ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

CP violation in the charm sector

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on behalf of the LHCb and Belle-II Collaboration

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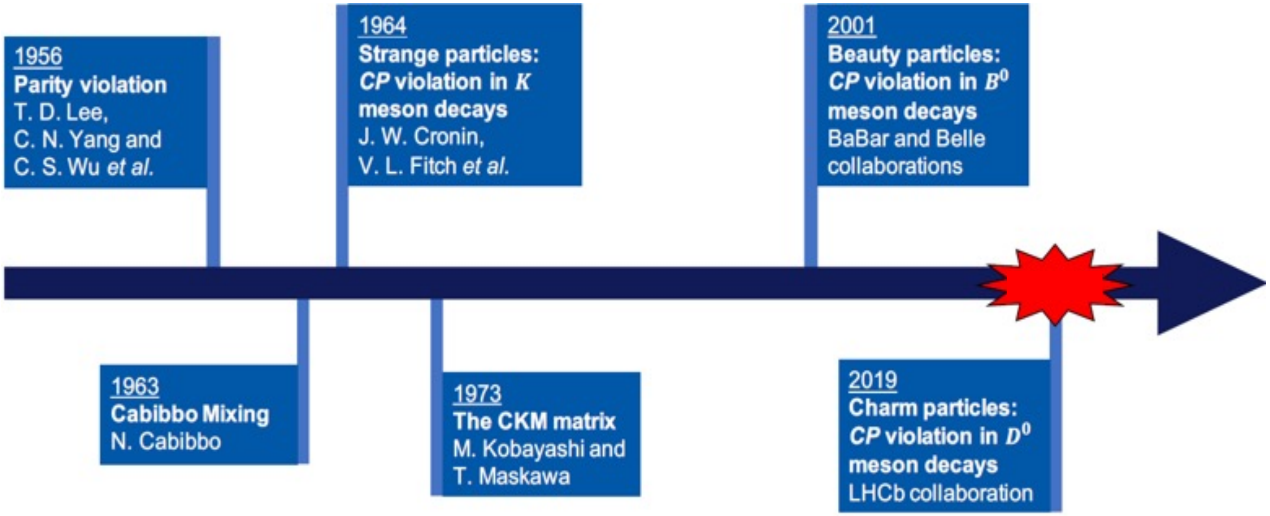
Importance of CP violation in charm physics

- Charm physics is a powerful tool for the indirect search for New Physics
- CP violation in charm decays was recently discovered
- It opens up a new field of research: the study of CP-violating effects in the sector of up-type quarks and searches for new physics effects
- CP violation in SM highly suppressed → relatively large observation of CP violation can reveal new physics



CP violation in the decay (or direct CPV)

CP Violation in the decay consists of a difference in decay amplitude between the decay of $D^0 \to f$ and its CP-conjugate $\bar{D}^0 \to \bar{f}$

$$A_f \equiv \langle f|H|D^0\rangle$$
$$\bar{A}_f \equiv \langle \bar{f}|H|\bar{D}^0\rangle$$

$$a_f^d = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

CPV can be observed if the total amplitude of $D^0 \to f$ (or $\bar{D}^0 \to \bar{f}$) consists of two interfering amplitudes with different phases

$$A_f = A_1 e^{i\phi_1} e^{i\delta_1} + A_2 e^{i\phi_2} e^{i\delta_2}$$
$$\bar{A}_{\bar{f}} = A_1\, e^{-i\phi_1} e^{i\delta_1} + A_2 e^{-i\phi_2} e^{i\delta_2}$$
$$|A_f|^2 - |\bar{A}_{\bar{f}}|^2 = 2|A_1||A_2|\sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2)$$

Only weak phases change under the action of the CP operator

Strong phases can enhance the observed CP violation

CP violation in the mixing and interference between mixing and decay

$$|D_1\rangle = p|D_0\rangle + q|\bar{D}^0\rangle$$
$$|D_2\rangle = p|D_0\rangle - q|\bar{D}^0\rangle$$

$$\left|\frac{q}{p}\right| \neq 1$$ CP violation in mixing

$$x = \frac{m_1 - m_2}{\Gamma}$$
$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$
$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

$$|D_{1,2}(t)\rangle = [p|D_0\rangle \pm q|\bar{D}^0\rangle]e^{-i\left(m_{1,2} - i\frac{\Gamma_{1,2}}{2}\right)t}$$

Four decay rates

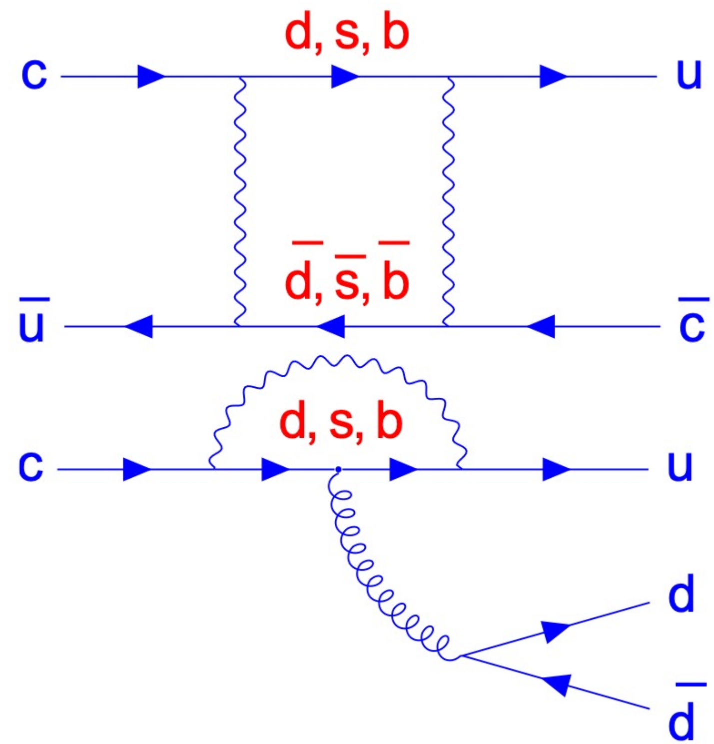
$$\Gamma_{D^0\to f}(t) = |\langle f|H|D^0(t)\rangle|^2$$
$$\Gamma_{\bar{D}^0\to \bar{f}}(t) = \left|\langle \bar{f}|H|\bar{D}^0(t)\rangle\right|^2$$
$$\Gamma_{D^0\to \bar{f}}(t) = \left|\langle \bar{f}|H|D^0(t)\rangle\right|^2$$
$$\Gamma_{\bar{D}^0\to f}(t) = |\langle f|H|\bar{D}^0(t)\rangle|^2$$

$$\Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$
$$\phi = \arg\left(\frac{q}{p}\right) \neq 0$$

