = 2\left|\Gamma_{12}\right|/\Gamma$
- $\phi_{12} = \arg\left(\frac{M_{12}}{\Gamma_{12}}\right) = \phi^M - \phi^\Gamma$
  - $\phi^M = \arg\left(M_{12}\right)$
  - $\phi^\Gamma = \arg\left(\Gamma_{12}\right)$

Mixing and CPV

Types of CPV

- CPV in decay

- CPV in mixing $|q/p| \neq 1$

- CPV in interference between mixing and decay $\phi \equiv \arg(q\bar{A}_f/pA_f) \neq 0$
  - ▶ $A_f = A(D^0 \to f)$

Mixing and CPV

To measure mixing, need to tag initial D^0 flavour

- $D^{*+} \to D^0\pi^+$
- $B \to \overline{D}^0\mu^+X$

When measuring asymmetries, need to carefully account for nuisance asymmetries

$$\mathcal{A}^{CP}(f,t) = \frac{\Gamma(D \to f,t) - \Gamma(\overline{D} \to \bar{f},t)}{\Gamma(D \to f,t) + \Gamma(\overline{D} \to \bar{f},t)}$$

We measure raw asymmetry

$$A_{\text{raw}}(f,t) \approx \mathcal{A}^{CP}(f,t) + A_{\text{det}}(f) + A_{\text{prod}}(D)$$

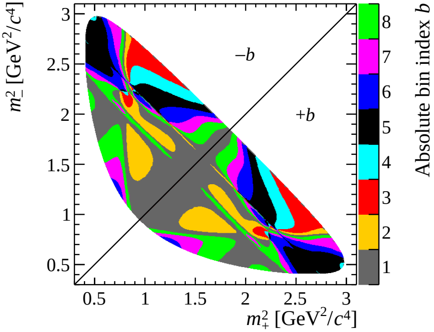
- $A_{\text{det}}(f)$ detection asymmetry
- $A_{\text{prod}}(D)$ production asymmetry

Need to calibrate nuisance asymmetries using control channels

- great care taken to keep systematic uncertainties low

Model-independent 'bin-flip' method [PRD 99, 012007 (2019)] using $D^0 \to K^0_S \pi^+ \pi^-$ decays

- divide phase-space into regions with constant strong-phase difference
  - relies on measurements by CLEO and BESIII [PRD 82, 112006 (2010)] [PRD 101, 112002 (2020)]
- measure ratio of negative and positive bins in decay-time intervals



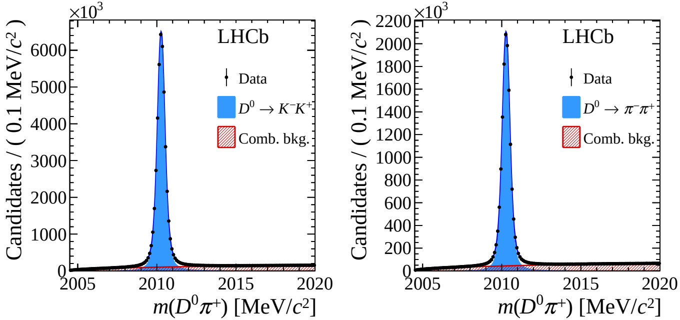
Method very sensitive to x

$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3}$$
$$y = (\ 4.6^{+1.5}_{-1.4}\ ) \times 10^{-3}$$
$$|q/p| = 0.996 \pm 0.052$$
$$\phi = -0.056^{+0.047}_{-0.051}$$

First observation of non-zero x

Measure difference in CP asymmetry between $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays $\Delta A_{CP} = A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$

- nuisance asymmetries cancel



- $\Delta A_{CP} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$ for π-tag
  - 44×10^6 $D^0 \to K^- K^+$, 14×10^6 $D^0 \to \pi^- \pi^+$
- $\Delta A_{CP} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$ for μ-tag
  - 9×10^6 $D^0 \to K^- K^+$, 3×10^6 $D^0 \to \pi^- \pi^+$

Combination with previous LHCb measurements $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$

