CPV and mixing in Charm

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On behalf of the LHCb collaboration

2024 Implications Workshop
23-25 October 2024

Charmed hadrons

Unique role of charmed hadron decays in flavor physics

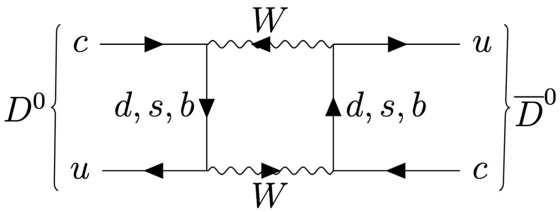
Only access to mixing and CPV involving **up-type quark**

Mixing and CPV highly suppressed at the SM level

Strong GIM suppression
(m_b << m_t)

+

CPV highly suppressed
(CKM hierarchy)



$$CPV \propto \mathrm{Im}\left(\frac{V_{cb}V^*_{bu}}{V_{cs}V^*_{su}}\right) \approx -6 \times 10^{-4}$$

↓

High sensitivity to BSM effects with SM null-tests

Past and present experiments

Charmed hadron properties extensively studied in the past decades

Several experiments involved, different facilities

CLEO

CLEO I.5

CLEO II

CLEO II.V

CLEO III

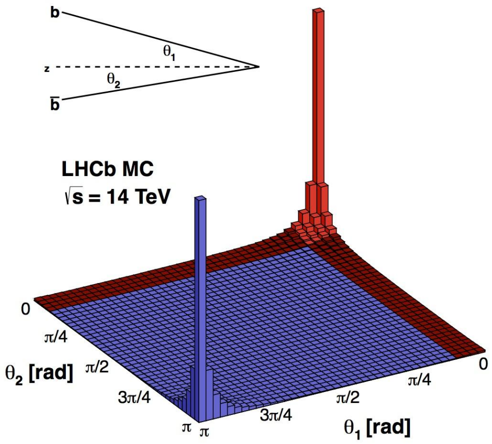
The LHCb experiment

LHCb has the perfect environment to study charm decays:

- $\sigma(pp \longrightarrow charm\ X) \times L_{\text{inst}}$ (Run 2) **∼1 MHz**
- large **acceptance** for b/c hadron decays with forward geometry
- precision **tracking** + **vertexing**
  ⟶ disentangle signal from background
- high quality **particle identification**
  ⟶ separate different hadrons species

(see previous talk by Patrick for an LHCb overview)

LHCb able to collect hundreds of millions of charm decays
⟶ measure the tiny expected effects



Int.J.Mod.Phys.A 30 (2015) 07, 1530022

What do we measure?

Time-dependent CP asymmetry → two contributions

$$A_{CP}(f,t) \equiv \frac{\Gamma(D^0 \to f,t) - \Gamma(\overline{D}^0 \to f,t)}{\Gamma(D^0 \to f,t) + \Gamma(\overline{D}^0 \to f,t)} \approx a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}}$$

CP asymmetry in the decay - time independent

Time-dependent CP asymmetry

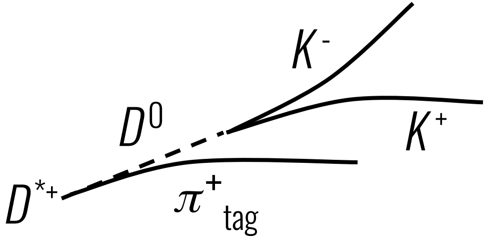
Or its **time-integrated** counterpart

$$A_{CP}(f) \approx a_f^d + \Delta Y_f \frac{\langle t \rangle_f}{\tau_{D^0}}$$

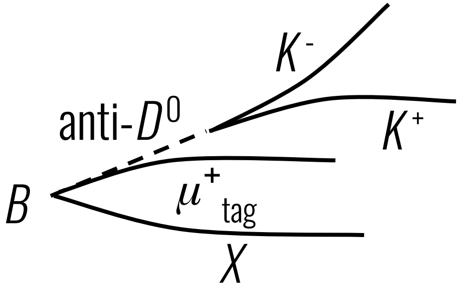
CP asymmetry integrated over all decay times

How do we measure A_{CP}?

Tag the flavor of the decaying hadron



D^{*+}-tagged



μ-tagged

Infer D flavor exploiting sign of π_{tag} or μ_{tag}

Two "nuisance" asymmetries appear:

- D^*/B production asymmetry
  → different probability for D^{*+}/D^{*-} B/anti-B
- final state detection asymmetry
  → asymmetric response of the detector

Experimental access to ***raw* asymmetry**

$$A_{\rm raw}(f,t) \approx A_{CP}(f,t) + A_{\rm det}(f) + A_{\rm prod}(D)$$

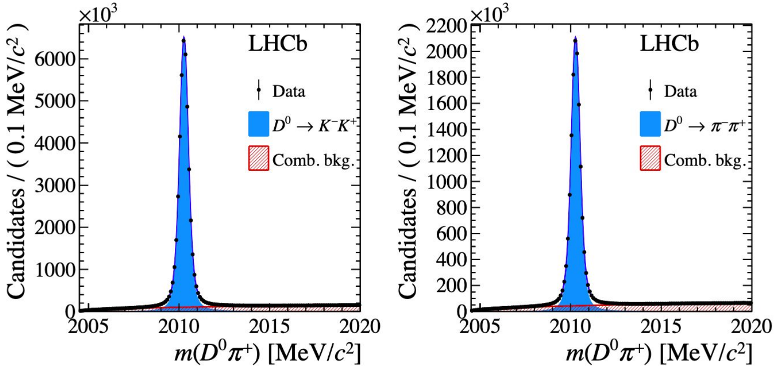
A_{det} and A_{prod} disentangled with a "**calibration channel**"
(process with same A_{det} and A_{prod} as signal)
↓
subtract the two A_{raw} to extract A_{CP}

Direct CPV

Two body decays: $D^0 \to h^+h^-$

$D^0 \to h^+h^-$ decays golden channel in LHCb
→ exploited in **discovery of CPV in Charm decays** in 2019

$$\Delta \mathcal{A}^{CP} = \mathcal{A}^{CP}(K^+K^-) - \mathcal{A}^{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$$



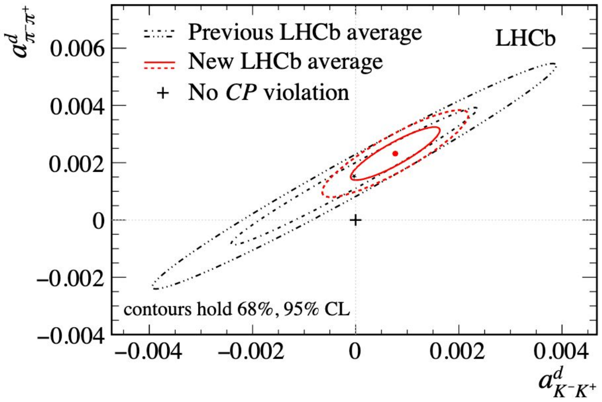
Phys.Rev.Lett. 122 (2019) 21, 211803

Recent measurement improved precision on $\mathbf{A_{CP}(K^+K^-)}$
→ disentangle CPV in K^+K^- and $\pi^+\pi^-$

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

Measure U-spin breaking size

3.8 σ → first evidence of charm CPV in a single channel



Phys.Rev.Lett. 131 (2023) 21,091802

Multibody decays: $D^+ \to K^+ K^- \pi^+$

Strong-phase variation across Dalitz plot → Possible local asymmetries enhancement