CP violation in interference between mixing and decay

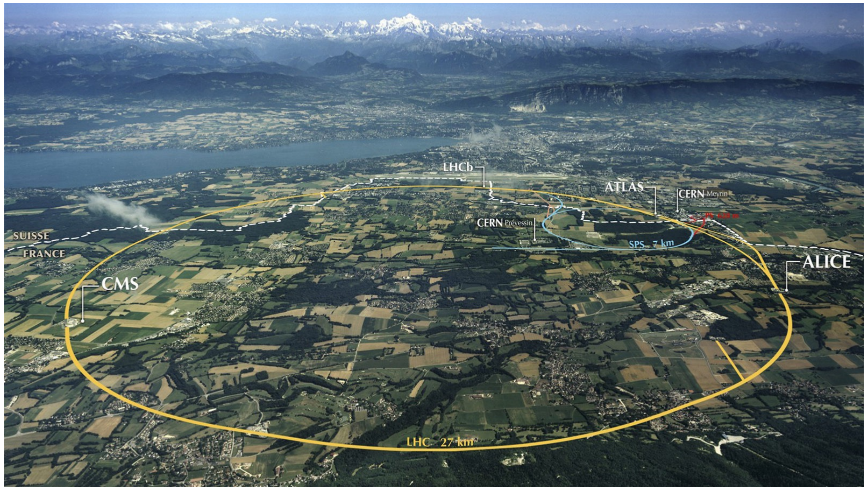
Charm CP violation in the SM model

- Observation of CP violation is highly suppressed in the SM
- Interference with loop diagrams of down-type quark
  - beauty loop → $V_{ub}V_{cb}\left(\frac{m_b}{m_W}\right)^2 \sim 10^{-6}$
  - strange-down loops → $\frac{(m_s^2 - m_d^2)}{m_W^2} \sim 0$ in the u-spin limit (GIM mechanism)
- QCD corrections are large and difficult to calculate
- Lifetime of charged hadrons are not affected by these mechanisms



Charm physics program in LHCb

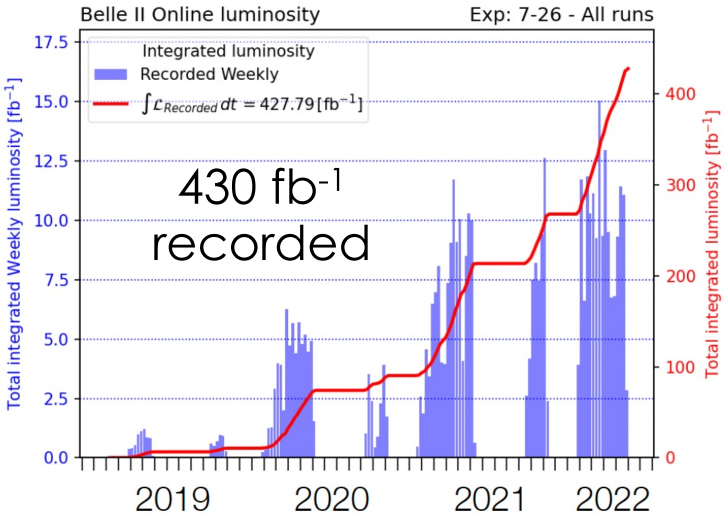
- Large $c\bar{c}$ production cross section ~2.8 mb@13 TeV
- Billions of $D^0 \to K^{\mp}\pi^{\pm}$ decays reconstructed with the full LHCb data sample
- Two ways to identify the flavour of D^0
  - Prompt tag: look at the π charge of $\mathrm{D}^{*+} \to D^0\pi^+$
  - Semileptonic tag: look at the μ charge in $\bar{B} \to D^0\mu^-\nu_\mu \mathrm{X}$



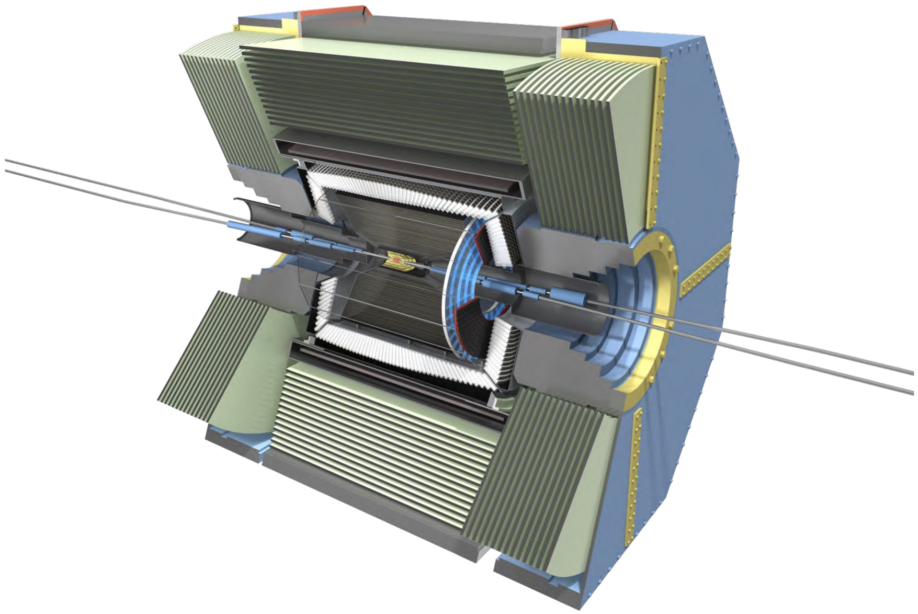
- Precise CP violation measurements need control of detection and production asymmetries at the per-mille level
- Direct CP violation → observed for the first time by LHCb in 2019
  - $\Delta A_{CP} = (-15.4 \pm 2.9)\times 10^{-4}$ [Phys. Rev. Lett. 122 (2019) 211803]
- CP violation due to mixing and interference between mixing and decay → per-mille level measurements performed