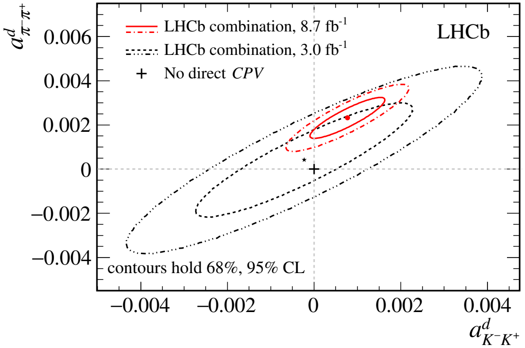
First observation of CPV in charm decays

Measure time-integrated asymmetry $A_{CP}(K^-K^+)$ with $D^0 \to K^-K^+$

- using $D^{*+} \to D^0\pi^+$

$A_{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}$

Use $A_{CP}(f) \approx a_f^d + \frac{\langle t \rangle_f}{\tau_D} \cdot \Delta Y_f$ with measured value of ΔY_f [PRD 104, 072010 (2021)] to extract direct CPV $a^d_{K^-K^+}$ and $a^d_{\pi^-\pi^+}$



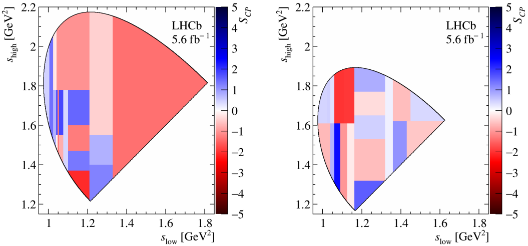
$a^d_{K^-K^+} = (\ 7.7 \pm 5.7) \times 10^{-4}$
$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$

First evidence for direct CPV in specific charm decay

Search for CPV with Miranda method [JHEP 2023, 67 (2023)]

"Search for CP violation in $D^+_{(s)} \to K^-K^+K^+$ decays" ($5.6\,\mathrm{fb}^{-1}$)

- search for direct CPV in (doubly-)Cabibbo-suppressed $D^+_{(s)}$ decays
  - 0.97×10^6 $D^+_s \to K^-K^+K^+$, 1.27×10^6 $D^+ \to K^-K^+K^+$
- model-independent technique in bins of Dalitz plot [PRD 80, 096006 (2009)]



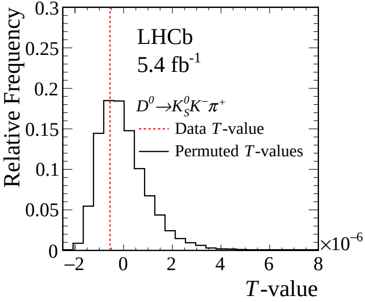
- fit $m(KKK)$ per bin
- significance $\mathcal{S}^i_{CP} = \dfrac{N^i(D^+_{(s)}) - \alpha N^i(D^-_{(s)})}{\sqrt{\alpha(\delta^2_{N^i(D^+_{(s)})} + \delta^2_{N^i(D^-_{(s)})})}}$

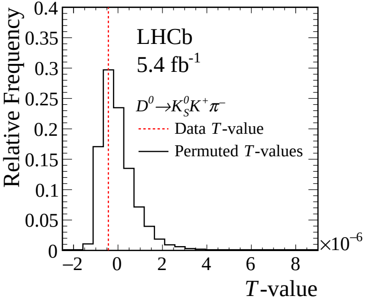
No evidence for CPV observed. CP conserved with p-values of 13.3% and 31.6%

Search for CPV with energy test [JHEP 2024, 107 (2024)]

"Search for CP violation in the phase space of $D^0 \to K^0_S K^{\pm}\pi^{\mp}$ decays with the energy test" (5.4 fb^{-1})

- 950×10^3 $D^0 \to K^0_S K^-\pi^+$, 620×10^3 $D^0 \to K^0_S K^+\pi^-$
- search for local CPV with unbinned, model-independent method [arXiv:1612.04705]
- quantify difference in phase space of two samples using test statistic

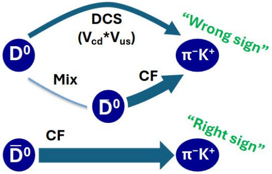




No evidence for local CPV. CP conserved with p-values of 70% and 66%

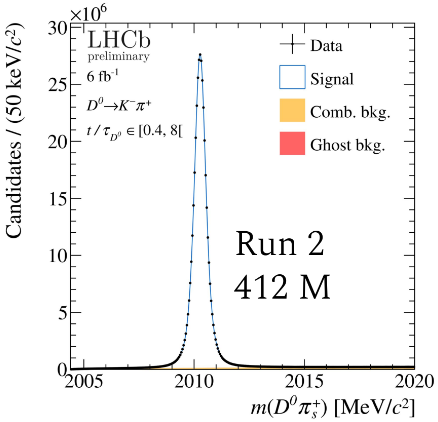
Measure ratio of DCS over CF $D^0 \to K\pi$ decays