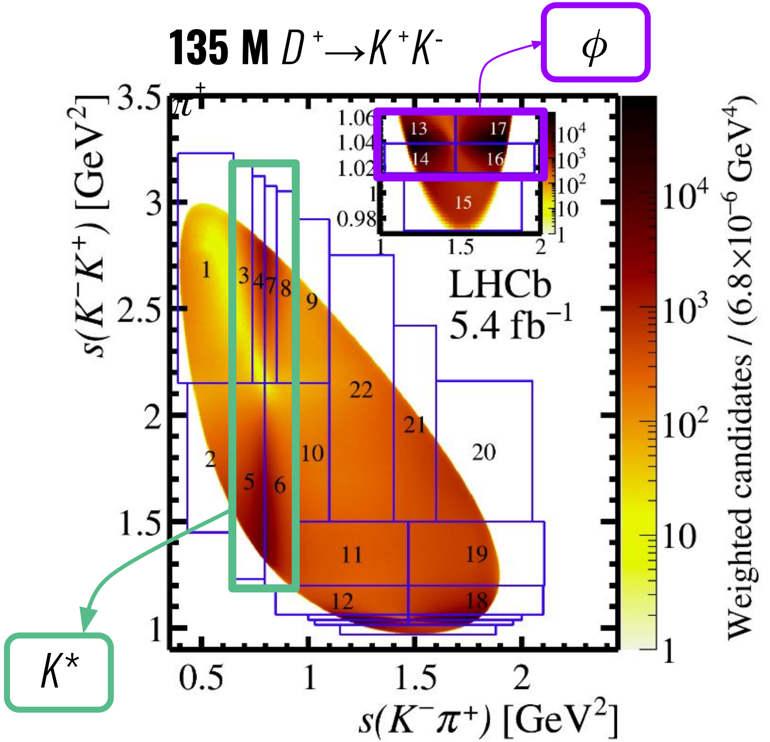
$D^+ \to K^+ K^- \pi^+$ is the singly Cabibbo-suppressed decay with largest *BF*
→ diagrams similar to $D^0 \to K^+ K^-$ - **similar A_{CP} size?**

We measure A_{CP} around K^* and ϕ resonances:

$$A_{CP|S} = \frac{1}{2}\left[\left(\Delta A_{\rm raw}^{\rm top\text{-}left} + \Delta A_{\rm raw}^{\rm bottom\text{-}right}\right) - \left(\Delta A_{\rm raw}^{\rm top\text{-}right} + \Delta A_{\rm raw}^{\rm bottom\text{-}left}\right)\right]$$

A_{CP} expected to change sign crossing resonance vertically and horizontally
Phys. Rev. D 78, 072003

$$A_{CP|S}^{\phi\pi^+} = (0.95 \pm 0.43 \pm 0.26) \times 10^{-3}$$
$$A_{CP|S}^{\overline{K}^{*0}K^+} = (-0.26 \pm 0.56 \pm 0.18) \times 10^{-3}$$



Most precise search through phase space of a multibody decay

Multibody decays: $D^+ \to K^+ K^- \pi^+$

arXiv:2409.01414

Simultaneous model-independent search→ any difference between D^+ and D^- amplitudes across all Dalitz plot

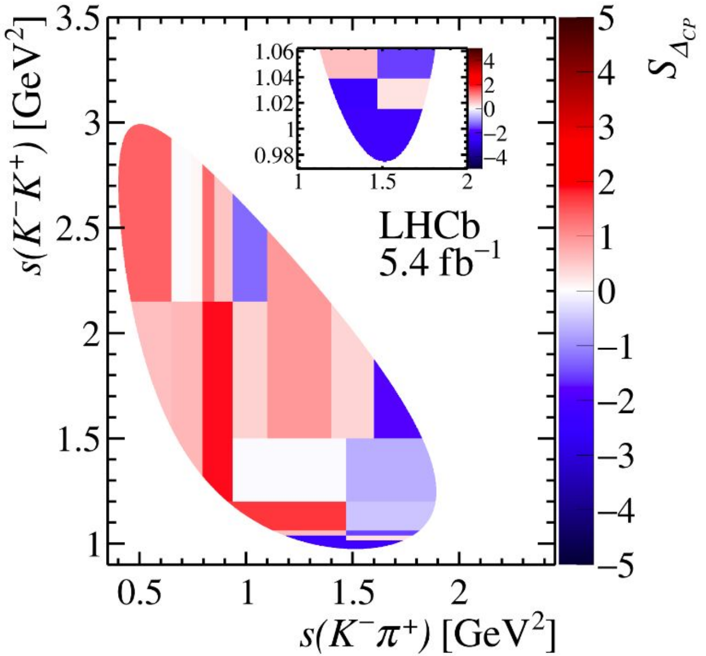
CP asymmetry significance measured in Dalitz-plot bins

$$\Delta A^i_{CP} = A^{i,S}_{\text{raw}} - A^{i,C}_{\text{raw}} - \Delta A^{\text{global}}_{\text{raw}} \qquad \mathcal{S}^i_{\Delta_{CP}} = \frac{\Delta A^i}{\sigma_{\Delta A^i}}$$

Hypothesis of no local CP violation is tested with

$$\chi^2(\mathcal{S}_{\Delta_{CP}}) = \sum_i^{N_{bins}} (\mathcal{S}^i_{\Delta_{CP}})^2$$

p-value for CP conservation hypothesis is 8.1%



No CPV evidence for both methods:

- sub-10^{-3} precision reached ~$\sigma(A_{CP}(K^+K^-))$
- $A_{CP}(K^+K^-)$ vs $A_{CP}(\pi^+\pi^-)$ suggesting a larger CPV size in $\pi^+\pi^-$ diagram

→ similar search with $D^+ \to \pi^+\pi^-\pi^+$ final state ongoing

Mixing
and
time-dependent CPV

D^0 mixing in a nutshell

D^0 time evolutions described by

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

Off shell transitions
↓
Sensitive to new physics

On shell transitions

Mixing parameters

$$x_{12} \equiv 2|M_{12}|/\Gamma$$

$$y_{12} \equiv |\Gamma_{12}|/\Gamma$$

CPV in mixing by mixing phases

$$\phi_2^M \sim \arg\left(M_{12}\right)$$

$$\phi_2^\Gamma \sim \arg\left(\Gamma_{12}\right)$$

Mixing with $D^0 \to K^+\pi^-$ decays

arXiv:2407.18001

New mixing + CPV measurement with full Run 2 dataset

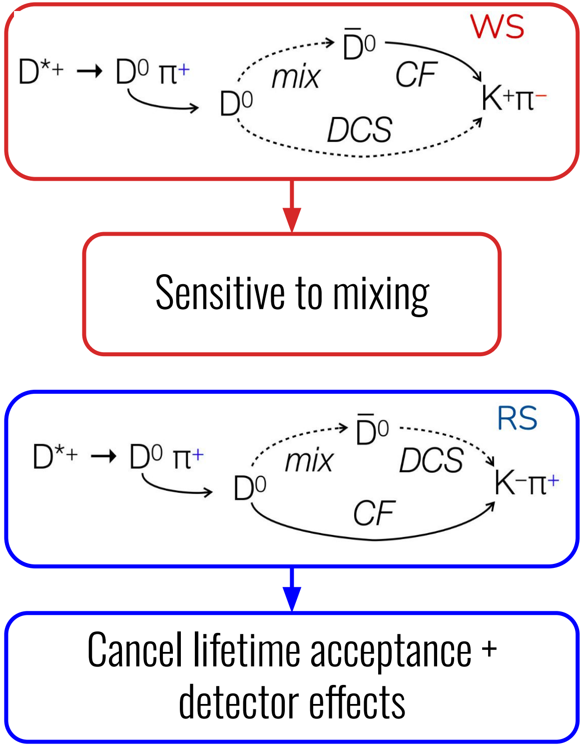
Measure ratio between:

- $D^{*+} \to D^0(\to K^+\pi^-)\pi^+$ → Wrong Sign (WS)
- $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ → Right Sign (RS)

(promptly produced D^{*+})

Separately measured for the two decay configurations:

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



Mixing with $D^0 \to K^+\pi^-$ decays

arXiv:2407.18001

$R_{K\pi}$ time evolution is

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

Mixing observables

$$c_{K\pi} \simeq y_{12} \cos\phi^{\Gamma}_{K\pi} \cos\delta_{K\pi} - x_{12} \cos\phi^{M}_{K\pi} \sin\delta_{K\pi}$$

$$c'_{K\pi} \simeq \frac{1}{4}\left(x_{12}^2 + y_{12}^2\right)$$

Strong phase difference $\delta_{K\pi}$ = 10°± 3°

LHCb-CONF-2022-002, Phys. Rev. D 86, 112001, Eur. Phys. J. C 82, 1009 (2022)

CPV observables

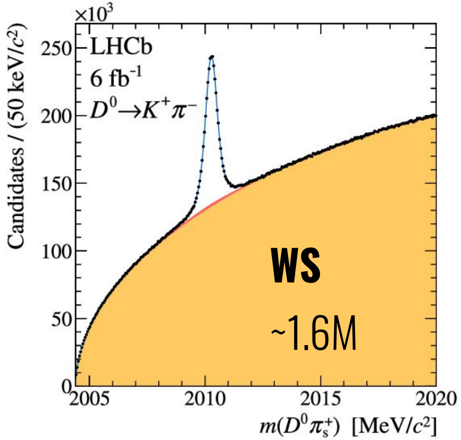
$$\mathcal{A}_{K\pi} = a^d_{WS} + a^d_{RS}$$

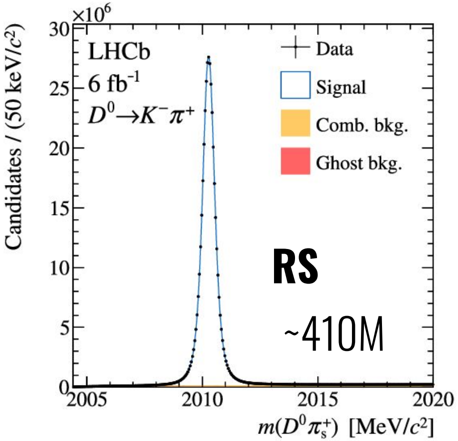
$$\Delta c_{K\pi} \simeq x_{12}\phi^M_{K\pi} \cos\delta_{K\pi} + y_{12}\phi^{\Gamma}_{K\pi} \sin\delta_{K\pi}$$

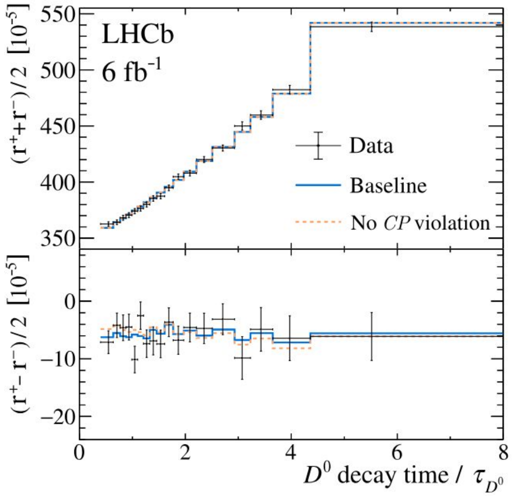
$$\Delta c'_{K\pi} \simeq \frac{1}{2} x_{12} y_{12} (\phi^M_{K\pi} - \phi^{\Gamma}_{K\pi})$$

Mixing with $D^0 \to K^+\pi^-$ decays

arXiv:2407.18001



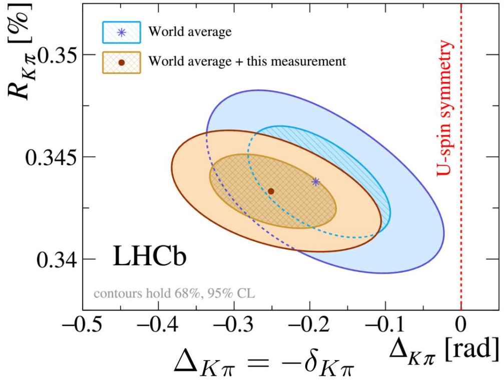




$$R_{K\pi} \quad (343.1 \pm 2.0) \times 10^{-5}$$
$$c_{K\pi} \quad (51.4 \pm 3.5) \times 10^{-4}$$
$$c'_{K\pi} \quad (13.1 \pm 3.7) \times 10^{-6}$$
$$A_{K\pi} \quad (-7.1 \pm 6.0) \times 10^{-3}$$
$$\Delta c_{K\pi} \quad (3.0 \pm 3.6) \times 10^{-4}$$
$$\Delta c'_{K\pi} \quad (-1.9 \pm 3.8) \times 10^{-6}$$

σ_{stat} down by x1.6
σ_{syst} down by x2
wrt PRD97,031101

No CP violation effects



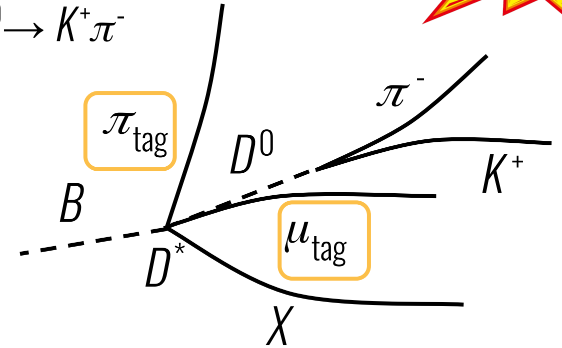
Mixing - double-tagged decays

LHCb-PAPER-2024-044
(In preparation)

NEW!

Mixing + CPV parameters performed by LHCb also with *double-tagged* (DT) $D^0 \to K^+\pi^-$

Just approved!