Charm physics program at Belle II

- Large $e^+e^- \to c\bar{c}$ cross-section provides low-background event samples
- 1.3M $c\bar{c}$ events per 1 fb^{-1}, all recorded to tape (~100% trigger efficiency uniform across decay time and kinematics)
- Rich program of charm physics
  - Excellent reconstruction of final states with neutrals: e.g., $D^0 \to \pi^0\pi^0$, $D^+ \to \pi^+\pi^0$, $D^0 \to \rho^0\gamma, \ldots$ to complement LHCb physics program with charged hadrons
- Unique access to final states with invisible particles: e.g., di-neutrino final states
- Novel charm flavour tagging (CFT) [PRD 107 (2023) 112010] → double the sample wrt D^{*+}-tagged

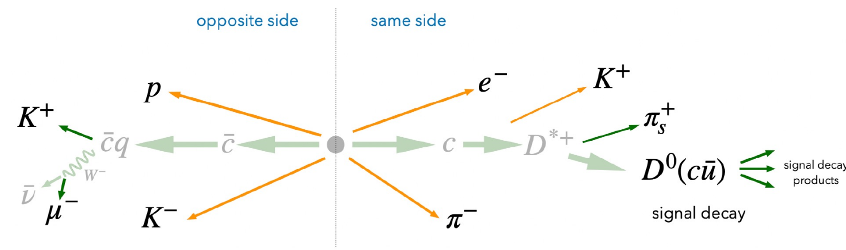


Latest results from Belle-II



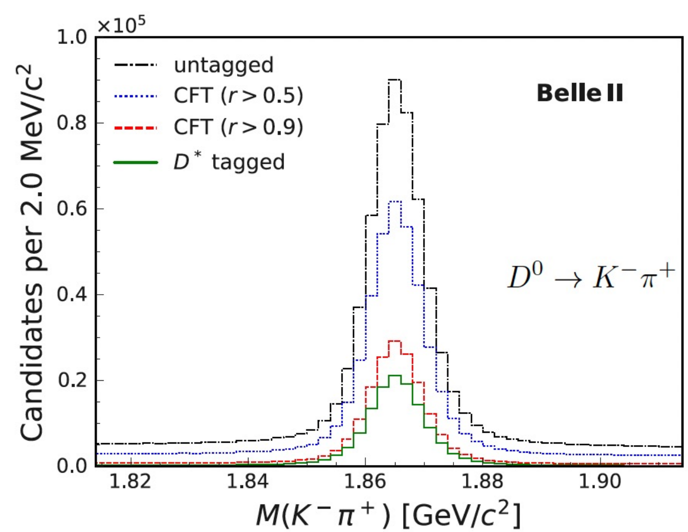
Novel charm flavour tagging (CFT)

- Inspired by opposite-side b-flavor tagging
- Reconstruct particles most collinear with signal meson, use machine learning
- Trained using simulation
  Performance measured and calibrated with data



$$\varepsilon_{\text{tag}}^{\text{eff}} = (47.91 \pm 0.07(\text{stat}) \pm 0.51(\text{syst}))\%$$

best performance across any flavor tagger



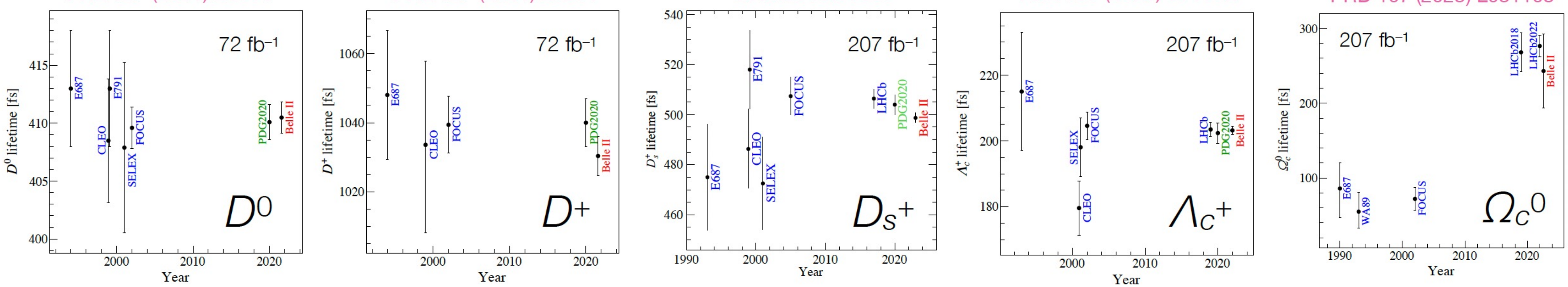
- Doubles the sample size w.r.t. D^{*+}-tagged decays
- Performance measured and calibrated on data

PRD 107 (2023) 112010

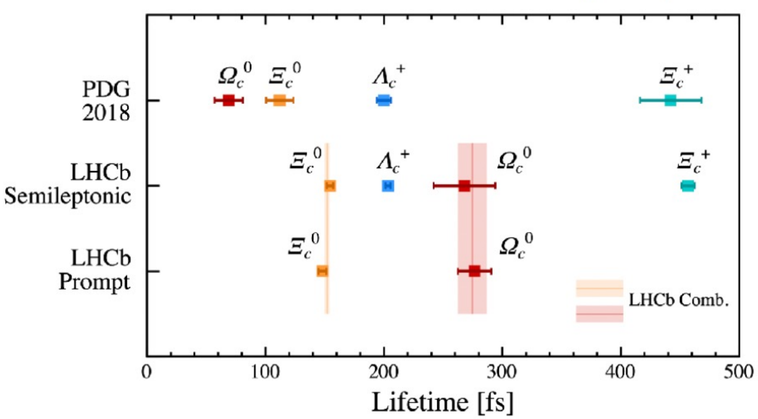
Charm lifetimes

- Lifetime hierarchy of heavy-flavoured hadrons crucial to constrain and validate predictions of mixing and CP violation based on heavy quark expansion (HQE)

PRL 127 (2021) 21801 | PRL 127 (2021) 21801 | arXiv:2306.00365 | PRL 130 (2023) 071802 | PRD 107 (2023) L031103