- using full Run 2 data set
  - previous LHCb measurement [PRD 97, 031101 (2018)]
- D^0 flavour tagged by using $D^{*+} \to D^0\pi^+$ decay

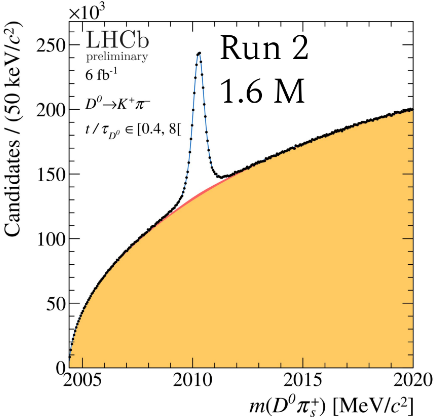


- use $D^0 \to K^+K^-$ mode to control nuisance asymmetries
  - known $\Delta Y_{K^+K^-}$, a^d_{KK} [PRD 104, 072010 (2021)] [PRL 131, 091802 (2023)]
- fit time-dependent wrong- and right-sign ratios

$$R^+_{K\pi}(t) \equiv \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D}^0(t) \to K^+\pi^-)} \quad \text{and} \quad R^-_{K\pi}(t) \equiv \frac{\Gamma(\overline{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}$$



×10^6
LHCb
preliminary
6 fb-1
$D^0 \to K^-\pi^+$
$t/\tau_{D^0} \in [0.4, 8[$
Data
Signal
Comb. bkg.
Ghost bkg.
Run 2
412 M
Candidates / (50 keV/c^2)
$m(D^0\pi_s^+)$ [MeV/c^2]
0
5
10
15
20
25
30
2005
2010
2015
2020



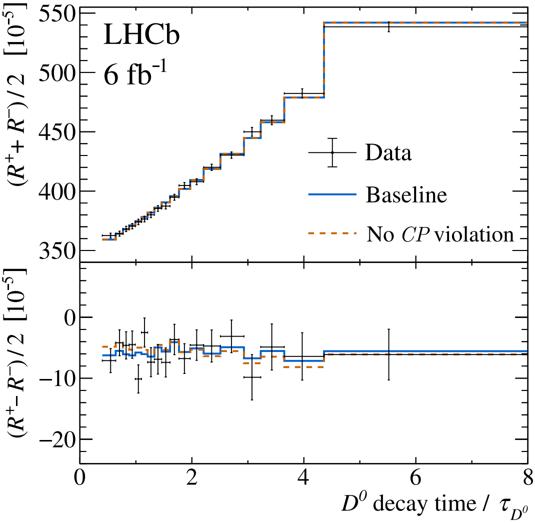
×10^3
LHCb
preliminary
6 fb-1
$D^0 \to K^+\pi^-$
$t/\tau_{D^0} \in [0.4, 8[$
Run 2
1.6 M
Candidates / (50 keV/c^2)
$m(D^0\pi_s^+)$ [MeV/c^2]
0
50
100
150
200
250
2005
2010
2015
2020

Expand ratio to extract parameters related to mixing and CPV

$$R^{\pm}_{K\pi}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})\,\frac{t}{\tau_{D^0}} + (c'_{K\pi} \pm \Delta c'_{K\pi})\,\left(\frac{t}{\tau_{D^0}}\right)^2$$

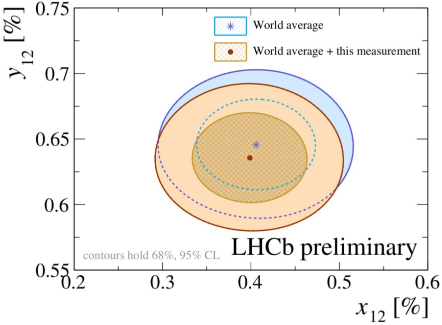
- $R_{K\pi}$: DCS/CF ratio
- mixing: $c_{K\pi}$, $c'_{K\pi}$
- CPV in decay: $A_{K\pi}$
  - sensitive null test of SM
- CPV in interference: $\Delta c_{K\pi}$
- CPV in mixing: $\Delta c'_{K\pi}$

