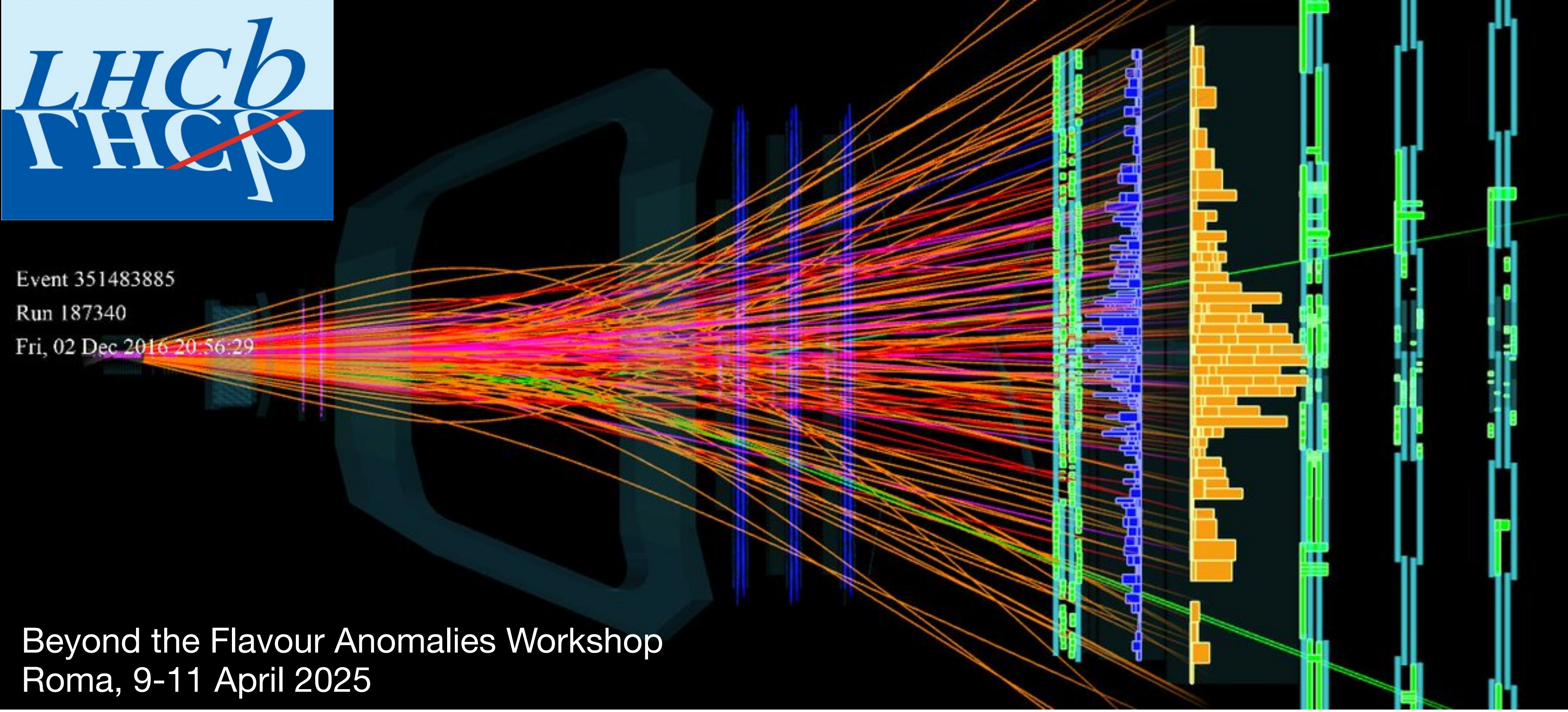


Beyond the Flavour Anomalies Workshop
Roma, 9-11 April 2025

CP violation in charm: experiment

Tommaso Pajero
CERN

tommaso.pajero@cern.ch

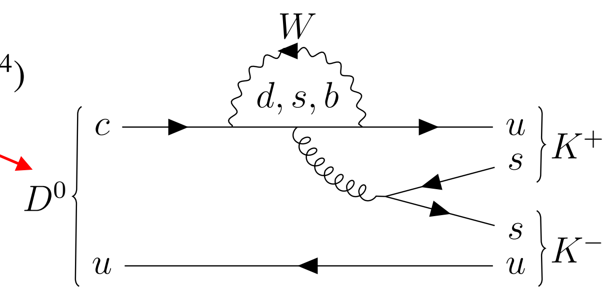
CPV in charm

$$A(D^0 \to K^-K^+) \equiv \lambda_s T + \lambda_b P$$

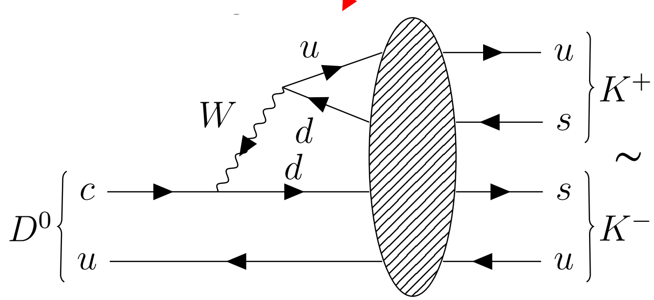
Detectable in Cabibbo-suppressed decays only

$$a^{\mathrm{d}}_{K^+K^-} \approx \underbrace{\boxed{-2\,\mathrm{Im}\left(\frac{\lambda_b}{\lambda_s}\right)}}_{1.3\times10^{-3}} \left|\frac{P}{T}\right| \sin(\delta_P - \delta_T)$$

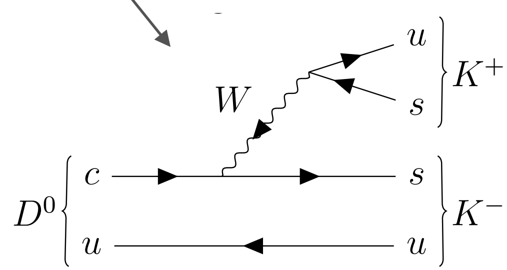
$$\begin{array}{cccc} & d & s & b \\ V_{\mathrm{CKM}} = & \left(\begin{array}{ccc} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda \; -iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{array}\right) & & \end{array} \begin{array}{c} u \\ c \\ t \end{array} + \mathcal{O}(\lambda^4)$$



QCD penguin $\sim \lambda_b$



$\sim \lambda_d = -\lambda_s - \lambda_b$



$\sim \lambda_s$

Tree

Tree + rescattering *(e.g. $D^0 \to \pi^+\pi^- \to K^+K^-$)*
CPV from tiny nonunitarity of 2×2 CKM submatrix

Contributes also to BFs

The $D^0 \to h^+h^-$ puzzle

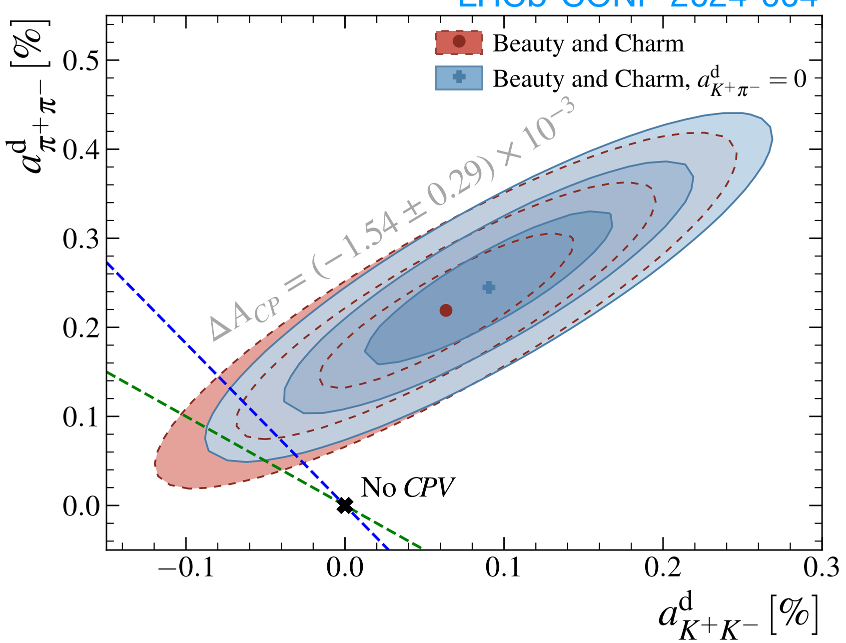
1. Branching fractions

$$\left| \frac{1}{tan^2\theta_C} \frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)} \right| = 1.15 \pm 0.03$$ O(20%) U-spin breaking

$$\left| \frac{A(D^0 \to K^+K^-)}{A(D^0 \to \pi^+\pi^-)} \right| = 1.81 \pm 0.02$$ O(1) U-spin breaking?

2. CP asymmetries

LHCb-CONF-2024-004



$$a^{d}_{K^-K^+} = (0.9 \pm 0.5) \times 10^{-3}$$
$$a^{d}_{\pi^-\pi^+} = (2.4 \pm 0.6) \times 10^{-3}$$

$$\left| \frac{P}{T} \right| \sin(\delta_P - \delta_T) = O(1)$$

Strict U-spin limit: $\frac{a^{d}_{K^+K^-}}{a^{d}_{\pi^+\pi^-}} = -1$

Improved U-spin limit: $\frac{a^{d}_{K^+K^-}}{a^{d}_{\pi^+\pi^-}} \left| \frac{A(D^0 \to K^+K^-)}{A(D^0 \to \pi^+\pi^-)} \right| = -1$

What about theory?

Experiment

$$\left|\frac{P}{T}\right| \sin(\delta_P - \delta_T) = O(1)$$

- **Light cone sum rules (LCSR)**: $\left|\frac{P}{T}\right| \sim 0.1$

  Khodjamirian Petrov 1706.07780
  Chala Lenz Rusov Scholtz 1903.10490
  Lenz Piscopo Rusov 2312.13245

- **Predictions based on $\pi\pi/KK$ rescattering data**: under debate
  Franco Mishima Silvestrini 1203.3131
  Bediaga Frederico Magalhaes 2203.04056
  Pich Solomonidi Vale Silva 2305.11951

- **Working hypothesis of large nonperturbative effects** leading to $\left|\frac{P}{T}\right| = O(1)$

  can explain both CP asymmetries and BFs at the same time,
  with O(20%) U-spin breaking
  - U-spin average of the penguin contraction is responsible for CPV
  - broken penguin is responsible for U-spin breaking in the BFs

  Brod Grossman Kagan Zupan 1203.6659
  Grossman Schacht 1903.10952

  Example of concrete model: enhancement through $f_0(1710)$ and $f_0(1790)$
  Schacht Soni 2110.07619

What about theory?