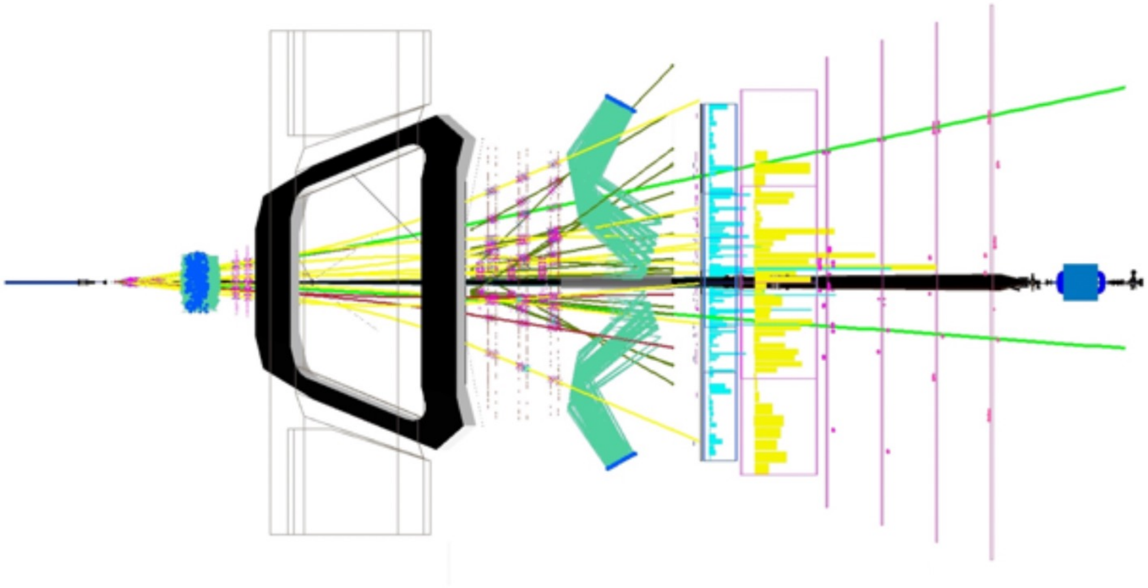


Sci. Bull. 67 (2022) 479



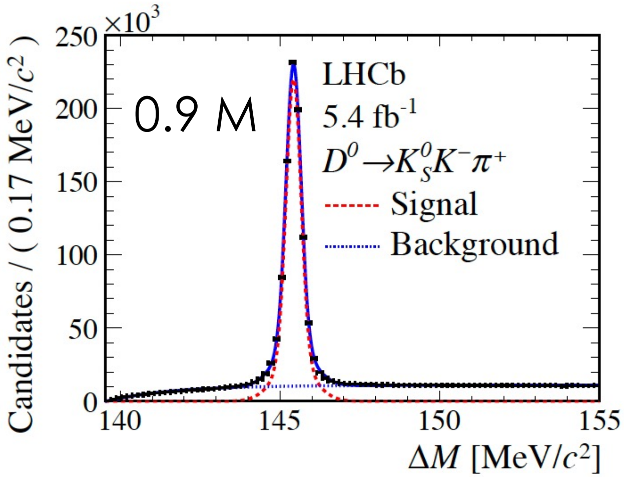
- Belle II data provide unique opportunity for precision measurements of absolute lifetimes
- World-best $D^0, D^+,\ D_s^+$ and Λ_c^+ lifetimes
- Confirmation of LHCb result indicating that the Ω_c^0 is not the shortest-lived weakly decaying charmed baryon
- High-precision measurements with systematics under control pave the way to time-dependent measurements at Belle II

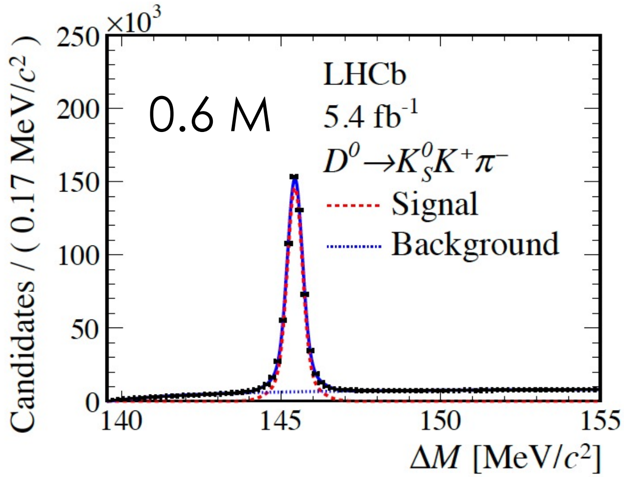
Latest results from LHCb



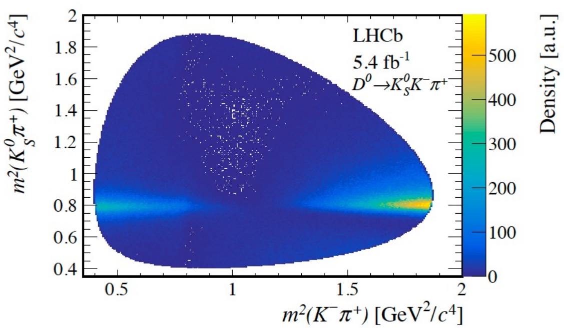
CP violation in $D^0 \to K_S^0 K^{\pm} \pi^{\mp}$ decays

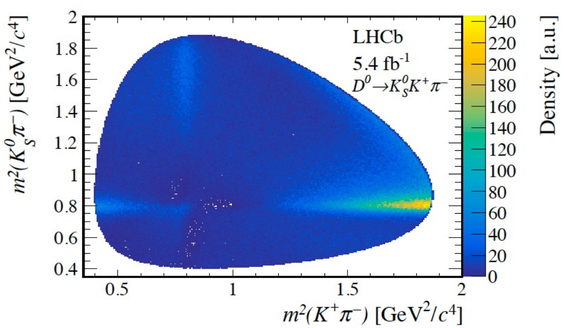
[LHCb-PAPER-2023-019]