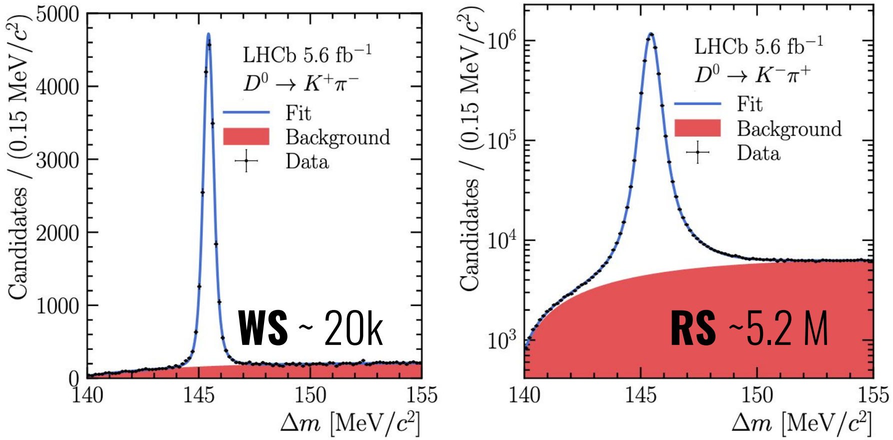


Complementary to measurement with prompt sample

↓

Larger acceptance at lower decay time

Different systematic uncertainties



Double-tagged results

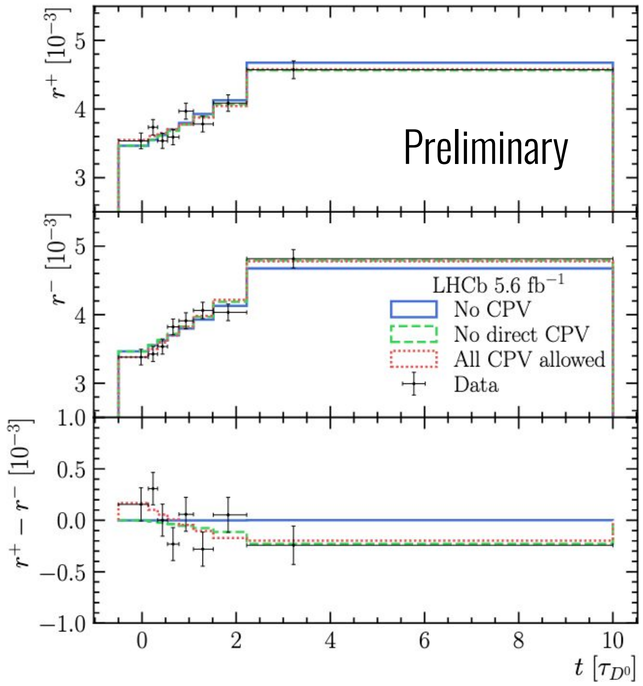
LHCb-PAPER-2024-044
(In preparation)

NEW!

WS/RS ratio is measured as before (slightly different parametrization)

$$R^{\pm}(t) = \frac{N^{\pm}_{WS}(t)}{N^{\pm}_{RS}(t)} = R^{\pm}_D + \sqrt{R^{\pm}_D}\, y'^{\pm} \left(\frac{t}{\tau}\right) + \frac{x'^{2\pm} + y'^{\pm 2}}{4} \left(\frac{t}{\tau}\right)^2$$

	Value	Statistical	Systematic
Mixing only			
R_D [10^{-3}]	3.47	0.06	0.01
y' [10^{-3}]	5.84	1.62	0.16
$(x')^2$ [10^{-5}]	0.04	12.25	1.06
All CPV allowed			
R_D^+ [10^{-3}]	3.55	0.08	0.02
y'^+ [10^{-3}]	3.56	2.23	0.26
$(x'^+)^2$ [10^{-5}]	10.86	16.17	1.35
R_D^- [10^{-3}]	3.39	0.08	0.02
y'^- [10^{-3}]	8.11	2.34	0.28
$(x'^-)^2$ [10^{-5}]	−11.29	18.55	1.28



(Results with prompt sample parametrization will also be added to the paper)

Charm + γ combination

LHCb-CONF-2024-004

CKM angle γ, Charm mixing and CPV parameters measurements included in a single fit
$\rightarrow$ improves precision on single observables exploiting full information

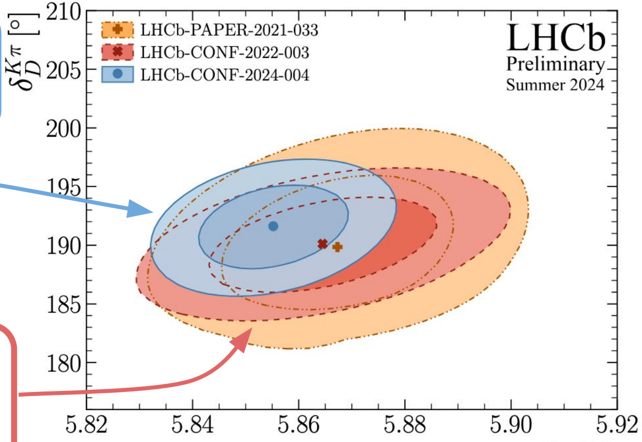
Previous combinations
LHCb-CONF-2022-003
JHEP 12 (2021) 141

New update to the combination just published (LHCb-CONF-2024-004)
$\rightarrow$ 9 new LHCb measurements included (2023-2024)
(Double-tagged $D^0 \rightarrow K^+\pi^-$ not included)

$$x = (0.41 \pm 0.05)\%$$
$$y = (0.621^{+0.022}_{-0.021})\%$$
$$|q/p| = 0.989 \pm 0.015$$
$$\phi = (-2.5 \pm 1.2)^\circ$$
$$\delta_D^{K\pi} = (191.6^{+2.4}_{-2.5})^\circ$$
$$a^d_{\pi^+\pi^-} = (22 \pm 6) \times 10^{-4}$$
$$a^d_{K^+K^-} = (6^{+6}_{-5}) \times 10^{-4}$$
$$\gamma = (64.6 \pm 2.8)^\circ$$

4.5σ deviation from U-spin symmetry

Previous determination is $\delta_D^{K\pi} = (190.2 \pm 2.8)^\circ$



$r_D^{K\pi} = \sqrt{R_D}$

a^d_{DCS} = 0 constraint

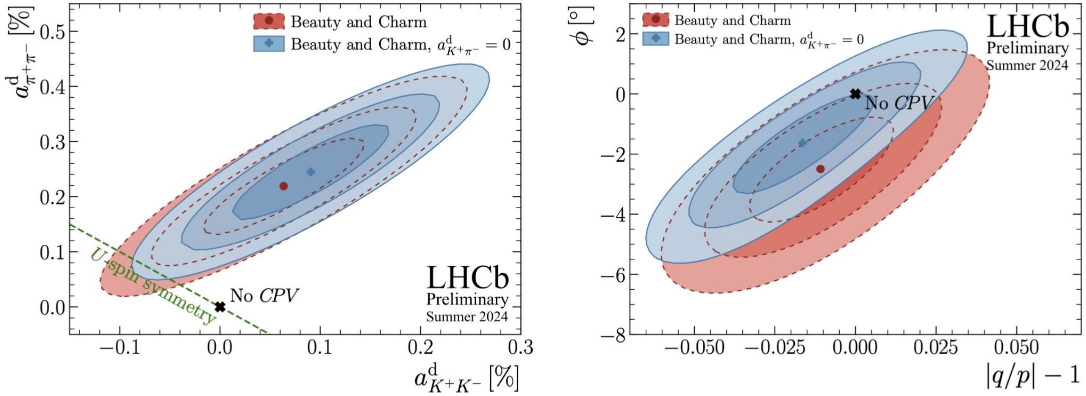
Novelty of latest update is a^d_{DCS} = 0 constraint application

Expected CPV for DCS within SM is 0 → only one amplitude contributing to decay

Fit is repeated applying external constraint to a^d_{DCS}
→ improved sensitivity to charm CPV observables

Enhancing $\pi^+\pi^-$ CPV evidence!

$$x = (0.41 \pm 0.05)\%$$
$$y = (0.619 \pm 0.021)\%$$
$$|q/p| = 0.984^{+0.014}_{-0.015}$$
$$\phi = (-1.6^{+1.1}_{-1.2})^\circ$$
$$a^d_{\pi^+\pi^-} = (24 \pm 6) \times 10^{-4}$$
$$a^d_{K^+K^-} = (9 \pm 5) \times 10^{-4}$$
$$\delta_D^{K\pi} = (191.4 \pm 2.4)^\circ$$