Experiment

$$\left|\frac{P}{T}\right| \sin(\delta_P - \delta_T) = O(1)$$

Can we measure the phase?
If << 1, will disfavour SM explanations

- **Light cone sum rules (LCSR)**: $\left|\frac{P}{T}\right| \sim 0.1$

  Khodjamirian Petrov 1706.07780
  Chala Lenz Rusov Scholtz 1903.10490
  Lenz Piscopo Rusov 2312.13245

- **Predictions based on $\pi\pi/KK$ rescattering data**: under debate

  Franco Mishima Silvestrini 1203.3131
  Bediaga Frederico Magalhaes 2203.04056
  Pich Solomonidi Vale Silva 2305.11951

  How useful would further experimental data be?

- **Working hypothesis of large nonperturbative effects** leading to $\left|\frac{P}{T}\right| = O(1)$

  can explain both CP asymmetries and BFs at the same time,
  with O(20%) U-spin breaking
  - U-spin average of the penguin contraction is responsible for CPV
  - broken penguin is responsible for U-spin breaking in the BFs

  Brod Grossman Kagan Zupan 1203.6659
  Grossman Schacht 1903.10952

  Example of concrete model: enhancement through $f_0(1710)$ and $f_0(1790)$
  Schacht Soni 2110.07619

  Coupled channel analysis, e.g. in CEP?

Can we test U-spin symmetry more thoroughly in CP asymmetries and BFs?
Can we say something more about the possible sources of enhancement, making predictions in other decay channels?

- E.g. f_0 could enhance also $\mathrm{BF}(D^0 \to \gamma\gamma)$, but not CPV in $D^+ \to K^+K^+K^-$ (due to phase space)

Measuring arg(P/T) from time-dependent CPV?

Kagan Silvestrini 2001.07207
LHCb 2105.09889

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

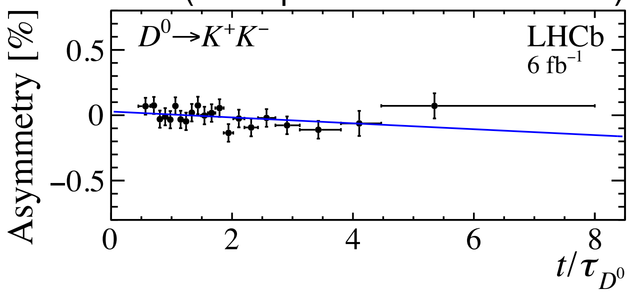
$$\Delta Y_f \approx -x_{12}\phi_2^M + y_{12}a_f^d + \boxed{x_{12}a_f^d}\cot\delta_f$$

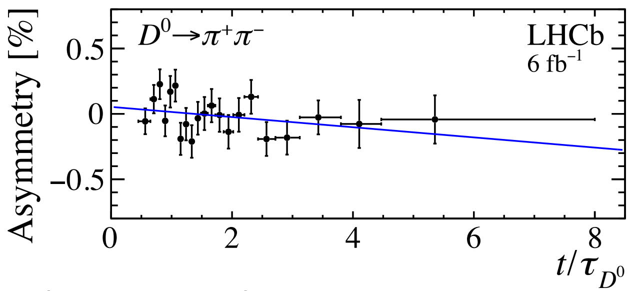
arg(P/T)

can be determined from
$D^0 \to K^+\pi^-$
$D^0 \to K^+\pi^-\pi^+\pi^-$
$D^0 \to K_S^0\pi^+\pi^-$

0.08×10^{-4}
(for $a_f^{\mathrm{d}} = 2 \times 10^{-3}$)

LHCb 2105.09889
(most precise determination)





WA 2025 (charm-fitter)

$$\Delta Y_{K^+K^-} = (-0.20 \pm 1.28 \pm 0.32) \times 10^{-4}$$
$$\Delta Y_{\pi^+\pi^-} = (-3.5 \pm 2.4 \pm 0.4) \times 10^{-4}$$

Projections at LHCb Upgrade II 1808.08865

$$\sigma(\Delta Y_{K^+K^-}) = 0.14 \times 10^{-4}$$
$$\sigma(\Delta Y_{\pi^+\pi^-}) = 0.25 \times 10^{-4}$$

LHCb-CONF-2024-004
$x_{12} = (4.1 \pm 0.5) \times 10^{-3}$
$y_{12} = (6.2 \pm 0.2) \times 10^{-3}$

Measuring arg(P/T) from time-dependent CPV?

Kagan Silvestrini 2001.07207
LHCb 2105.09889

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

$$\Delta Y_f \approx -x_{12}\phi_2^M + y_{12}a_f^d + \boxed{x_{12}a_f^d}\cot\delta_f$$

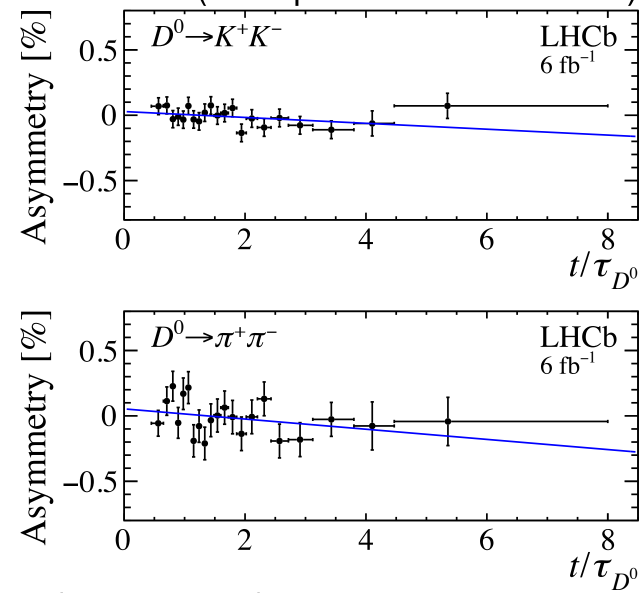
arg(P/T)

can be determined from
$D^0 \to K^+\pi^-$
$D^0 \to K^+\pi^-\pi^+\pi^-$
$D^0 \to K_S^0\pi^+\pi^-$

0.08×10^{-4}
(for $a_f^{\mathrm{d}} = 2 \times 10^{-3}$)

can get some sensitivity only if $|\delta_f| \ll 1$
(unlikely, but would strengthen the tension with SM expectations)

LHCb 2105.09889
(most precise determination)



WA 2025 (charm-fitter)

$$\Delta Y_{K^+K^-} = (-0.20 \pm 1.28 \pm 0.32) \times 10^{-4}$$
$$\Delta Y_{\pi^+\pi^-} = (-3.5 \pm 2.4 \pm 0.4) \times 10^{-4}$$

Projections at LHCb Upgrade II 1808.08865

$$\sigma(\Delta Y_{K^+K^-}) = 0.14 \times 10^{-4}$$
$$\sigma(\Delta Y_{\pi^+\pi^-}) = 0.25 \times 10^{-4}$$

LHCb-CONF-2024-004
$x_{12} = (4.1 \pm 0.5) \times 10^{-3}$
$y_{12} = (6.2 \pm 0.2) \times 10^{-3}$

Measuring arg(P/T) from time-dependent CPV?

Kagan Silvestrini 2001.07207
LHCb 2105.09889

$$A^f_{CP}(t) \approx a^{\rm d}_f + \Delta Y_f \frac{t}{\tau_{D^0}}$$

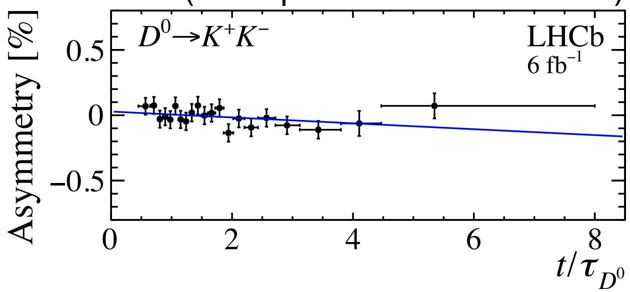
arg(P/T)

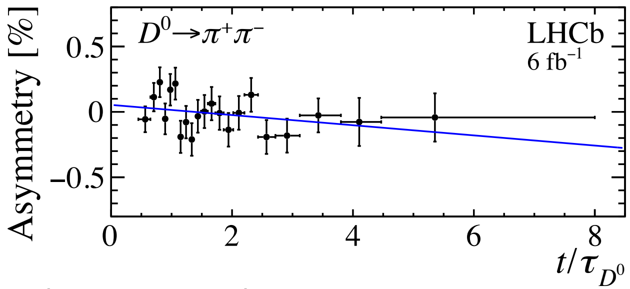
$$\Delta Y_f \approx -x_{12}\phi_2^M + y_{12}a_f^d + \boxed{x_{12}a_f^d}\cot\delta_f$$

can be determined from
$D^0 \to K^+\pi^-$
$D^0 \to K^+\pi^-\pi^+\pi^-$
$D^0 \to K^0_S\pi^+\pi^-$

0.08×10^{-4}
(for $a_f^{\rm d} = 2 \times 10^{-3}$)

LHCb 2105.09889
(most precise determination)





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

~1.7

LHCb 1903.08726

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

All results by LHCb/HFLAV neglect the $x_{12}a_f^d \cot\delta_f$ contribution to ΔY_f (achieve better uncertainty, but prone to bias in case $|\delta_f| \ll 1$)

→ alternative fit where this approximation is removed foreseen for the next update of LHCb-CONF-2024-004

WA 2025 (charm-fitter)

$$\Delta Y_{K^+K^-} = (-0.20 \pm 1.28 \pm 0.32) \times 10^{-4}$$
$$\Delta Y_{\pi^+\pi^-} = (-3.5 \pm 2.4 \pm 0.4) \times 10^{-4}$$

Projections at LHCb Upgrade II 1808.08865

$$\sigma(\Delta Y_{K^+K^-}) = 0.14 \times 10^{-4}$$
$$\sigma(\Delta Y_{\pi^+\pi^-}) = 0.25 \times 10^{-4}$$

LHCb-CONF-2024-004
$x_{12} = (4.1 \pm 0.5) \times 10^{-3}$
$y_{12} = (6.2 \pm 0.2) \times 10^{-3}$

Measuring arg(P/T) from a Dalitz plot?