Rich Dalitz structure





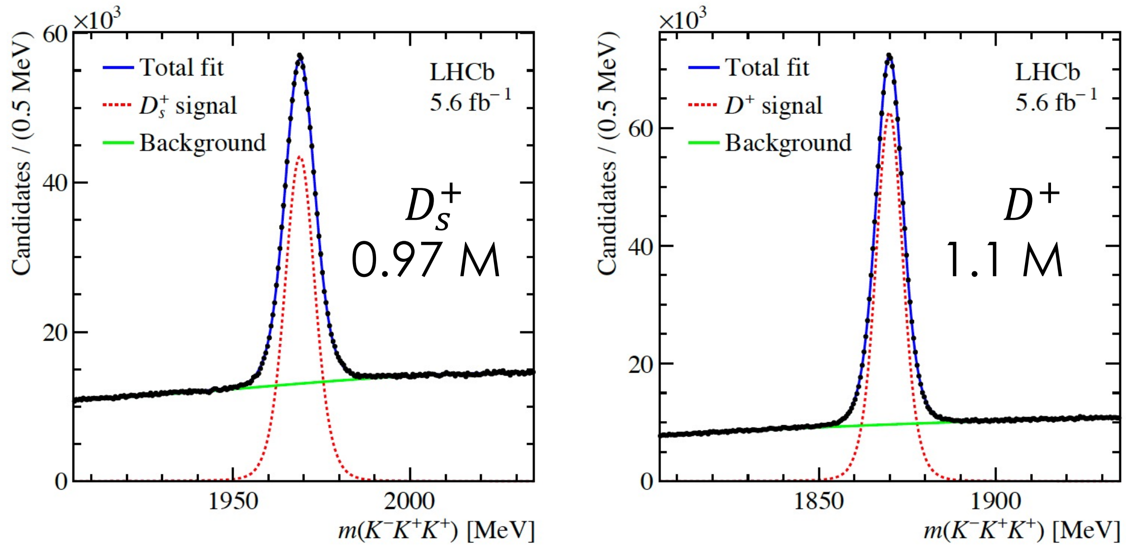
Energy test

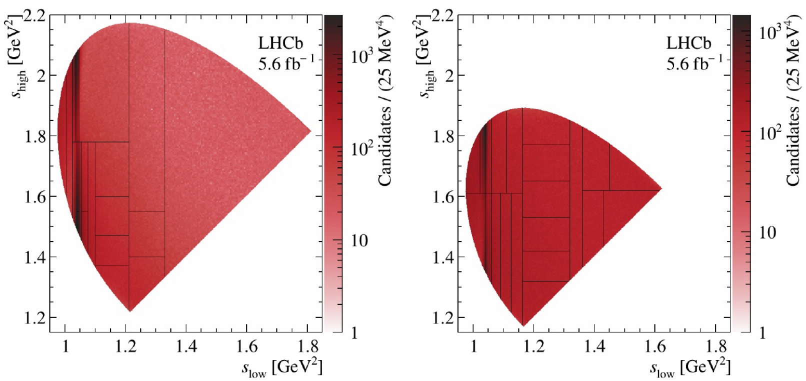
Search for differences in the D^0 and $\overline{D}^0$ Dalitz plot via the distances between decays in the phase-space distributions.

No significant difference was observed between D^0 and $\overline{D}^0$

CP violation in $D_{(s)}^{+} \to K^{+}K^{-}K^{+}$ decays

[JHEP 07 (2023) 067]





Miranda technique
[Phys. Rev. D **80**, 096006]

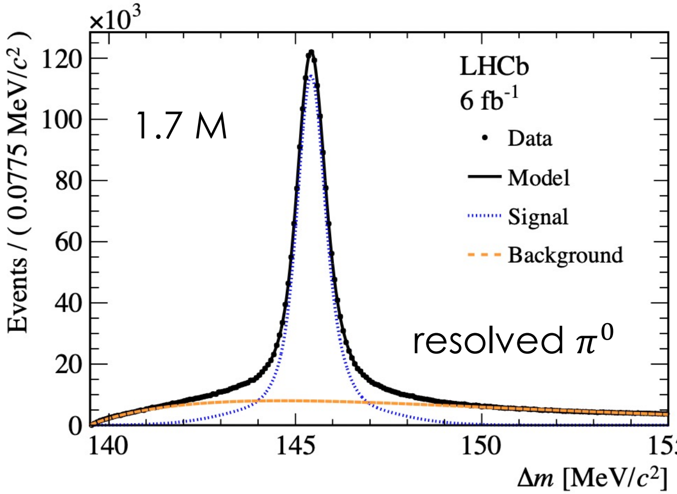
binned model-independent technique that measures CP violation observables in each bin

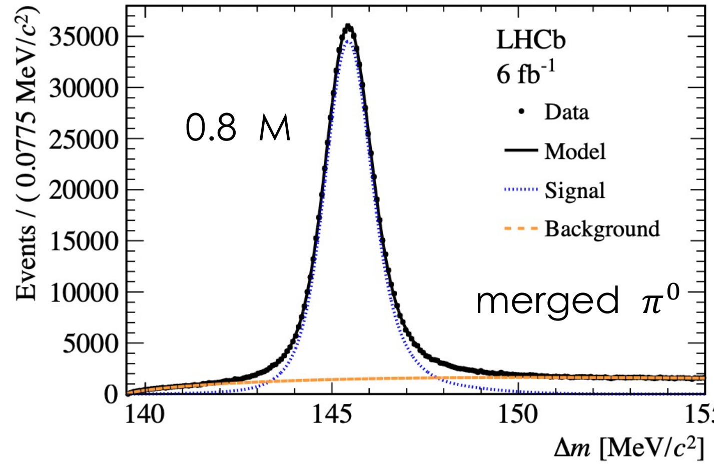
χ^2-test against null-hypothesis (no CPV) to search for CPV

No evidence of CP violation was observed
p-values wrt null-hypothesis 13.3% for D_s^+ and 31.6% for D^+

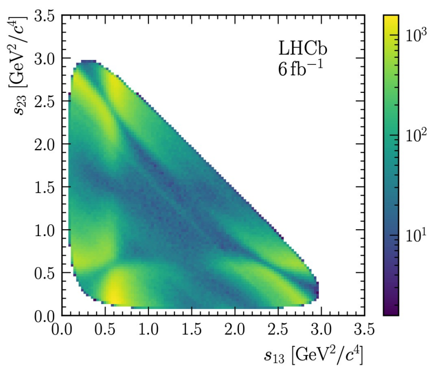
CP violation in $D^+ \to \pi^+\pi^-\pi^0$ decays

[JHEP 09 (2023) 129]



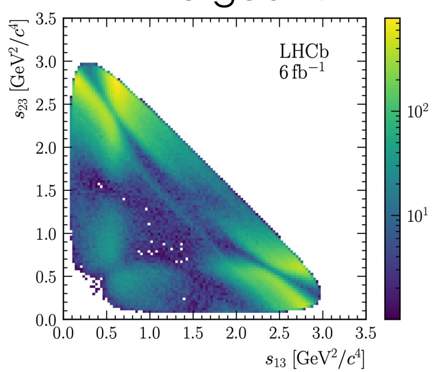


resolved π^0



reconstructed from two photons

merged π^0



single cluster in electromagnetic calorimeter

Energy test

Search for differences in the D^0 and $\overline{D}^0$ Dalitz plot via the distances between decays in the phase-space distributions.