LHCb upgrade

Data hunger

All reported measurements are **statistically limited**

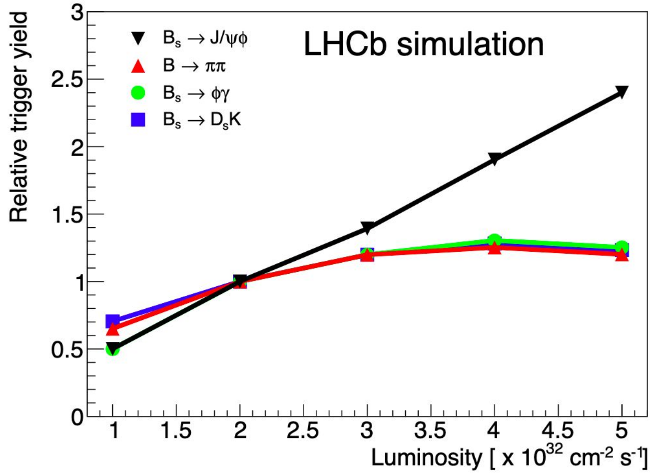
Larger dataset to improve precision

↓

Increase data acquisition rate

LHCb went through a major upgrade (*JINST* 19 (2024) 05, P05065):
- **x5** instantaneous luminosity increase wrt Run 2
- increase trigger efficiency
  (more signal events with same data)

No-upgrade scenario



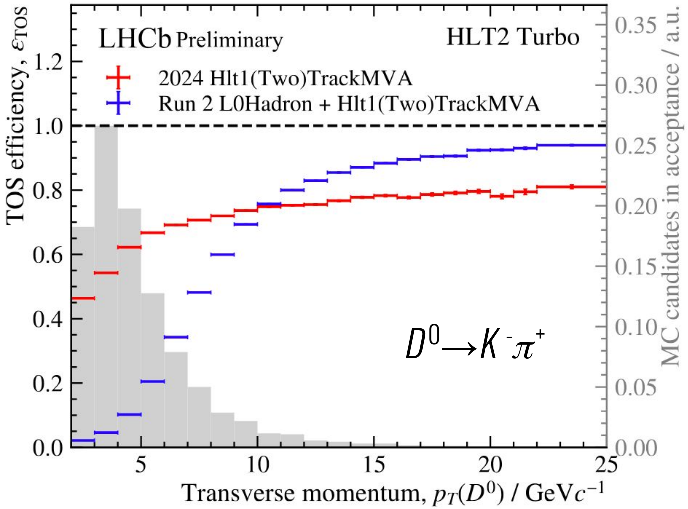
JINST 19 (2024) 05, P05065

Trigger efficiency for Charm decays limited in Run 2 by first hardware-level trigger thresholds (lower p_T wrt Beauty)

Upgraded trigger performances

We started taking data at nominal luminosity with upgraded system
→ expected improvements verified on data

LHCB-FIGURE-2024-030



Major **trigger efficiency increase** for hadronic final-state charm decays

Variety of channels involved:

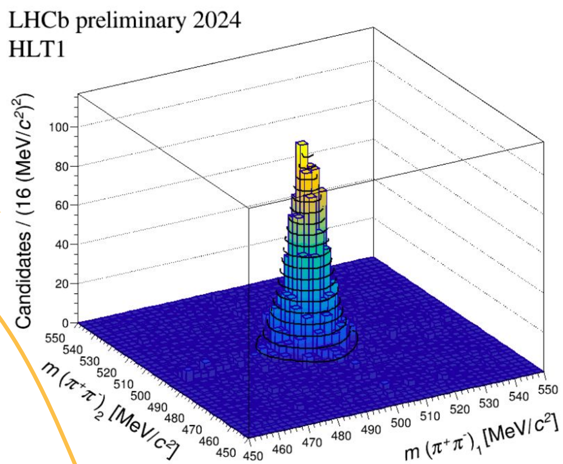
- $D^0 \to KK$, $D^0 \to \pi\pi$ → ΔA_{CP}, $A_{CP}(KK)$, $A_{CP}(\pi\pi)$
- $D^+_{(S)} \to 3h$ → multibody CPV
- $D^0 \to K\pi$ → mixing
- $D^0 \to K_S^0 \pi\pi$ → CPV + mixing Phys. Rev. Lett. 127 (2021) 111801

First level K_S^0 triggering

K_S^0 and K_S^0 pairs selections at first trigger level with novel system

$\rightarrow$ commissioned and fully operational

LHCB-FIGURE-2024-013



Increase K_S^0 final state trigger efficiency

- $D^0 \rightarrow K_S^0 K_S^0 \rightarrow A_{CP}(K_S^0 K_S^0)$

  $\rightarrow$ limited yield in Run 2 because of trigger

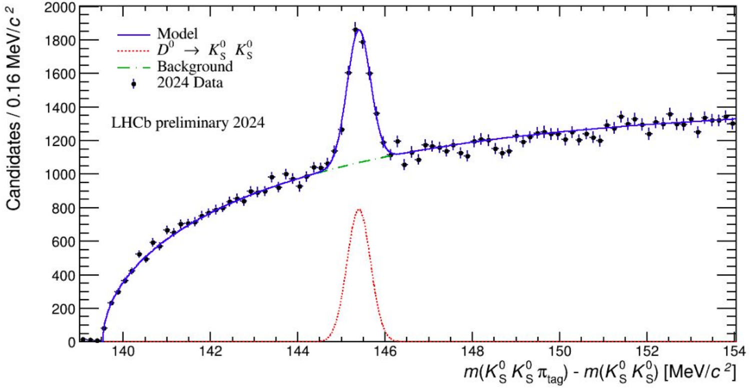
  Phys. Rev. D 104 , L031102 (2021)

- $D^0 \rightarrow K_S^0 \pi\pi \rightarrow$ select decays w/o requirement on π pair

  $\rightarrow$ help reduce systematic due to efficiency variation across Dalitz plot (biggest in previous analysis)

  Phys. Rev. Lett. 127 (2021) 111801

LHCB-FIGURE-2024-008



Summary

LHCb on the front line of Charm physics since years:

- discovery of Charm CPV in 2019 with ΔA_{CP}

World-leading results still coming from **Run 2** (2015-18) data analysis:

- Most precise search in multibody phase space with $D^+ \to K^+ K^- \pi^+$
- two measurements of mixing + CPV parameters with $D^0 \to K^+ \pi^-$
  $\to$ x1.6 factor improvement wrt previous measurement

Several **other activities ongoing** not mentioned because of time constraints - a couple of examples:

- material effects on D^0 mixing (see Alexey's dedicated talk in this session)
- feasibility studies for $A_{CP}(K^+K^-)$ with different different calibration channel
- search for local CPV in other multibody D decays (as $D^+ \to \pi^+ \pi^- \pi^+$)
- D^+, D_S^+, D^0 meson-antimeson production asymmetry with Run 3 data

Prospects

A lot more data needed to reach desired sensitivity ~10^{-4}-10^{-3}

→ LHCb is already at work on this

2024 datataking just concluded (with upgraded detector and trigger)

9.6 fb^{-1} collected in 2024

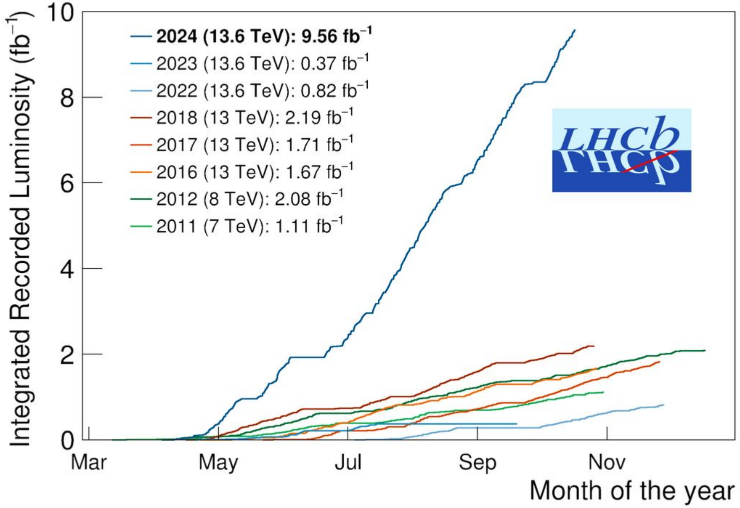
→ huge amount of data ready to be analyzed