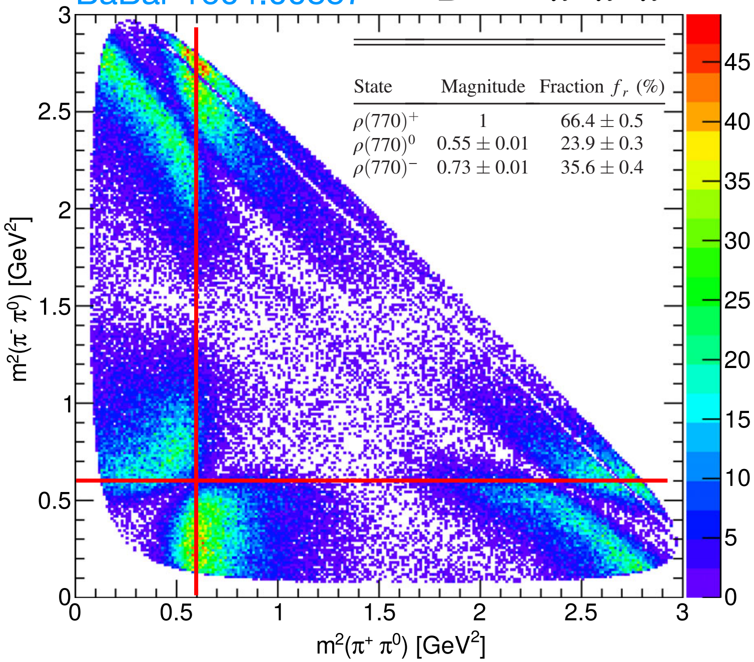
δ_{QCD} varies across the Dalitz plot. However, it “dresses” T and P in the same way

- not visible in the asymmetry of the fit fractions
- visible in the interference with other resonances
  Dery Grossman Schacht Soffer 2101.02560

Ideal scenario:

- significant overlap of two resonances in a region where δ_{QCD} change fast
- amplitudes similar in magnitude

BaBar 1604.00857 $D^0 \to \pi^+\pi^-\pi^0$



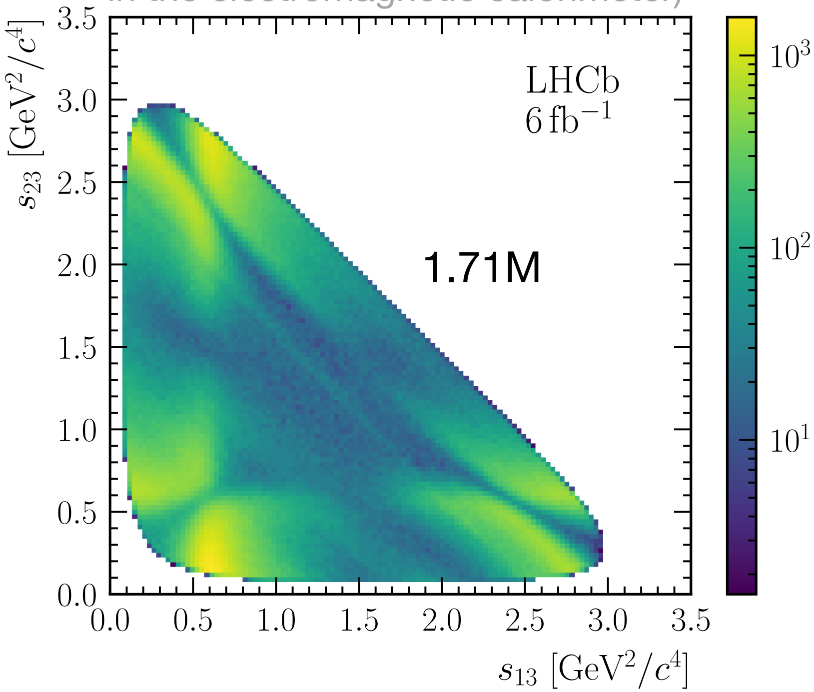
$$A_1(s_{12}, s_{13}) \sim \left[T_1 + \left(\frac{\lambda_b}{\lambda_d}\right) P_1 e^{i\delta_1}\right] r_1(s_{12}, s_{13}) e^{i\delta_{r_1}(s_{12}, s_{13})}$$

$$A_2(s_{12}, s_{13}) \sim \left[T_2 + \left(\frac{\lambda_b}{\lambda_d}\right) P_2 e^{i\delta_2}\right] r_2(s_{12}, s_{13}) e^{i\delta_{r_2}(s_{12}, s_{13})}$$

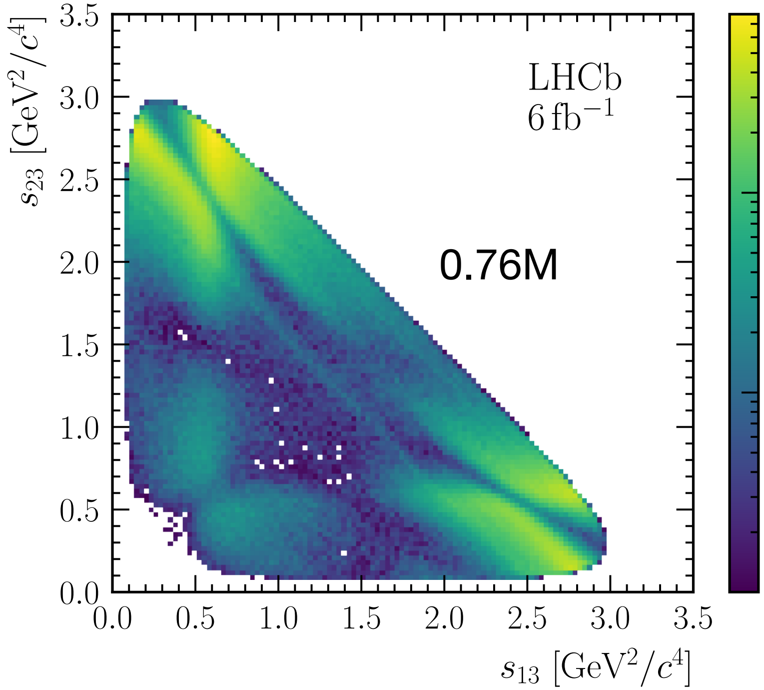
$D^0 \to \pi^+\pi^-\pi^0$ at LHCb

Search for CPV based on a model-independent method (Energy Test) published with Run 2 data
- consistent with CP conservation

Resolved π^0
(can distinguish the two photons in the electromagnetic calorimeter)



Merged π^0
(cannot)



Amplitude analysis based on the same data sample ongoing

Clean discovery channels

- Isospin selection rules, e.g. $A_{CP}(D^+ \to \pi^+\pi^0) = 0 \quad (\Delta I = 3/2)$
- SU(3)$_F$-based sum rules
  (if you believe that U-spin symmetry is broken only at O(20%) level)
- $\mathrm{BF}(D^0 \to \mu^+\mu^-)$, angular/CP asymmetries in $c \to u\ell^+\ell^-$
- LFU ($D^0 \to \mu^+e^-$ etc.)

However

- most of SU(3) sum rules include at least one π^0
  → lower precision than final states with charged particles only
  → even worse if coming from $D^+_{(s)}$ rather than D^0 (no $m(D^0\pi^+) - m(D^0)$ trick)
- it is possible that we observe CPV in many channels, but won't be able to test the corresponding sum rules with comparable precision
  → improved understanding of long-distance contributions is imperative to eventually assess the compatibility of CPV with the SM

A side note on control channels

$$A_{\rm raw}(f) = \frac{N(D\to f) - N(\bar{D}\to\bar{f})}{N(D\to f) + N(\bar{D}\to\bar{f})}$$

$$\boxed{A_{\rm raw}(f)} \approx \boxed{A_{CP}(f)} + \boxed{A_{\rm D}(f)} + \boxed{A_{\rm P}(D)}$$

production asymmetry

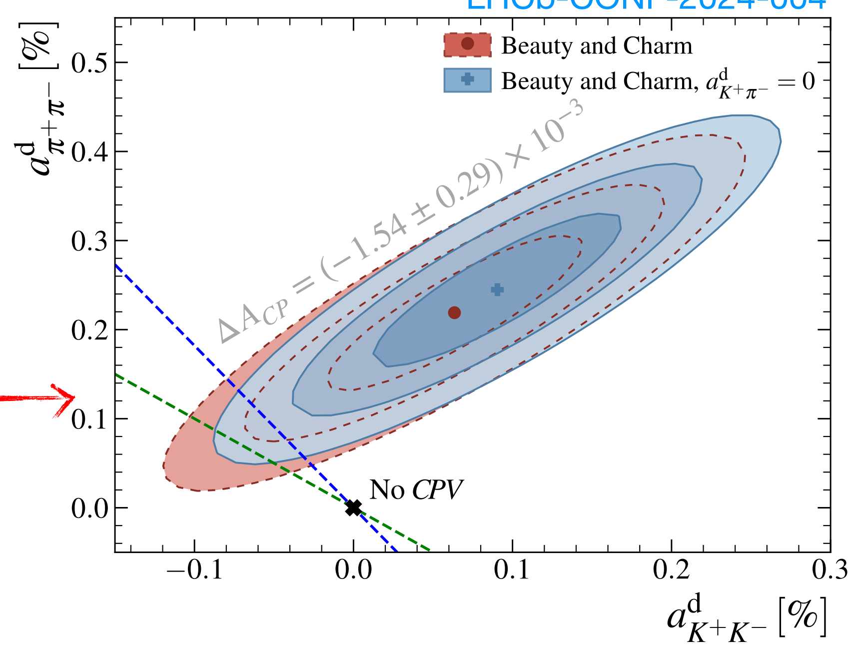
our target

detection asymmetry of tagging and final-state particles

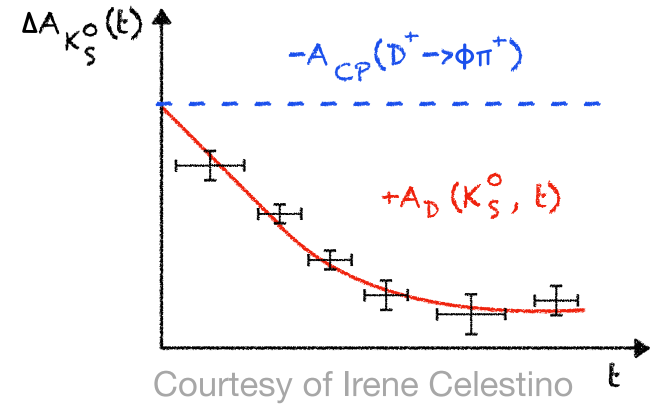
- Few observables are self-calibrating:
  $\Delta A_{CP},\ \Delta Y(D^0\to h^+h^-),\ y_{CP}(D^0\to h^+h^-)$
  $\dfrac{\Gamma(D^0\to K^+\pi^-(\pi^+\pi^-))}{\Gamma(D^0\to K^-\pi^+(\pi^+\pi^-))},\ D^0\to K^0_S\pi^+\pi^-$
  variation of CPV across the phase space of multi-body decays