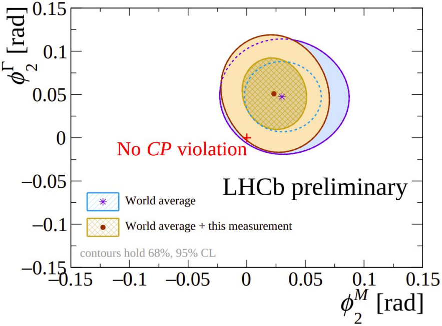
Parameters	
$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$



No evidence for CPV

Extract mixing and CPV parameters

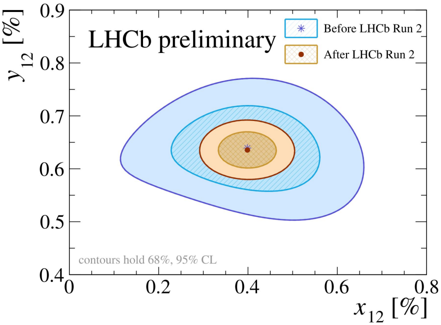


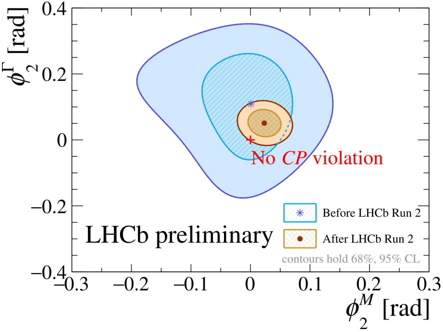


- $c_{K\pi} \approx y_{12} \cos\phi_2^\Gamma \cos\Delta_{K\pi} + x_{12}\cos\phi_2^M \sin\Delta_{K\pi}$
- $c'_{K\pi} \approx \frac{1}{4}\left(x_{12}^2 + y_{12}^2\right)$
- $\Delta c_{K\pi} \approx x_{12}\sin\phi_2^M \cos\Delta_{K\pi} - y_{12}\sin\phi_2^\Gamma \sin\Delta_{K\pi}$
- $\Delta c'_{K\pi} \approx \frac{1}{2} x_{12} y_{12} \sin(\phi_2^M - \phi_2^\Gamma)$

using strong phase difference $\Delta_{K\pi} = -10^\circ \pm 3^\circ$ (from LHCb, CLEO, BESIII)

LHCb Run 2 very impactful, but many measurement still statistically limited



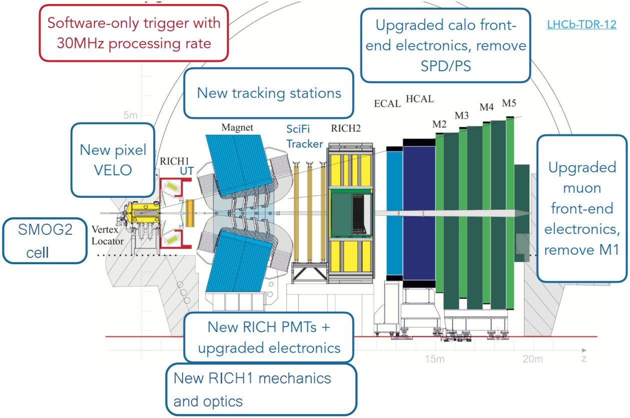


Can we do better?

Charm@LHCb Upgrade I

Virtually new detector!

- aim to collect $\approx 50\,\text{fb}^{-1}$



[LHCb-TDR-12][arXiv:2305.10515]

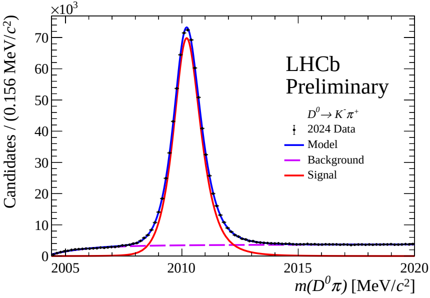
Taking data right now!