Scoping document for Upgrade 2 just sent to the LHCC:
(Framework TDR is CERN-LHCC-2021-012)

- up to **x7.5** instantaneous luminosity increase wrt Run 3
- start taking data in Run 5 (~2036)

→ LHCb U2 is the only experiment able to reach the precision of SM predictions for time-dependent CPV

2024 dataset > 2011-2018



A new season of precision measurements is on the way

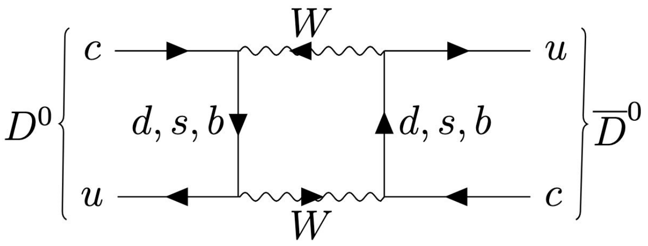
BACKUP SLIDES

Difficult predictions

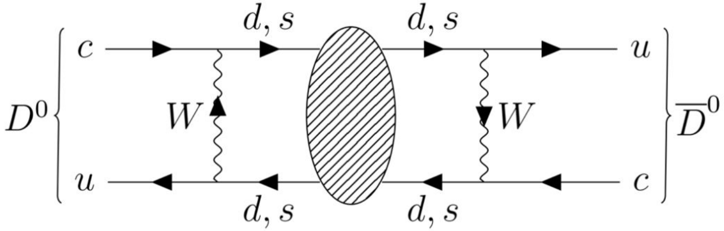
Large SM effects suppression comes with a major side effect

Mixing proceeds through:

Short distance - perturbative



Long distance - non-perturbative



Long distance contributions relevant because of GIM suppression

Non-perturbative contributions extremely difficult to determine
(see Felix's talk right after this for most recent progresses in lattice QCD)

Providing a precise prediction of Charm mixing and CPV is extremely challenging

Discovery of CP violation in Charm decays

Can ΔA_{CP} be explained by SM?

Yes, according to some authors
JHEP 05 (2012) 140, *JHEP* 07 (2019) 020,
Phys. Rev. D 100 (2019) 093002

No, according to others
JHEP 07 (2019) 161 *JHEP* 12 (2019) 104,
Phys. Rev. D 101 (2020) 115006

Additional A_{CP} measurements in other charm decays crucial at this stage

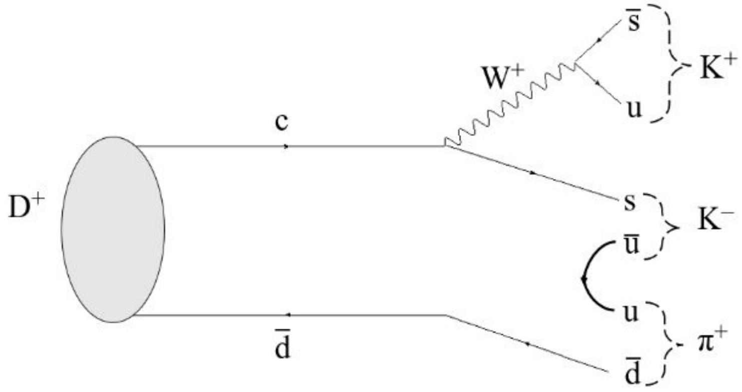
Additional observables
↓
Different testing handles

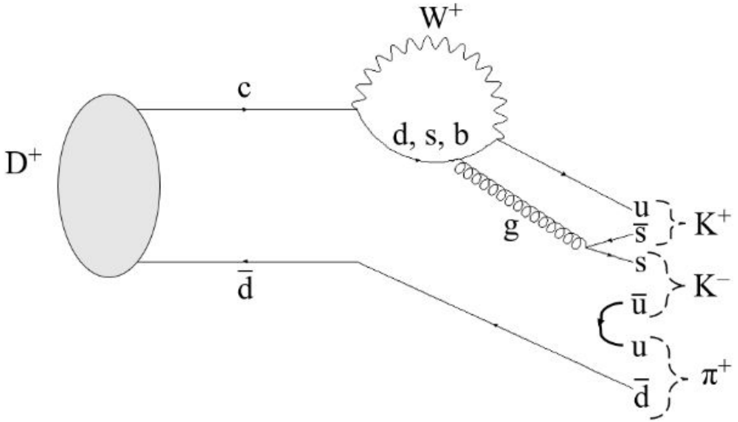
Input into theory
↓
More precise predictions

LHCb can significantly contribute to this:

- data collected in Run 1-2 + Run 3 with upgraded system (more later)

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





$A_{CP}(K^+K^-)$ with $D^0 \to K_S^0\pi^+\pi^-$

Previous measurement extracted $A_{CP}(K^+K^-)$ exploiting two independent methods

$$\mathcal{A}^{CP}(K^-K^+) = A(K^-K^+) - A(K^-\pi^+) + A(K^-\pi^+\pi^+) - A(\overline{K}^0\pi^+) + A(\overline{K}^0)$$

$$\mathcal{A}^{CP}(K^-K^+) = A(K^-K^+) - A(K^-\pi^+) + A(\phi\pi^+) - A(\overline{K}^0K^+) + A(\overline{K}^0)$$

New methods exploits $D^0 \to K_S^0\pi^+\pi^-$ as calibration channel

Well understood - can be computed and subtracted
Already done here PRL 131.091802

Extract $A_{CP}(K^+K^-)$ with:

$$\mathcal{A}^{CP}(K^+K^-) = \mathcal{A}^{raw}(K^+K^-) - \mathcal{A}^{raw}(K_S^0\pi^+\pi^-) =$$

$$= \mathcal{A}^{CP}(K^+K^-) + \mathcal{A}^{prod}(D^{*+}) + \mathcal{A}^{det}(\pi_{tag}) - \mathcal{A}^{CP}(K_S^0\pi^+\pi^-) - \mathcal{A}^{prod}(D^{*+}) - \mathcal{A}^{det}(\pi_{tag}) - \mathcal{A}^{det}(\pi^+\pi^-) - \mathcal{A}^{det}(K^0)$$

Expected < 1 x 10^{-4}

Asymmetric kinematics of $\pi^+\pi^-$ pair in $K_S^0\pi^+\pi^-$ decay
→ weight candidates to make it symmetric

Combine the two results

ΔY with $D^0 \to \pi^+\pi^-\pi^0$

First ΔY measurement performed exploiting $D^0 \to \pi^+\pi^-\pi^0$ decays ($D^0 \to K^-\pi^+\pi^0$ exploited as calibration channel)

Full Run 1 + Run 2 statistics analyzed → 7.7 fb^{-1}

Diluted ΔY measured in multibody decays:

$$A_{CP}(f_{CP},t) \equiv \frac{\Gamma_{D^0\to f_{CP}}(t) - \Gamma_{\bar{D}^0\to f_{CP}}(t)}{\Gamma_{D^0\to f_{CP}}(t) + \Gamma_{\bar{D}^0\to f_{CP}}(t)} \approx a^{\mathrm{dir}}_{f_{CP}} + \Delta Y_{f_{CP}} \frac{t}{\tau_{D^0}}$$

$$\Delta Y_f^{\mathrm{eff}} = (2F_+^f - 1)\Delta Y, \qquad F_+^{\pi\pi\pi} = 0.973 \pm 0.017$$