- Otherwise we rely on calibration channels
  - Cabibbo-favoured decays (A_{CP} = 0)
  - often include K_S and limit our sensitivity (e.g. $D^+\to K^0_S\pi^+$ or $D^+_s\to K^0_S K^+$)

LHCb-CONF-2024-004



Example: $A_{CP}(D^+ \to \phi\pi^+)$

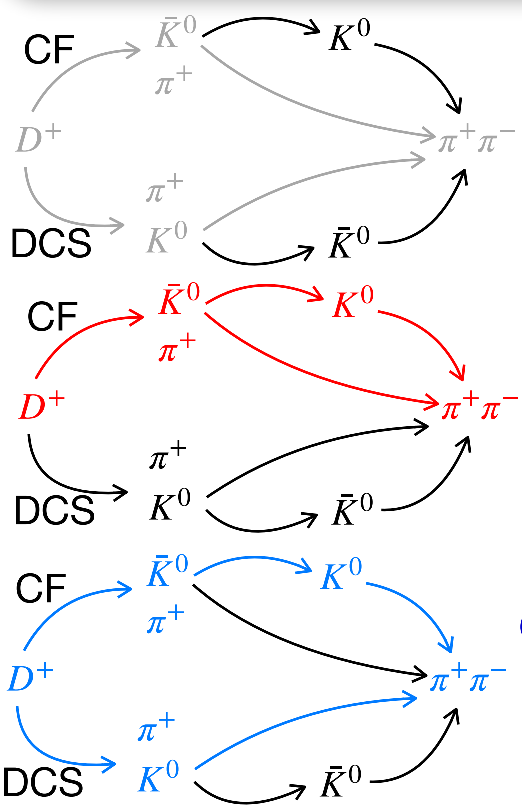


Courtesy of Irene Celestino

$$\mathbf{\Delta A_{K^0_S}(t)} \equiv A_{raw}(D^+ \to K^0_S(t)\pi^+) - A_{raw}(D^+ \to \phi\pi^+)$$

$$= \boxed{A_D(K^0_S, t)} - \boxed{A_{CP}(D^+ \to \phi\pi^+)}$$

$A_D(K^0_S, t) = A^{\text{decay}}_{CP} + A^{\bar{K}^0}_{CP}(t) + A^{\text{int}}_{CP}(t)$ **+ regeneration (and interference)**



CPV in charm decay

$$\text{Im}\left(\frac{V^*_{cd}V_{us}}{V^*_{cs}V_{ud}}\right) \approx 10^{-5}$$

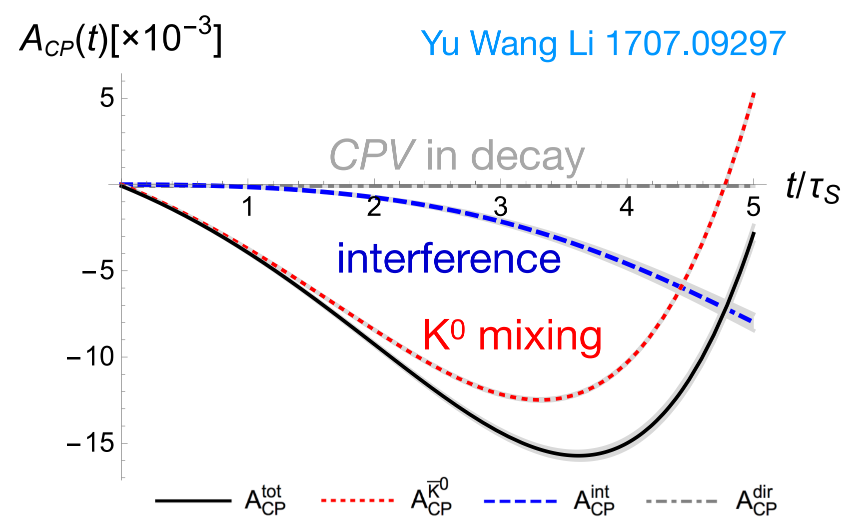
CPV in kaon mixing

$\approx \text{Re}(\epsilon) \approx 10^{-3}$

CPV in interference between D^+ decay and kaon mixing

$$\text{Im}(\epsilon)\text{Re}\left(\frac{V^*_{cd}V_{us}}{V^*_{cs}V_{ud}}\right) \approx 10^{-3}$$

Yu Wang Li 1707.09297



Interference crucially depends on:

$$\frac{A(D^+ \to K^0\pi^+)}{A(D^+ \to \bar{K}^0\pi^+)} \equiv r_\pi e^{i\delta_\pi}$$

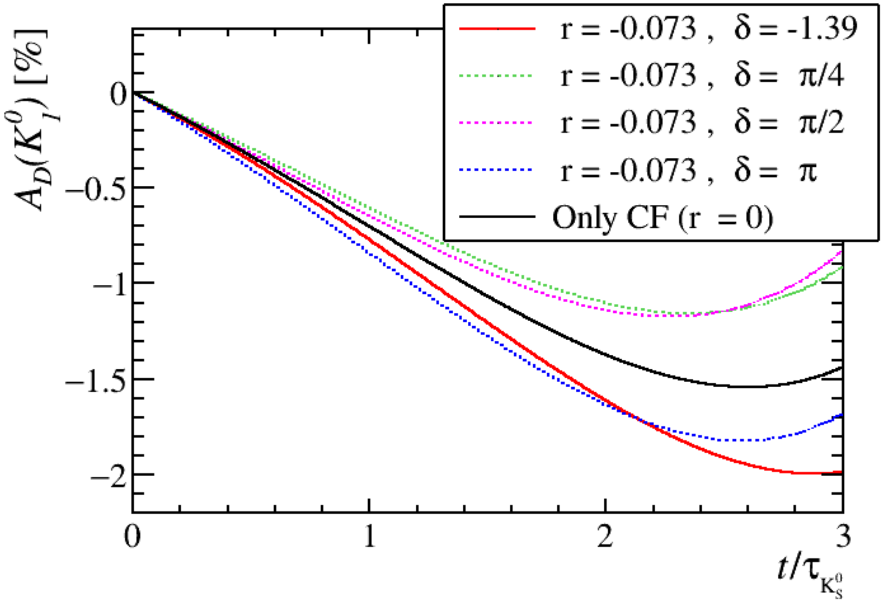
Kind request to our theory colleagues

$$\frac{A(D^+ \to K^0\pi^+)}{A(D^+ \to \bar{K}^0\pi^+)} \equiv r_\pi e^{i\delta_\pi}$$

The values of these parameters have been extracted from data only in the FAT approach:

$$r_{\pi^+} = -0.073 \pm 0.004, \qquad \delta_{\pi^+} = -1.39 \pm 0.05,$$ Yu Wang Li 1707.09297

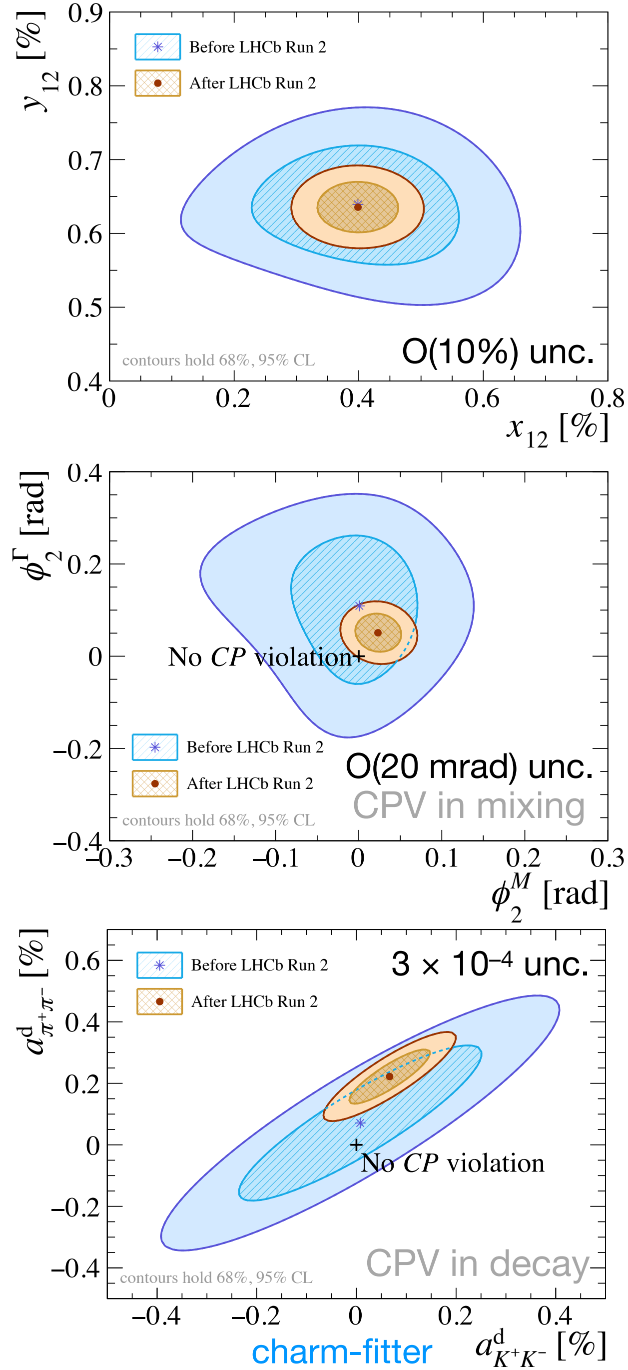
Systematic uncertainties are debated. Can alternative estimates be provided? Otherwise treating them as nuisance parameters will limit our precision in Upgrade I