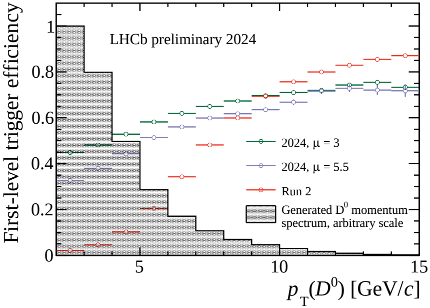
Hardware-level trigger limiting factor for hadronic decay modes in Run 1+2

- removed in Upgrade I

Fully software-based trigger processing events at 30 MHz

- first stage on GPUs



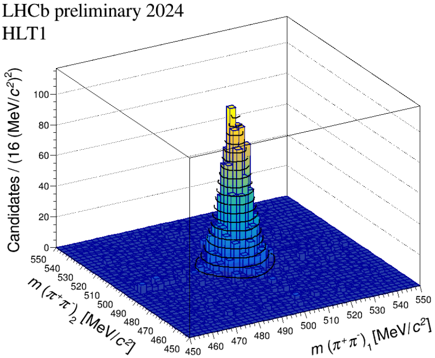


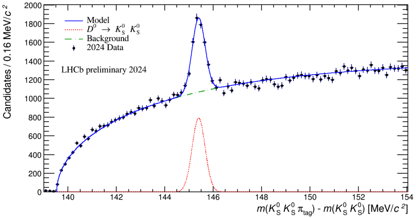
[LHCB-FIGURE-2024-006]

Improvements in trigger efficiency already evident

Software trigger allows flexible selections

- single and pair-wise K^0_S reconstructed and selected in first trigger stage
- already about $\times 3.7$ more $D^0 \to K^0_S K^0_S$ per pb^{-1} w.r.t Run 2





[LHCB-FIGURE-2024-008]

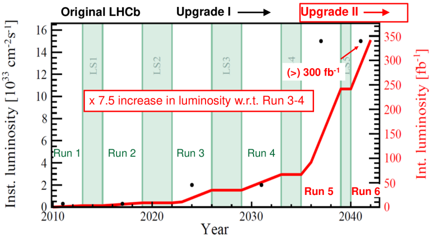
[LHCB-FIGURE-2024-013]

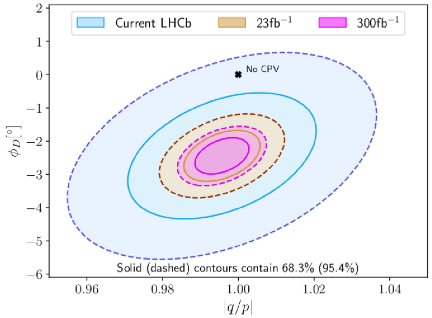
Run 2: $\mathcal{A}^{CP}(D^0 \to K^0_S K^0_S) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$ [PRD 104, 031102 (2021)]

Charm@LHCb Upgrade II

Upgrade II is key to ultimate precision

- aim to collect 300 fb^{-1}





[LHCb-PUB-2022-012]

CPV in mixing at 5σ within reach

Summary

LHCb Run 1+2 delivered many contributions to our understanding of charm

- many key measurements performed with full sample
  - more to come: search for CPV using three- and four-body decays and baryons

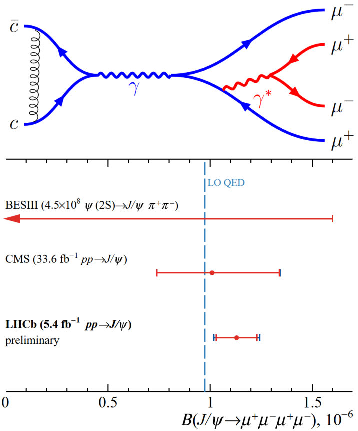
LHCb Upgrade I will further improve statistically limited measurements

- novel software-level trigger greatly increases charm yields

LHCb Upgrade II will achieve ultimate precision in charm sector

- observation of CPV in mixing possible

Thank you for your attention!



Observation of $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ by CMS [arXiv:2403.11352] and LHCb [LHCb-CONF-2024-001]

Happy anniversary Charm!