No significant difference was observed between D^0 and $\overline{D}^0$

CP violation in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$

CP violation was observed in 2019 by LHCb with $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays measuring the difference of the time-integrated CP asymmetry

$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$$

LHCb observed (5.3 σ) CP violation in the neutral charm decay

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

Time-integrated CP asymmetry

$$A_{CP}(f) = \frac{\int \epsilon(t)[\Gamma(D^0\to f)(t) - \Gamma(\bar{D}^0\to \bar{f})(t)]dt}{\int \epsilon(t)[\Gamma(D^0\to f)(t) + \Gamma(\bar{D}^0\to \bar{f})(t)]dt} = a_f^d + \frac{<t>_f}{\tau_{D^0}}\Delta Y_f$$

$\epsilon(t)$ is the time-depedent reconstruction efficiency
ΔY_f is related to the parameters descibing mixing and interference between mixing and decay
$< t >_f$ is the average acceptance-dependent decay time of the D^0 mesons in the experimental sample

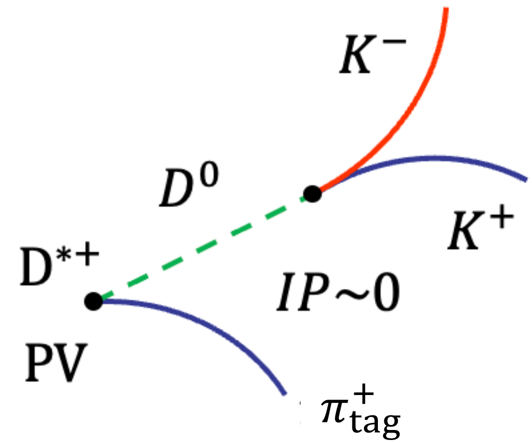
[Phys. Rev. Lett. 122 (2019) 211803]

CP violation in $D^0 \to K^- K^+$

[JHEP 07 (2023) 228]

The flavour of the initial state (D^0 or $\bar{D}^0$) is tagged by the charge of the pion from $D^{*+} \to D^0\pi^+_{\mathrm{tag}}$ and $D^{*-} \to \bar{D}^0\pi^-_{\mathrm{tag}}$ coming from primary verteces

Prompt D^{*+} decay



The asymmetry, made of the number of reconstructed D^0 and $\bar{D}^0$, is defined as

$$A = \frac{N(D^0 \to f) - N\left(\bar{\mathrm{D}}^0 \to \bar{f}\right)}{N(D^0 \to f) + N\left(\bar{\mathrm{D}}^0 \to \bar{f}\right)}$$

and it is related to the CP asymmetry as

$$A = A_{CP} + \underbrace{A_D(\pi) + A_P(D^{*+})}_{\text{nuisance asymmetries}}$$

production asymmetry

$$A_P = \frac{\sigma(D) - \sigma(\bar{D})}{\sigma(D) + \sigma(\bar{D})}$$

reconstruction asymmetry

$$A_D = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})}$$

[JHEP 07 (2023) 228]

Final results

The value of the CP asymmetries are

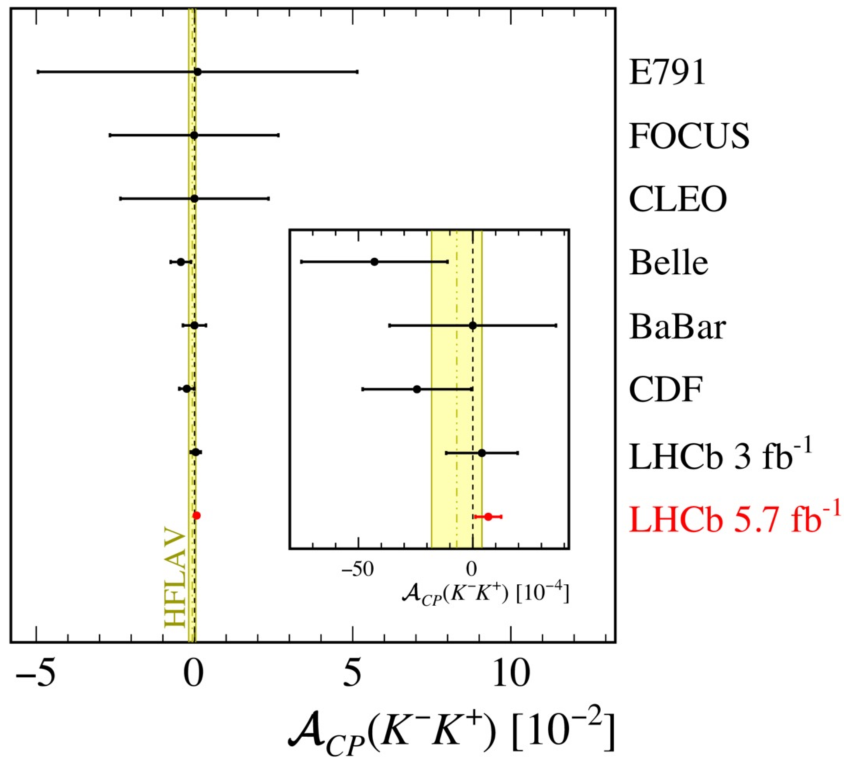
$$\mathrm{C}_{D^+}: \; \mathcal{A}_{CP}(K^-K^+) = [13.6 \pm 8.8\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst})] \times 10^{-4},$$
$$\mathrm{C}_{D_s^+}: \; \mathcal{A}_{CP}(K^-K^+) = [\;2.8 \pm 6.7\,(\mathrm{stat}) \pm 2.0\,(\mathrm{syst})] \times 10^{-4}.$$