Conclusions

- After 50 years and huge recent experimental progress, charm is still a "young" field with many open questions and promises many developments in the near future

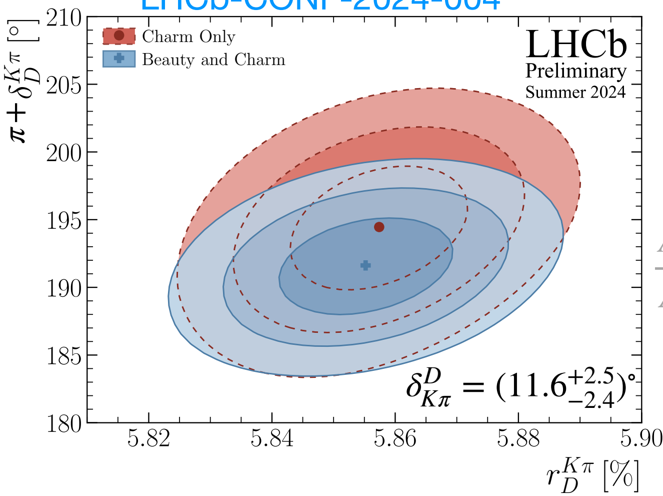
- Theory input essential for the success of our upgrades
  - if your favourite measurement is not being performed at LHCb, the time to complain is now
    - e.g. we are adding $D^0 \to \eta^{(\prime)}\eta$ in Run 3
  - do not forget "boring" CP-conserving measurements (BFs etc.)



Conclusions

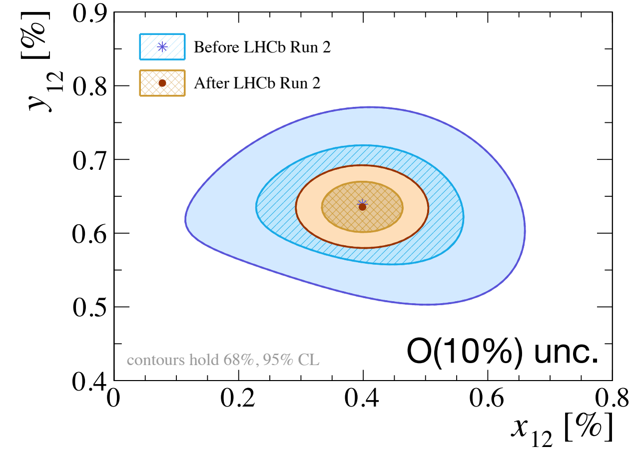
- After 50 years and huge recent experimental progress, charm is still a “young” field with many open questions and promises many developments in the near future
- Theory input essential for the success of our upgrades
  - if your favourite measurement is not being performed at LHCb, the time to complain is now
    - e.g. we are adding $D^0 \to \eta^{(\prime)}\eta$ in Run 3
  - do not forget “boring” CP-conserving measurements (BFs etc.)

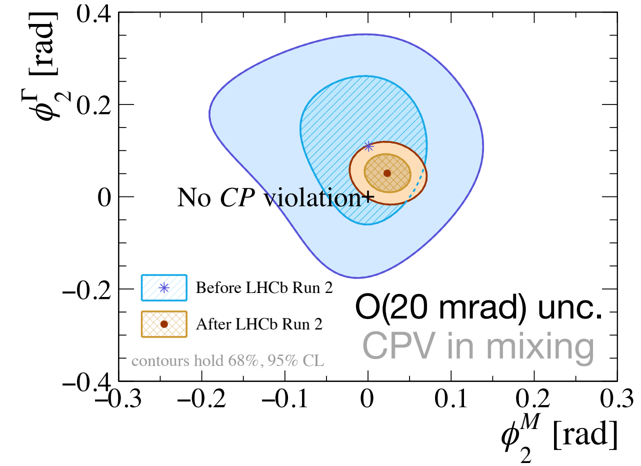
LHCb-CONF-2024-004

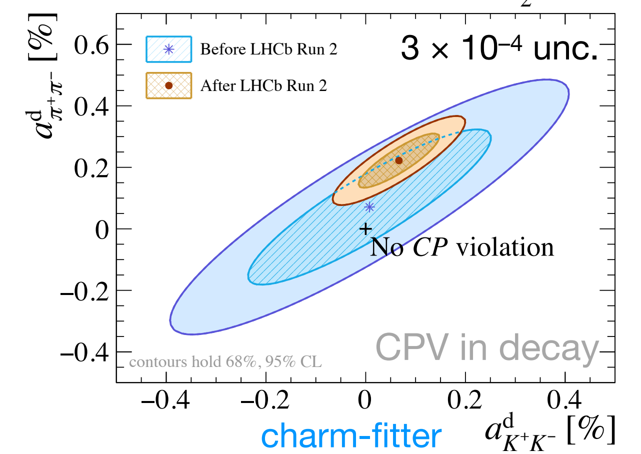


> 4σ evidence for U-spin breaking in the phase

$$\frac{A(D^0 \to K^+\pi^-)}{A(\bar{D}^0 \to K^+\pi^-)} \approx -\, r_D^{K\pi}\, e^{-i\delta_D^{K\pi}}$$

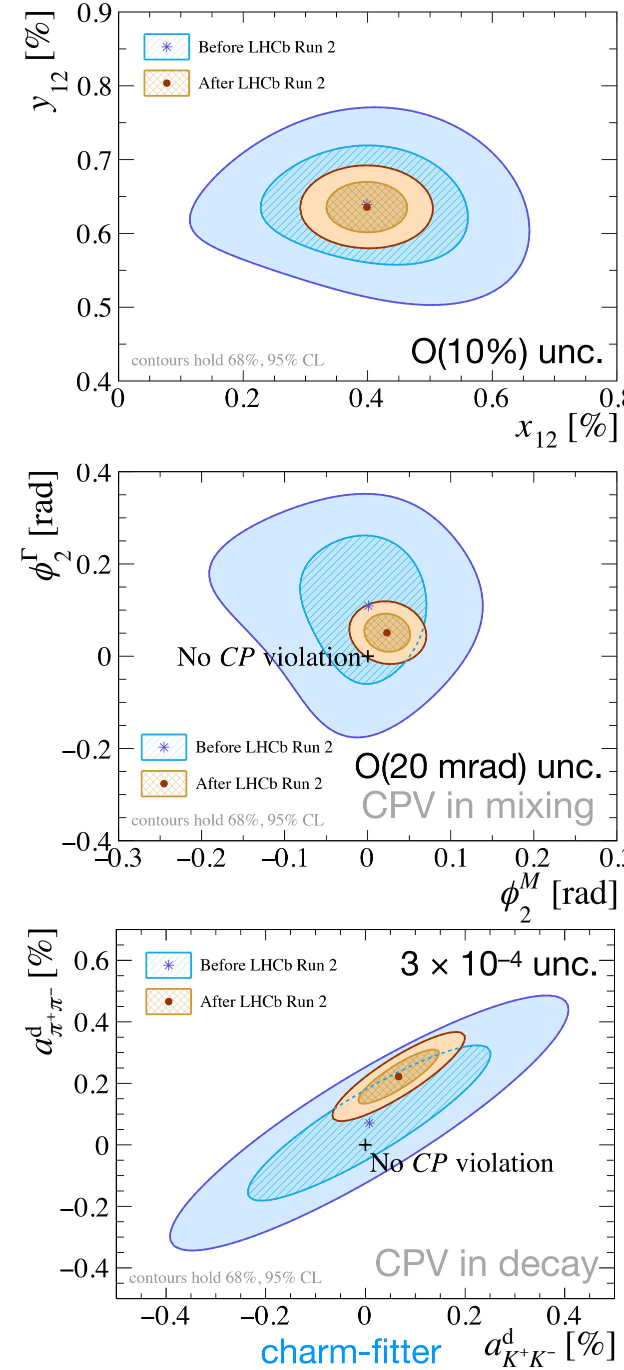






Conclusions

- After 50 years and huge recent experimental progress, charm is still a “young” field with many open questions and promises many developments in the near future
- Theory input essential for the success of our upgrades
    - if your favourite measurement is not being performed at LHCb, the time to complain is now
        - e.g. we are adding $D^0 \to \eta^{(\prime)}\eta$ in Run 3
    - do not forget “boring” CP-conserving measurements (BFs etc.)
- Multibody decays are becoming more and more important. We welcome feedback on how to best tackle them (besides amplitude analyses) to make the results most useful for theorists while waiting for new observations
    - binned measurements
    - triple-product asymmetries
    - etc.