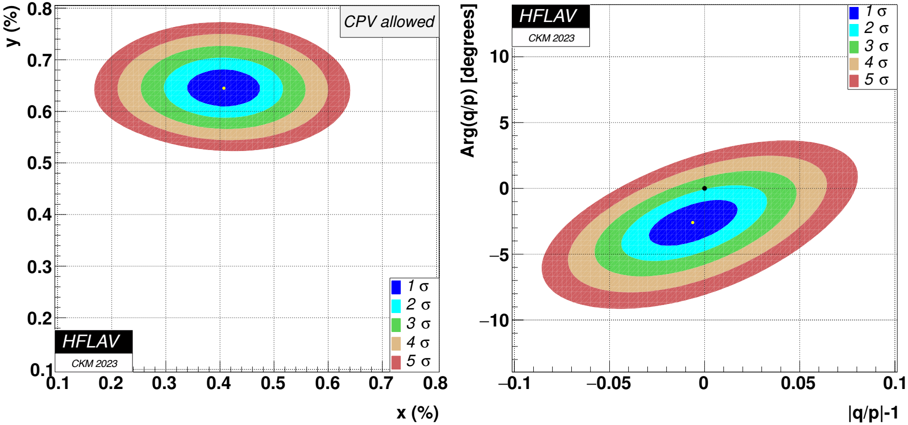
Back-up

Systematic uncertainties for the Ω_c^0 mass measurement.

Source	Uncertainty [MeV]
Momentum scale calibration	0.27
Energy loss correction	0.03
Fit model	0.01
Total	0.27
External input masses	0.30

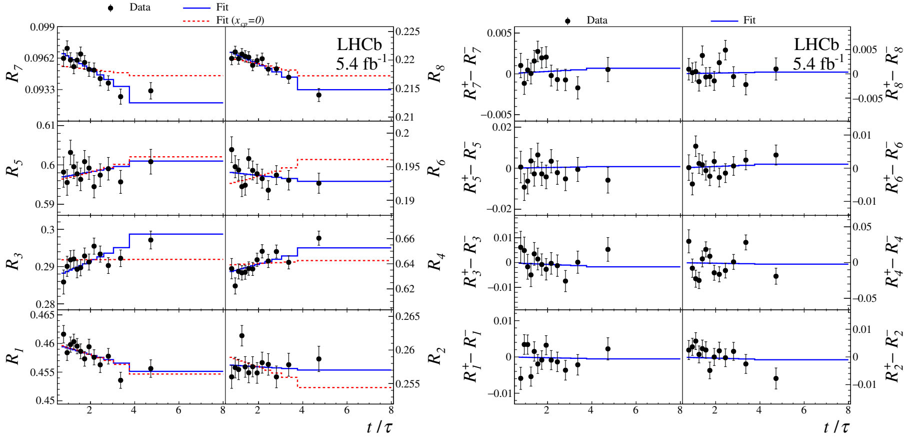
Systematic uncertainties (in percentages) for the BF ratio measurement.

Source	$\mathcal{B}(\Omega^- K^+)/\mathcal{B}(\Omega^-\pi^+)$	$\mathcal{B}(\Xi^-\pi^+)/\mathcal{B}(\Omega^-\pi^+)$
Tracking efficiency	1.78	1.78
PID efficiency	3.37	0.62
Trigger efficiency	1.26	0.69
Fit model	0.16	0.54
Decay model	3.59	1.32
Lifetimes of Ω^- and Ξ^-		0.59
Simulation sample size	0.07	0.08
Reweight strategy	2.82	0.52
Mass resolution	2.35	0.97
Total	6.51	2.76
External input BFs		1.04


CPV allowed
y (%)
x (%)
HFLAV
CKM 2023
1 σ
2 σ
3 σ
4 σ
5 σ
Arg(q/p) [degrees]
|q/p|-1
HFLAV
CKM 2023
1 σ
2 σ
3 σ
4 σ
5 σ

[HFLAV]