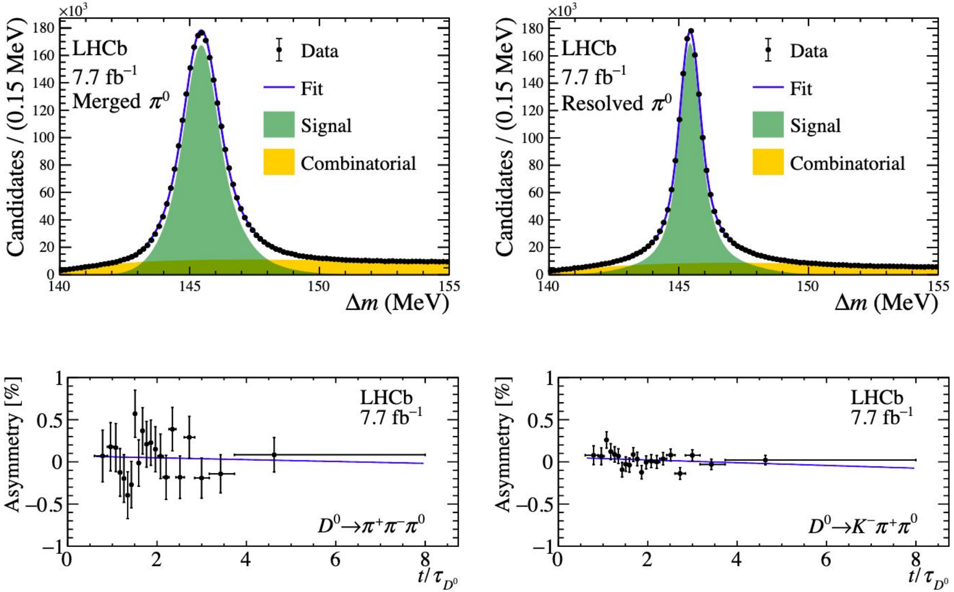
Phys.Lett. B747 (2015) 9

→ small dilution in case of $\pi\pi\pi$ final state

Results are:

$$\Delta Y^{\mathrm{eff}}_{\pi\pi\pi} = (-1.2 \pm 6.0 \pm 2.3) \times 10^{-4}$$

$$\Delta Y = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$$



Compatible with previous world average: $\Delta Y = (0.9 \pm 1.1) \times 10^{-4}$

D^0 mixing notation

$$\delta = \delta_D^{K\pi} - \pi = -\Delta_{K^-\pi^+}$$

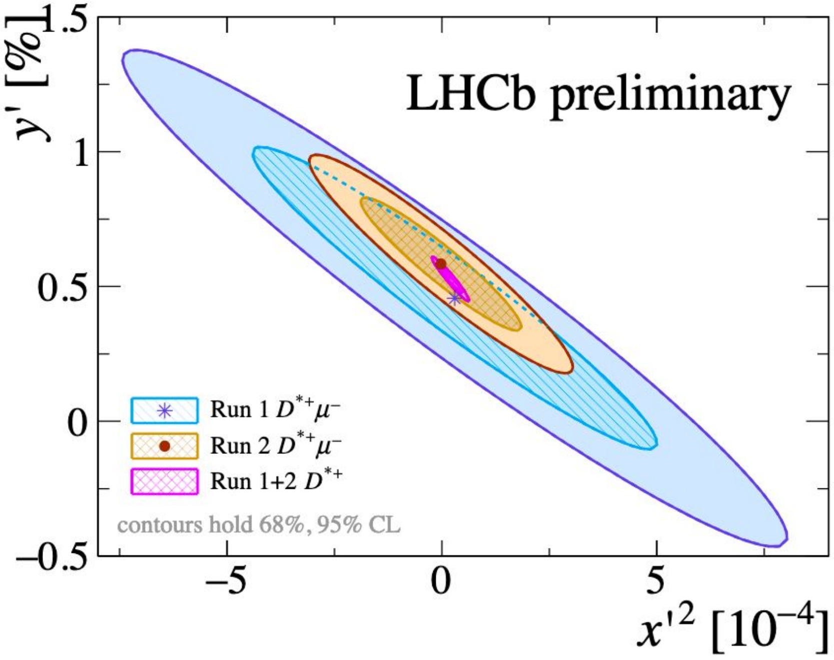
$$\begin{aligned} c_{K\pi} &\simeq y\cos\delta_{K\pi} - x\sin\delta_{K\pi} \\ &\simeq y_{12}\cos\phi^{\Gamma}_{K\pi}\cos\delta_{K\pi} - x_{12}\cos\phi^{M}_{K\pi}\sin\delta_{K\pi} \\ &\simeq y_{CP}\cos\delta_{K\pi} - x_{CP}\sin\delta_{K\pi} \\ &\simeq \frac{1}{2}(y'^{+} + y'^{-}), \end{aligned}$$

$$\begin{aligned} c'_{K\pi} &\simeq \frac{1}{4}(x^2 + y^2) \\ &\simeq \frac{1}{4}(x_{12}^2 + y_{12}^2) \\ &\simeq \frac{1}{4}(y_{CP}^2 + x_{CP}^2) \\ &\simeq \frac{1}{8}(y'^{2+} + x'^{2+} + y'^{2-} + x'^{2-}) \end{aligned}$$

$$\begin{aligned} \Delta c_{K\pi} &\simeq (y\cos\delta_{K\pi} - x\sin\delta_{K\pi})\left(\left|\frac{q}{p}\right| - 1\right) - (x\cos\delta_{K\pi} + y\sin\delta_{K\pi})\,\phi^{\lambda}_{K\pi} \\ &\simeq x_{12}\phi^{M}_{K\pi}\cos\delta_{K\pi} + y_{12}\phi^{\Gamma}_{K\pi}\sin\delta_{K\pi} \\ &\simeq \Delta y\cos\delta_{K\pi} - \Delta x\sin\delta_{K\pi}, \\ &\simeq \frac{1}{2}(y'^{+} - y'^{-}), \end{aligned}$$

$$\begin{aligned} \Delta c'_{K\pi} &\simeq \frac{1}{2}(x^2 + y^2)\left(\left|\frac{q}{p}\right| - 1\right) \\ &\simeq \frac{1}{2}x_{12}y_{12}(\phi^{M}_{K\pi} - \phi^{\Gamma}_{K\pi}) \\ &\simeq \frac{1}{2}(y_{CP}\Delta y_{K\pi} + x_{CP}\Delta x_{K\pi}) \\ &\simeq \frac{1}{8}(y'^{2+} + x'^{2+}) - \frac{1}{8}(y'^{2-} - x'^{2-}) \end{aligned}$$

DT-prompt results comparison



$A_{CP}(KK)$ and mixing correlation

Ratios measured on data exploiting *KK* as calibration sample:

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

Direct CPV term measured on data is

$$a^d_{DCS} + a^d_{CF} - 2 \cdot a^d_{KK}$$

Only one amplitude within SM
a^d_{DCS} , a^d_{CF} = 0

Independent a^d_{KK} measurement!