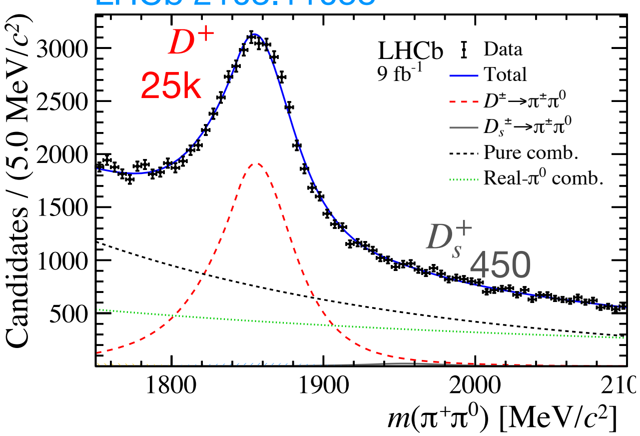
Backup slides

Neutral efficiencies

$$\epsilon(\pi^0/\gamma) < \epsilon(\eta^{(\prime)}) < \epsilon(K_S^0)$$

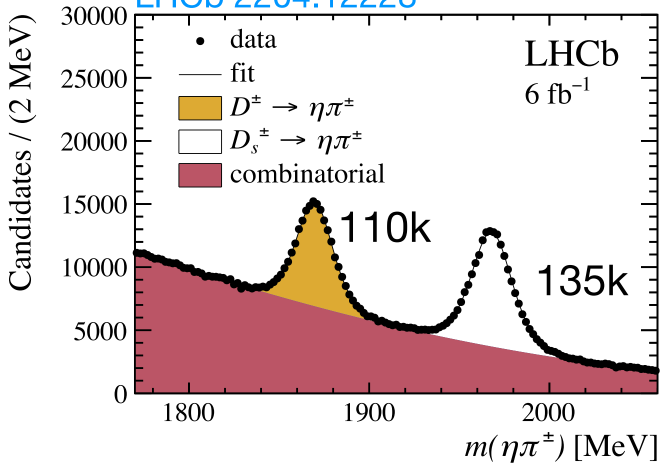
my personal, rough rule of thumb for Run 2: ~3% … ~10%

LHCb 2103.11058



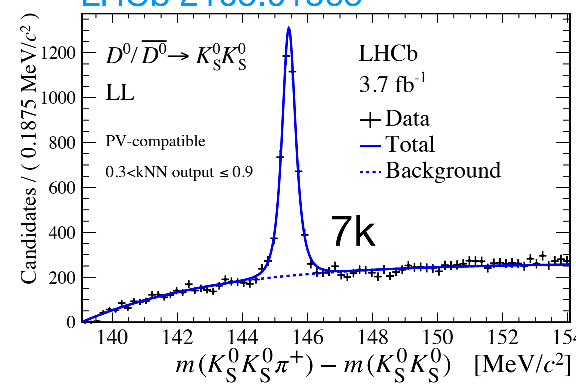
$A_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\,\%$

LHCb 2204.12228

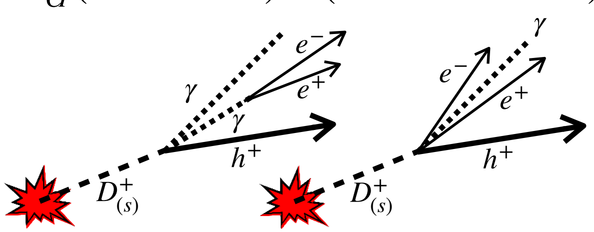


$A_{CP}(D^+ \to \eta\pi^+) = (0.34 \pm 0.66 \pm 0.14)\,\%$

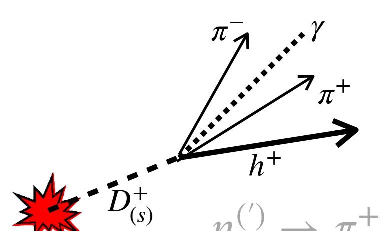
LHCb 2105.01565



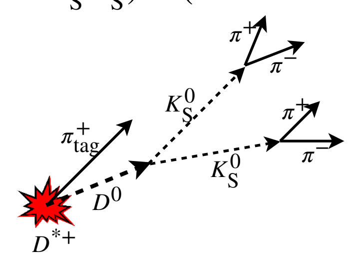
$A_{CP}(D^0 \to K_S^0K_S^0) = (-3.1 \pm 1.2 \pm 0.4)\,\%$



Photon conversion Dalitz decay



$\eta^{(\prime)} \to \pi^+\pi^-\gamma$

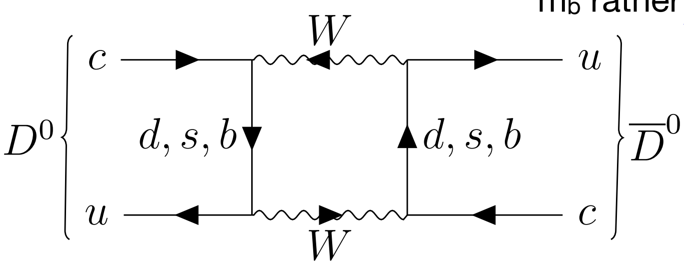


Many KS decay outside of the vertex tracker

The peculiar phenomenology of charm

FCNC are <u>extremely</u> suppressed

GIM mechanism broken by m_b rather than m_t



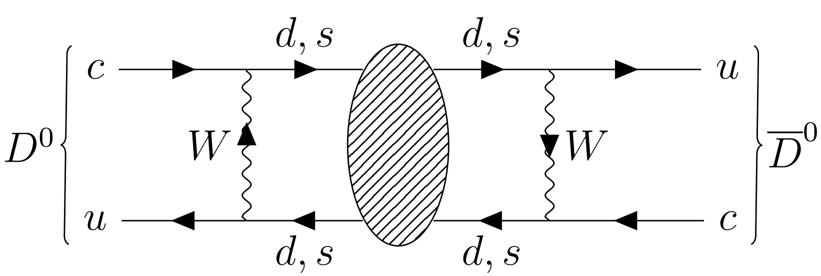
$$\propto \left(\frac{m_{d,s,b}}{m_W}\right)^2$$

mixing – short distance

$$\begin{array}{cccccc} & & d & s & b & \\ V_{\mathrm{CKM}} = & \Bigg(& 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) & \Bigg) \; u \\ & & -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 & \; c \quad +\mathcal{O}(\lambda^4) \\ & & A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 & \; t \end{array}$$

$\lambda = \sin\theta_C \approx 0.23$

- **CKM suppression** → third generation nearly decouples from the first two
- (**d** + **s** contribution) → 0 in the limit of U-spin symmetry, i.e. $m_s = m_d$

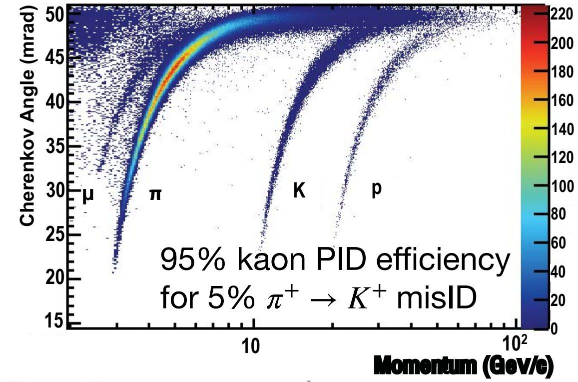


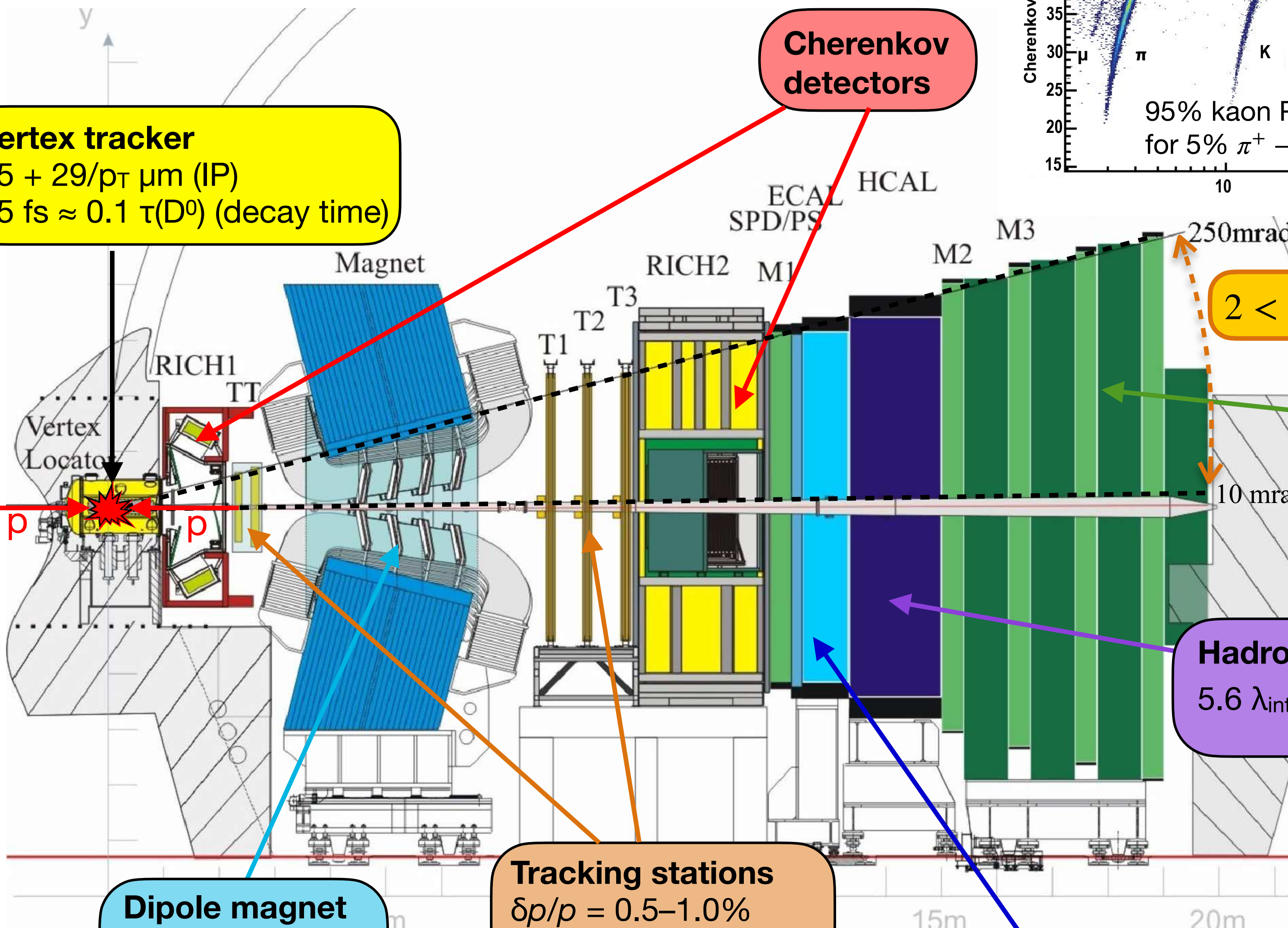
mixing – long distance

Main contributions from low-energy QCD. Charm is:

- too heavy for ChPT or exclusive analysis
- arguably too light for HQET ($\Lambda_{QCD}/m_c \approx 1$)

The LHCb detector





Vertex tracker
15 + 29/p_T µm (IP)
45 fs ≈ 0.1 τ(D^0) (decay time)