with a total correlation corresponding to $\rho = 0.06$

The average corresponds to

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

consistent with the previous results

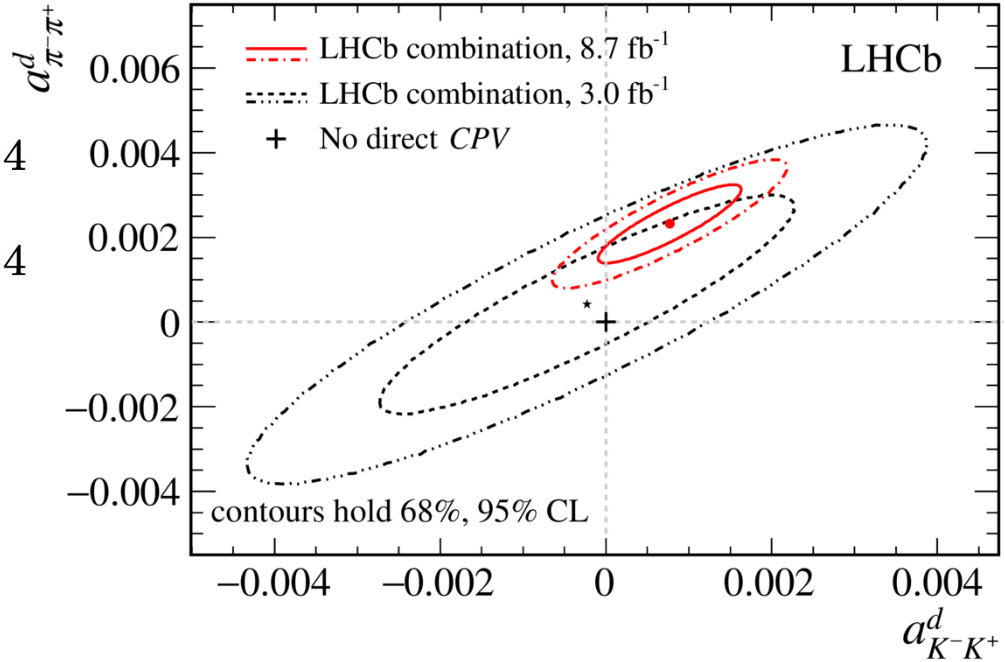


First evidence for direct CP violation

Combining this measurement with the ΔA_{CP} and ΔY_f LHCb measurements

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

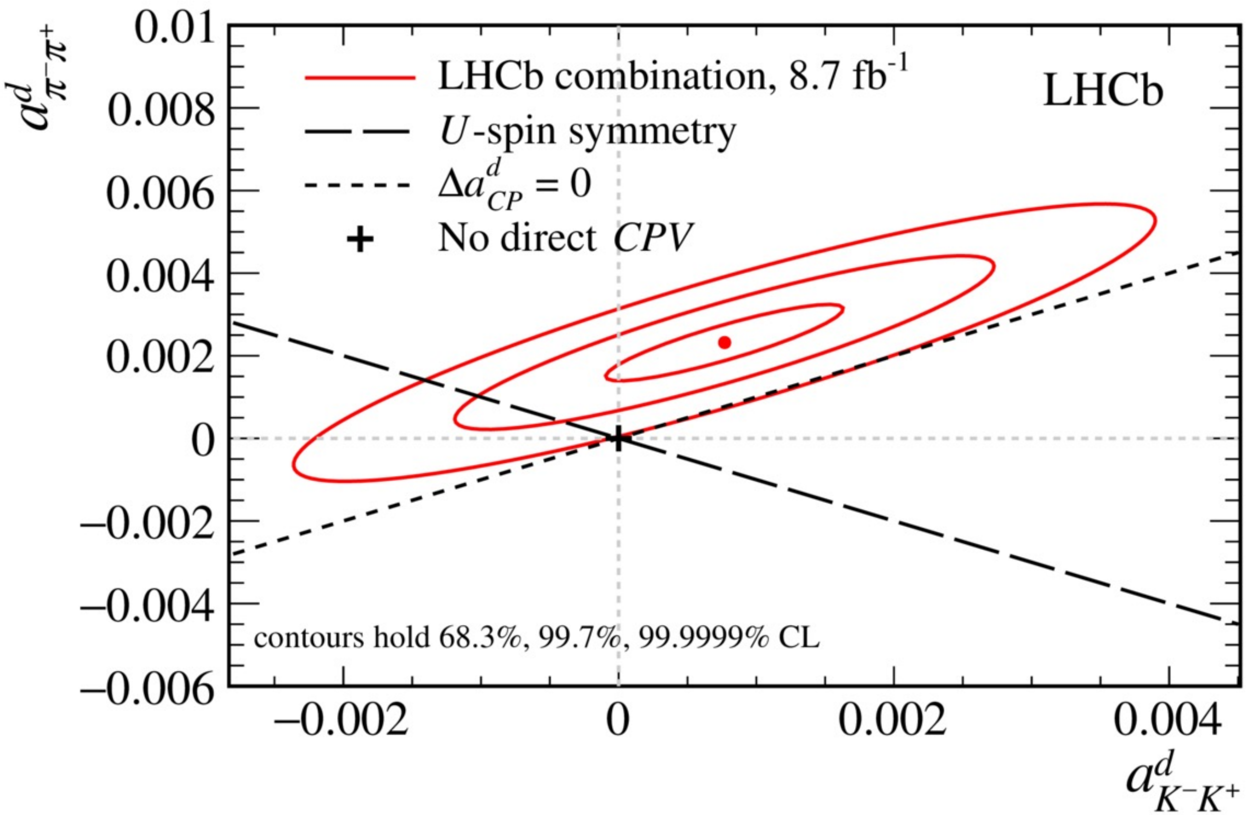
with $\rho(a^d_{KK}, a^d_{\pi\pi}) = 0.88$



This is the first evidence of CP violation in $D^0 \to \pi^-\pi^+$ (3.8σ) in an individual charm meson decay

[JHEP 07 (2023) 228]

U-spin symmetry



$a^d_{KK} + a^d_{\pi\pi} \neq 0$ at the level of 2.7 standard deviation

[JHEP 07 (2023) 228]

CP violation in mixing with $D^0 \to K_s^0\pi^+\pi^-$ from B decays (bin-flip method)

For each decay-time interval (j), the ratio of the number of decays in each negative Dalitz-plane bin (−b) to its positive counterpart (+b) is measured

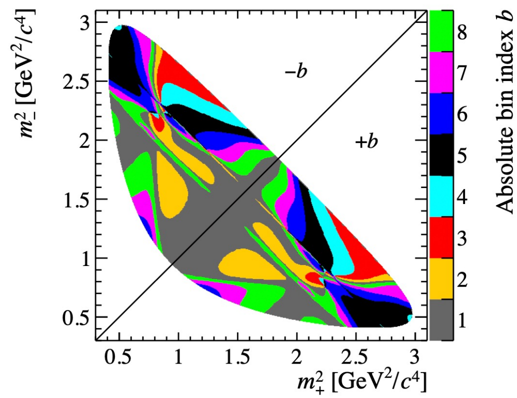
$$R_{bj}^{\pm} \approx \frac{r_b + \frac{1}{4} r_b \langle t^2\rangle_j \mathrm{Re}(z_{CP}^2 - \Delta z^2) + \frac{1}{4}\langle t^2\rangle_j |z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\langle t\rangle_j \mathrm{Re}[X_b^*(z_{CP} \pm \Delta z)]}{1 + \frac{1}{4}\langle t^2\rangle_j \mathrm{Re}(z_{CP}^2 - \Delta z^2) + r_b \frac{1}{4}\langle t^2\rangle_j |z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\langle t\rangle_j \mathrm{Re}[X_b(z_{CP} \pm \Delta z)]}.$$

r_b → value of the ratio for $t = 0$

$< t >$ ($< t^2 >$) → average (squared) decay time

$z = (-y + ix)$ with $z_{CP} \pm \Delta z \equiv \left(\frac{q}{p}\right)^{\pm 1} z$