Model-independent ‘bin-flip’ method using $D^0 \to K^0_S\pi^+\pi^-$ decays

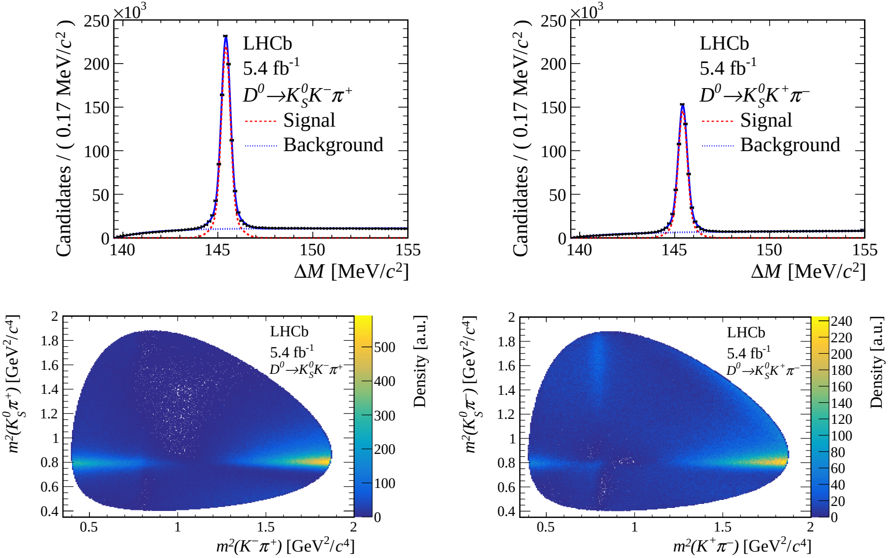


"Search for CP violation in the phase space of $D^0 \to K^0_\mathrm{S} K^\pm \pi^\mp$ *decays with the energy test"* ($5.4\,\mathrm{fb}^{-1}$)

- search for local CPV with unbinned, model-independent method
- quantify difference in phase space of two samples using test statistic

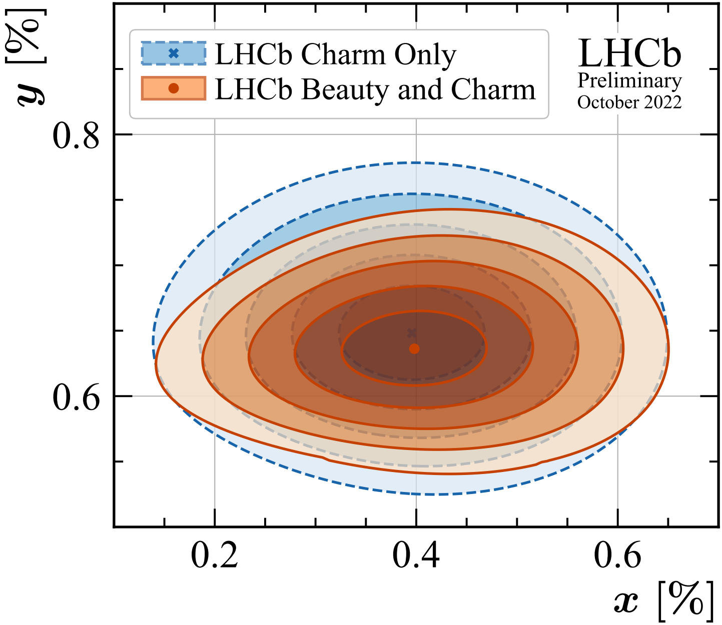
$$T \equiv \frac{1}{2n(n-1)} \sum_{i,j\neq i}^{n} \psi_{ij} + \frac{1}{2\bar{n}(\bar{n}-1)} \sum_{i,j\neq i}^{\bar{n}} \psi_{ij} - \frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi_{ij}.$$