Cherenkov detectors

$2 < \eta < 5$

Muon chambers

Hadron calorimeter
5.6 λ_{int} $\frac{\sigma(E)}{E} = 9\% \oplus \frac{69\,\%}{\sqrt{E/GeV}}$

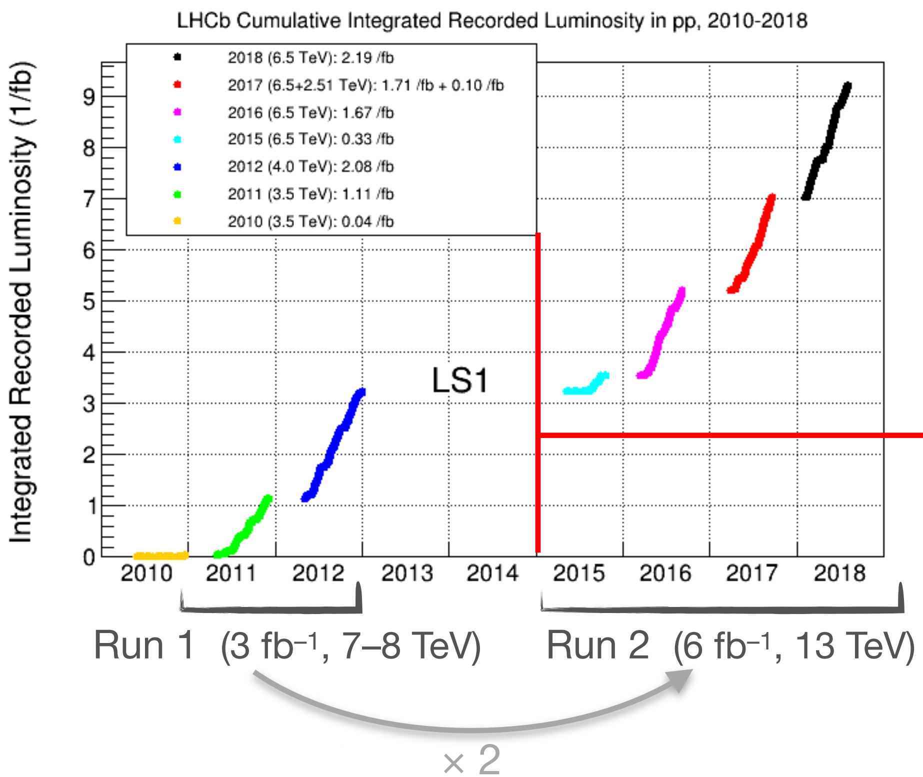
Dipole magnet
4 T·m (vertical)

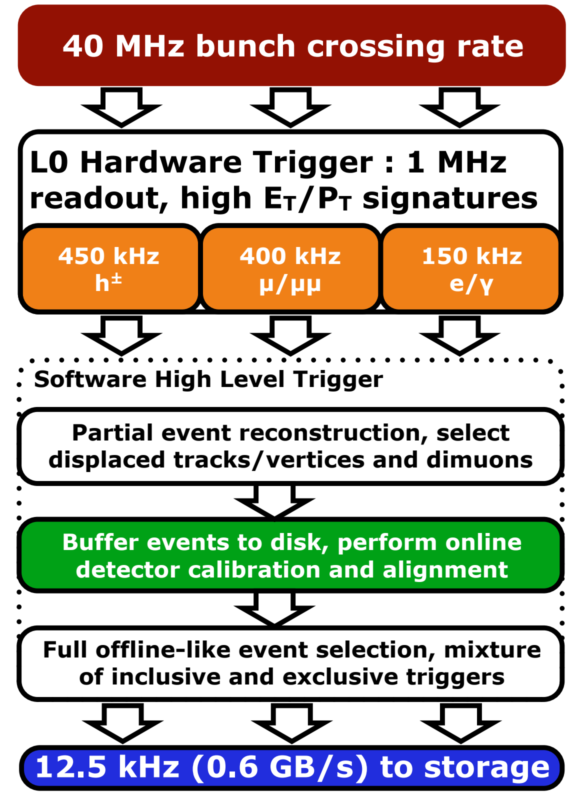
Tracking stations
δp/p = 0.5–1.0%
for p = 20–200 GeV/c

Electromagnetic calorimeter
25 X_0, 1.2 λ_{int} $\frac{\sigma(E)}{E} = 1\% \oplus \frac{10\,\%}{\sqrt{E/GeV}}$

JINST 3 S08005 (2008)
Int. J. Mod. Phys. A 30 (2015) 7, 1530022

LHCb trigger and data-taking strategy





Comput. Phys. Commun. 208 (2016) 35

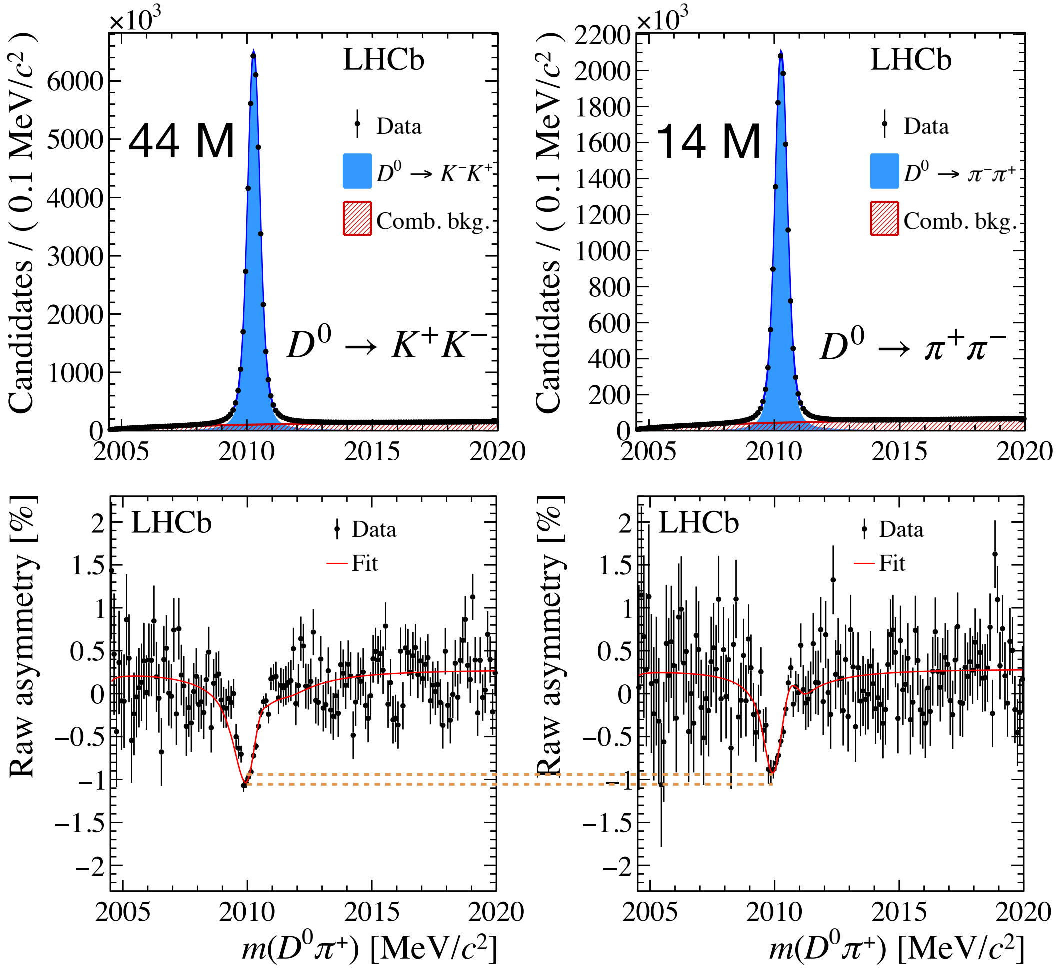
Yield has more than doubled between Run 1 and 2:

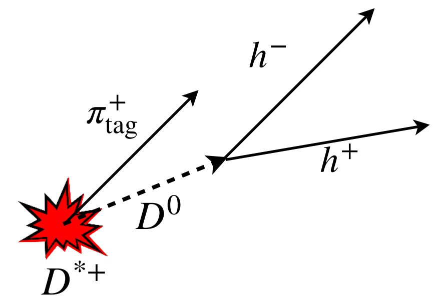
- × 1.7 increase in production cross-section;
- new “Turbo" data taking paradigm
  - only the signal candidates are recorded, rest of the event is discarded;
  - improved efficiency, higher rate recorded.

Pioneered by charm triggers

First observation of CPV

$$D^*(2010)^+ \to D^0\pi^+$$





$$\frac{N(D \to f) - N(\bar{D} \to \bar{f})}{N(D \to f) + N(\bar{D} \to \bar{f})}$$