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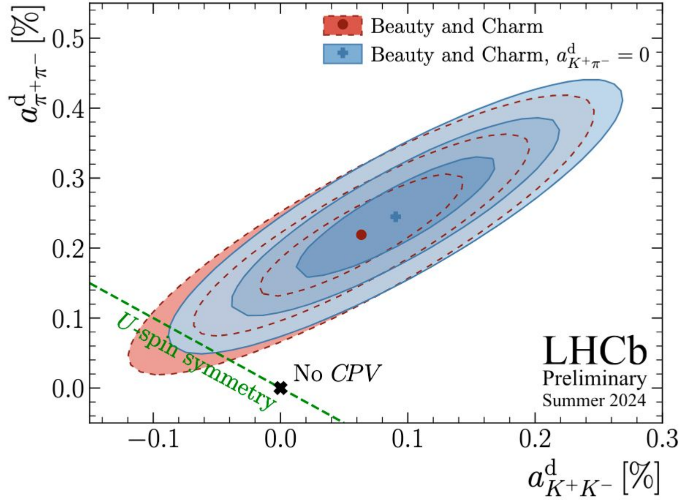


10% improvement in a^d_{KK} precision when constraining a^d_{DCS} , a^d_{CF} = 0

Prompt + DT combination

Combination of prompt+DT results, no CPV:

R_D	$(343.7 \pm 1.9) \times 10^{-5}$	R_D	$(3.44 \pm 0.02) \times 10^{-3}$
$c_{K\pi}$	$(50.7 \pm 3.3) \times 10^{-4}$	y'	$(5.08 \pm 0.33) \times 10^{-3}$
$c'_{K\pi}$	$(13.7 \pm 3.6) \times 10^{-6}$	$(x')^2$	$(2.87 \pm 1.75) \times 10^{-5}$

CPV allowed:

R_D	$(343.7 \pm 1.9) \times 10^{-5}$	R_D^+	$(3.42 \pm 0.03) \times 10^{-3}$
$c_{K\pi}$	$(50.7 \pm 3.3) \times 10^{-4}$	y'^+	$(5.16 \pm 0.48) \times 10^{-3}$
$c'_{K\pi}$	$(13.7 \pm 3.6) \times 10^{-6}$	$(x'^+)^2$	$(2.79 \pm 2.54) \times 10^{-5}$
A_D	$(-3.6 \pm 5.6) \times 10^{-3}$	R_D^-	$(3.45 \pm 0.03) \times 10^{-3}$
$\Delta c_{K\pi}$	$(0.9 \pm 3.4) \times 10^{-4}$	y'^-	$(5.03 \pm 0.47) \times 10^{-3}$
$\Delta c'_{K\pi}$	$(-0.1 \pm 3.7) \times 10^{-6}$	$(x'^-)^2$	$(2.77 \pm 2.47) \times 10^{-5}$

Data hunger

All reported measurements are **statistically limited**

Larger dataset to improve precision

↓

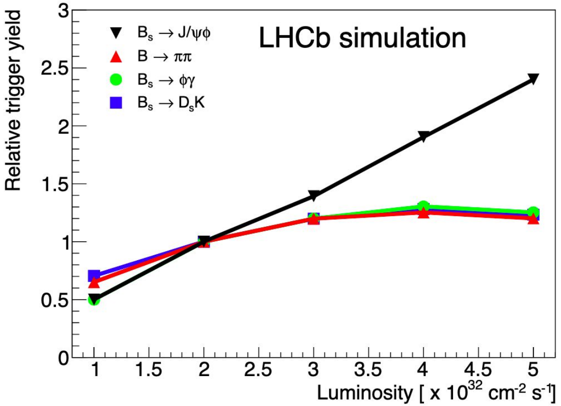
Increase data acquisition speed

LHCb went through a major upgrade (*JINST* 19 (2024) 05, P05065):

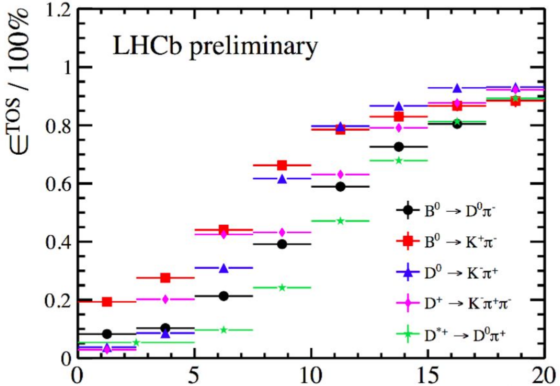
- **x5** instantaneous luminosity increase
  (more data in the same period)
- increase trigger efficiency
  (more signal events with same data)

Charm decays significantly benefit from this → lower efficiency wrt B in Run 2

No-upgrade scenario



Hardware trigger efficiency



2014 JINST 9 C09015

Mixing - doubly tagged decays

LHCb-PAPER-2024-044

NEW!

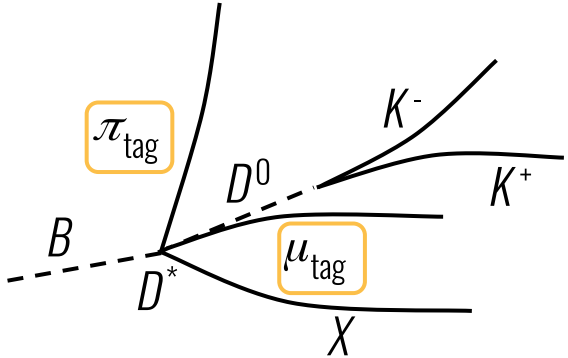
Mixing + CPV parameters performed by LHCb also with *doubly-tagged* $D^0 \to K^+\pi^-$ (**just approved!**)

Complementary to measurement with prompt sample:

$\rightarrow$ lower decay time sensitivity + different systematic uncertainties

WS/RS ratio is measured as before (slightly different parametrization)

$$R^{\pm}(t) = \frac{N^{\pm}_{WS}(t)}{N^{\pm}_{RS}(t)} = R_D^{\pm} + \sqrt{R_D^{\pm}}\, y'^{\pm} \left(\frac{t}{\tau}\right) + \frac{x'^{2\pm} + y'^{\pm 2}}{4} \left(\frac{t}{\tau}\right)^2$$



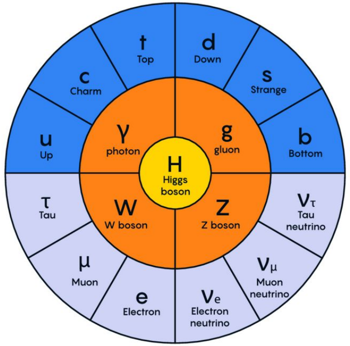
	Value	Statistical	Systematic
Mixing only			
R_D $[10^{-3}]$	3.47	0.06	0.01
y' $[10^{-3}]$	5.84	1.62	0.16
$(x')^2$ $[10^{-5}]$	0.04	12.25	1.06
All CPV allowed			
R_D^+ $[10^{-3}]$	3.55	0.08	0.02
y'^+ $[10^{-3}]$	3.56	2.23	0.26
$(x'^+)^2$ $[10^{-5}]$	10.86	16.17	1.35
R_D^- $[10^{-3}]$	3.39	0.08	0.02
y'^- $[10^{-3}]$	8.11	2.34	0.28
$(x'^-)^2$ $[10^{-5}]$	−11.29	18.55	1.28

Introduction

Standard Model (SM) is theoretical description of particle physics since the ‘70s

Many extremely precise predictions - a couple of examples:

- $BR(B_S^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$ Phys. Rev. Lett. 112 (2014) 101801
- $(g-2)/2 = 116\,591\,810(43) \times 10^{-11}$ Phys. Rept. 887 (2020) 1-166



Huge efforts to “break” SM → find beyond Standard Model effects - **New Physics**

High precision measurements are a crucial test of SM
→ sensitive to possible BSM contributions
→ access large energy scales through off-shell interactions

Flavor Physics provides several extremely sensitive SM tests