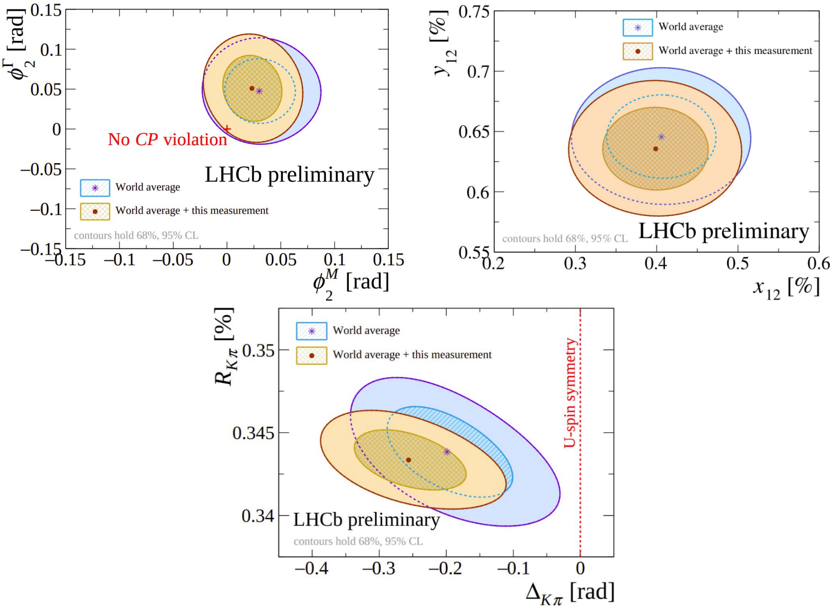
function ψ_{ij} provides a weight to each pair of candidates, and is taken to be $\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$, where $d_{ij}^2 = (s_{12,i} - s_{12,j})^2 + (s_{13,i} - s_{13,j})^2 + (s_{23,i} - s_{23,j})^2$



LHCb
5.4 fb-1
$D^0 \to K_S^0 K^- \pi^+$
Signal
Background
Candidates / (0.17 MeV/c^2)
ΔM [MeV/c^2]
LHCb
5.4 fb-1
$D^0 \to K_S^0 K^+ \pi^-$
Signal
Background
Candidates / (0.17 MeV/c^2)
ΔM [MeV/c^2]
LHCb
5.4 fb-1
$D^0 \to K_S^0 K^- \pi^+$
$m^2(K_S^0 \pi^+)$ [GeV$^2/c^4$]
$m^2(K^- \pi^+)$ [GeV$^2/c^4$]
Density [a.u.]
LHCb
5.4 fb-1
$D^0 \to K_S^0 K^+ \pi^-$
$m^2(K_S^0 \pi^-)$ [GeV$^2/c^4$]
$m^2(K^+ \pi^-)$ [GeV$^2/c^4$]
Density [a.u.]

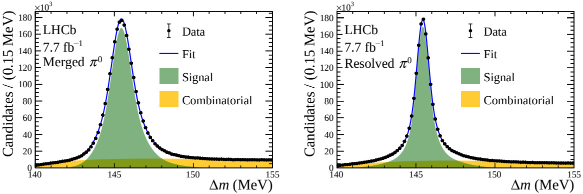
Mixing and CPV





ϕ_2^Γ [rad]
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
No CP violation
LHCb preliminary
World average
World average + this measurement
contours hold 68%, 95% CL
−0.15
−0.1
−0.05
0
0.05
0.1
0.15
ϕ_2^M [rad]
y_{12} [%]
0.75
0.7
0.65
0.6
0.55
World average
World average + this measurement
contours hold 68%, 95% CL
LHCb preliminary
0.2
0.3
0.4
0.5
0.6
x_{12} [%]
$R_{K\pi}$ [%]
0.35
0.345
0.34
World average
World average + this measurement
U-spin symmetry
LHCb preliminary
contours hold 68%, 95% CL
−0.4
−0.3
−0.2
−0.1
0
$\Delta_{K\pi}$ [rad]

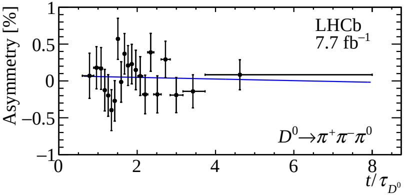
"Search for time-dependent CP violation in $D^0 \to \pi^+\pi^-\pi^0$ decays" ($7.7\,\text{fb}^{-1}$)



- using $D^{*+} \to D^0\pi^+$
  - 2.3×10^6 merged, 1.5×10^6 resolved
  - $\Delta m = m(D^{*+}) - m(D^0)$

$$A_{CP}(f_{CP}, t) \equiv \frac{\Gamma_{D^0\to f_{CP}}(t) - \Gamma_{\bar{D}^0\to f_{CP}}(t)}{\Gamma_{D^0\to f_{CP}}(t) + \Gamma_{\bar{D}^0\to f_{CP}}(t)}$$

$$\approx a^{\text{dir}}_{f_{CP}} + \Delta Y_{f_{CP}} \frac{t}{\tau_{D^0}}.$$



no CPV: $\Delta Y_{\pi^+\pi^-\pi^0} = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$