production cross-section

$$A_{\rm raw}(f) \approx A_{CP}(f) + A_{\rm det}(\pi^+) + A_{\rm prod}(D^{*+})$$

a_f^d (CPV in decay) + small time-dependent contributions

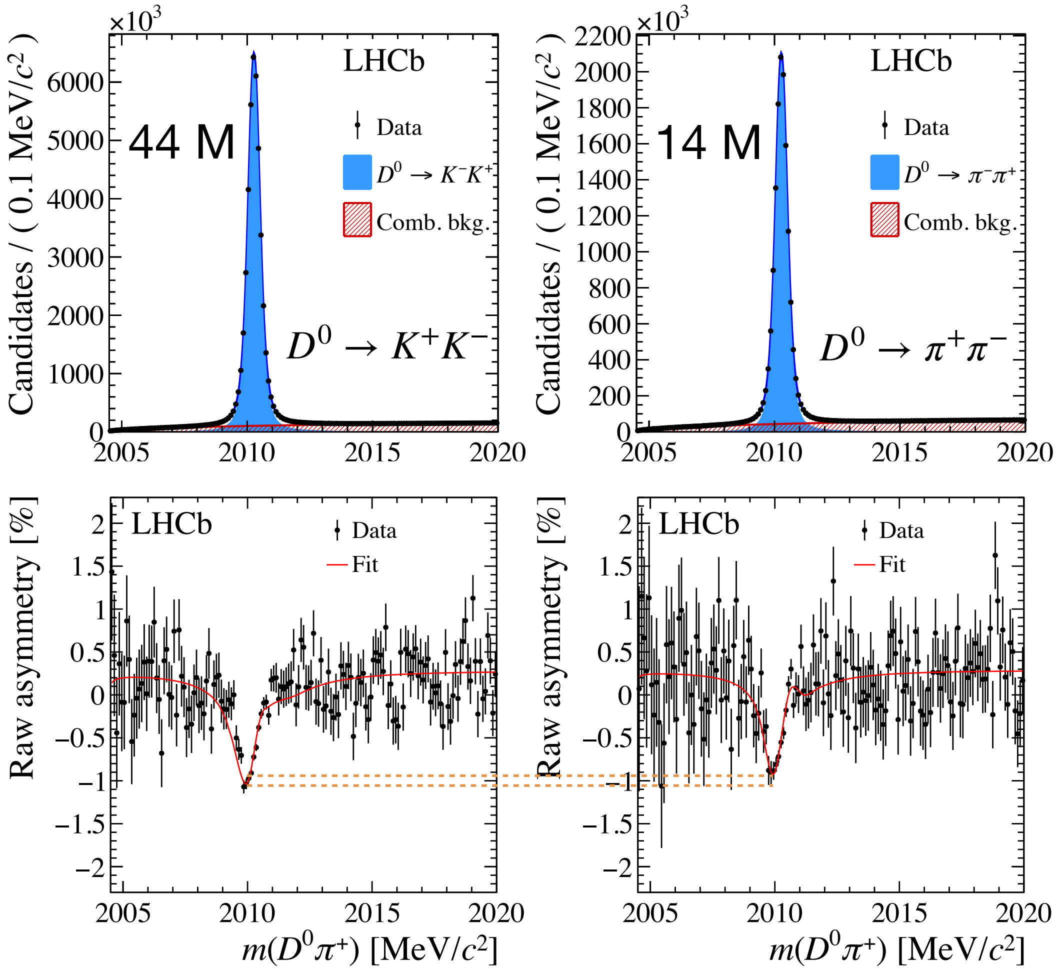
detection of tagging π⁺

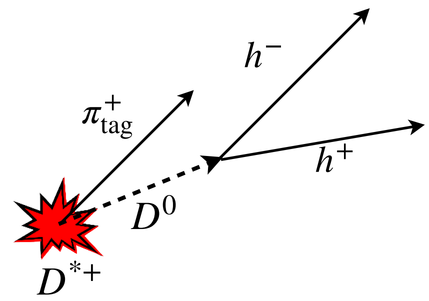
$$\Delta A_{CP} = A_{\rm raw}(K^+K^-) - A_{\rm raw}(\pi^+\pi^-)$$
$$\approx a^d_{K^+K^-} - a^d_{\pi^+\pi^-} = (-1.54 \pm 0.29) \times 10^{-3} \quad (5.3\sigma)$$

PRL 122 (2019) 211803
6 fb^{-1}, 2015–2018

First observation of CPV

$D^*(2010)^+ \to D^0\pi^+$





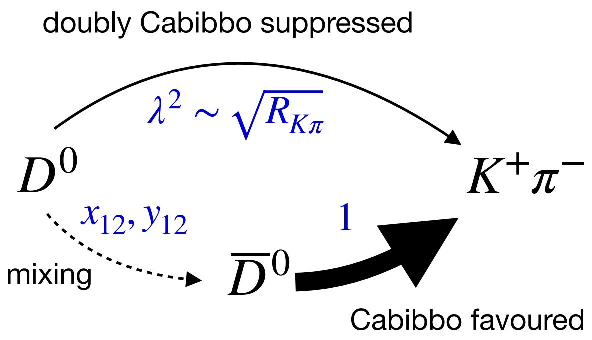
- Larger than most SM predictions
  - Franco, Mishima & Silvestrini, JHEP 05 (2012) 140
  - Li et al, Phys. Rev. D 86 (2012) 036012
  - Cheng & Chiang, Phys. Rev. D 85 (2012) 034036
  - Khodjamirian & Petrov, Phys. Lett. B 774 (2017) 235
  - Pich, Solomonidi & Vale Silva, Phys. Rev. D 108 (2023) 3, 036026
  - Lenz, Piscopo & Rusov, JHEP 03 (2024) 151
- O(1–10) enhancement of QCD rescattering or BSM?
  - Chala et al, JHEP 07 (2019) 161
  - Grossman & Schacht, JHEP 07 (2019) 020
  - Buccella et al, Phys. Rev. D 99 (2019) 11, 113001
  - Cheng & Chiang, Phys. Rev. D 100 (2019) 9, 093002
  - Schacht & Soni, Phys. Lett. B 825 (2022) 136855
  - Dery & Nir, JHEP 12 (2019) 104
  - Wang et al, JHEP 09 (2021) 126
  - Bause et al, Phys. Rev. D 101 (2020) 11, 115006
  - Dery et al, JHEP 05 (2021) 179
  - Cheng & Chiang, Phys. Rev. D 104 (2021) 7, 073003
  - Gavrilova, Grossman & Schacht, Phys. Rev. D 109 (2024) 3, 033011

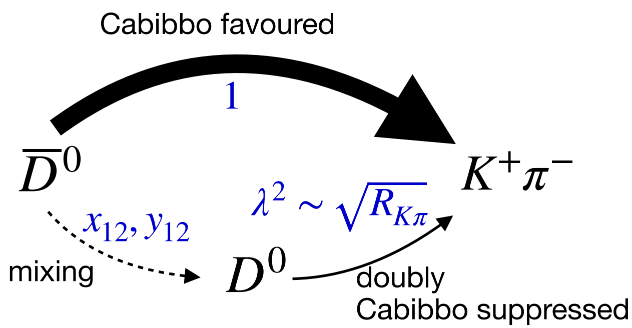
PRL 122 (2019) 211803
6 fb^{-1}, 2015–2018

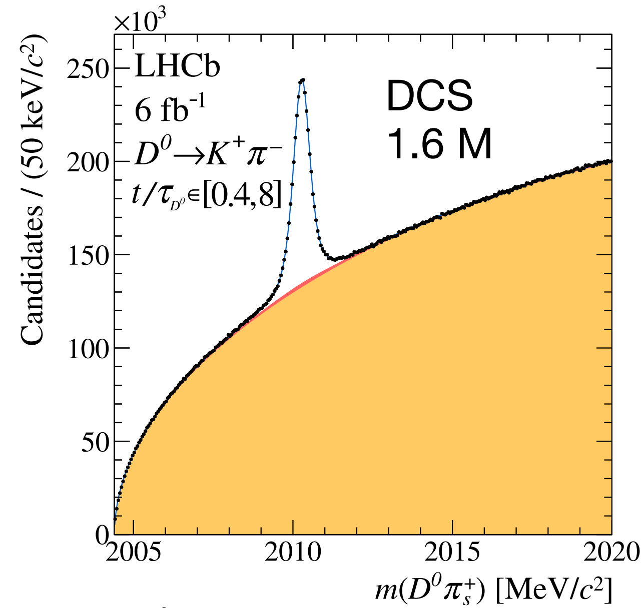
$$\Delta A_{CP} = A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-)$$
$$\approx a^d_{K^+K^-} - a^d_{\pi^+\pi^-} = (-1.54 \pm 0.29) \times 10^{-3} \quad (5.3\sigma)$$

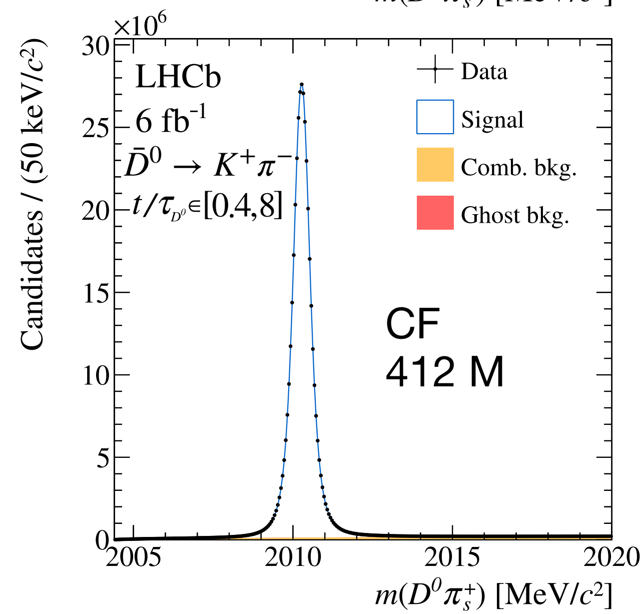
Mixing and CPV with $D^0 \to K^+\pi^-$

LHC seminar 26.03.2024
LHCb-PAPER-2024-008
(in preparation)









$$R(t) = \frac{\Gamma(D^0 \to K^+\pi^-;t)}{\Gamma(\bar{D}^0 \to K^+\pi^-;t)} = \overbrace{R_{K\pi}}^{\text{DCS}} + \overbrace{\sqrt{R_{K\pi}}\, \underbrace{c_{K\pi}}_{y_{12}\cos\Delta_{K\pi} + x_{12}\sin\Delta_{K\pi}} \left(\frac{t}{\tau}\right)}^{\text{interference}} + \overbrace{\underbrace{c'_{K\pi}}_{\frac{x_{12}^2+y_{12}^2}{4}} \left(\frac{t}{\tau}\right)^2}^{\text{mixing + CF}}$$

$$\frac{A(D^0 \to K^+\pi^-)}{A(\bar{D}^0 \to K^+\pi^-)} \approx -\sqrt{R_{K\pi}}\, e^{i\Delta_{K\pi}}$$

Measuring $A_{CP}(D^0 \to K^+K^-)$

Nuisance asymmetries subtracted through Cabibbo-favoured ($c \to us\bar{d}$) decay channels

- no QCD penguin, no chromomagnetic dipole → negligible CPV

$$A_{CP}(D^0 \to K^+K^-) \approx A_{\text{raw}}(D^{*+} \to D^0(\to K^+K^-)\pi^+) - A_{\text{raw}}(D^{*+} \to D^0(\to K^-\pi^+)\pi^+)$$
$$+A_{\text{raw}}(D_s^+ \to K^+K^-\pi^+) - A_{\text{raw}}(D_s^+ \to K^+K_S^0) + A_{\text{det}}(K^0)$$

bottleneck to final precision

regeneration and CPV in mixing explicitly calculated (cf. next slide)
CERN-THESIS-2014-274