X_b is the amplitude-weighted average strong phase as measured by CLEO and BESIII Collaboration [Phys. Rev. D82 (2010) 112006, Phys. Rev. D 101 (2020) 112002]



$$x_{CP} = -\mathrm{Im}(z_{CP}) = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

$$\Delta x = -\mathrm{Im}(\Delta z) = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

$$y_{CP} = -\mathrm{Re}(z_{CP}) = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

$$\Delta y = -\mathrm{Re}(\Delta z) = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

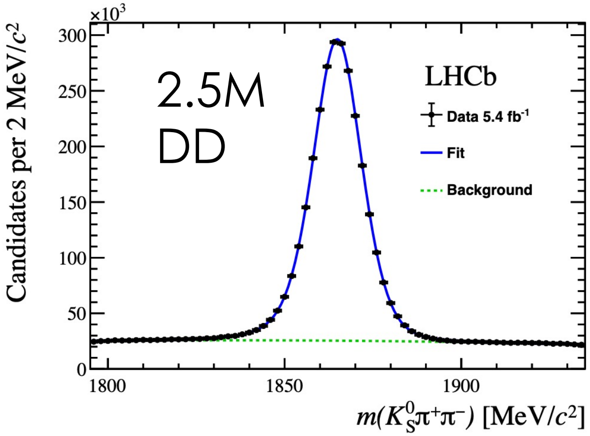
Useful parametrisation in terms of mixing parameters

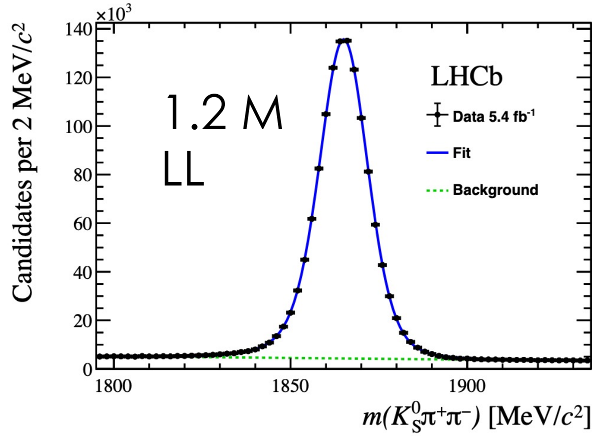
$$x_{CP}, y_{CP}, \Delta x, \Delta y \to x, y, \phi, \left|\frac{q}{p}\right|$$

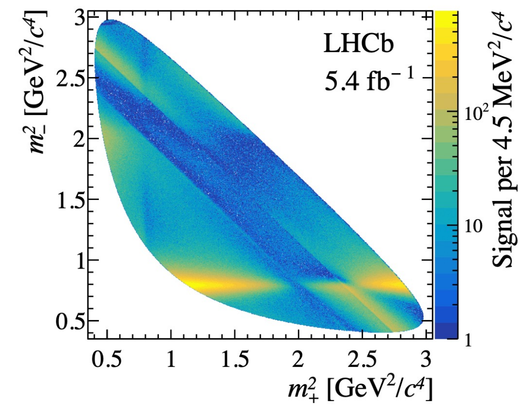
[Phys. Rev. D108 (2023) 052005]

CP violation in mixing with $D^0 \to K_s^0\pi^+\pi^-$ from B decays

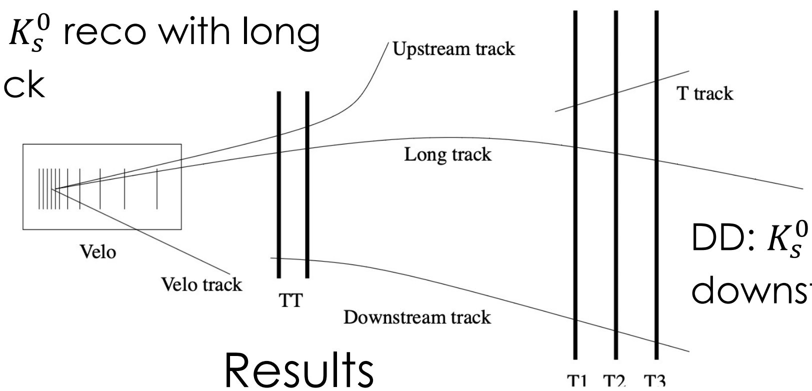
LHCb-PAPER-2022-020







LL: K_s^0 reco with long track



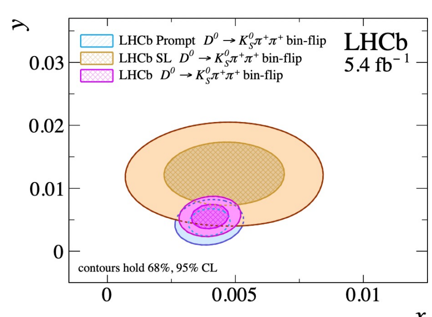
DD: K_s^0 reco with downstream track

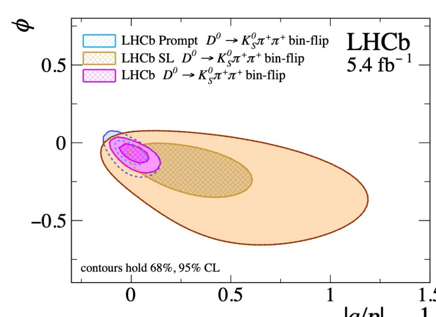
Results

$$
\begin{aligned}
x_{CP} &= [\;\;\, 4.29 \pm 1.48 \pm 0.26] \times 10^{-3}, \\
y_{CP} &= [\;12.61 \pm 3.12 \pm 0.83] \times 10^{-3}, \\
\Delta x &= [-0.77 \pm 0.93 \pm 0.28] \times 10^{-3}, \\
\Delta y &= [\;\;\, 3.01 \pm 1.92 \pm 0.26] \times 10^{-3},
\end{aligned}
$$

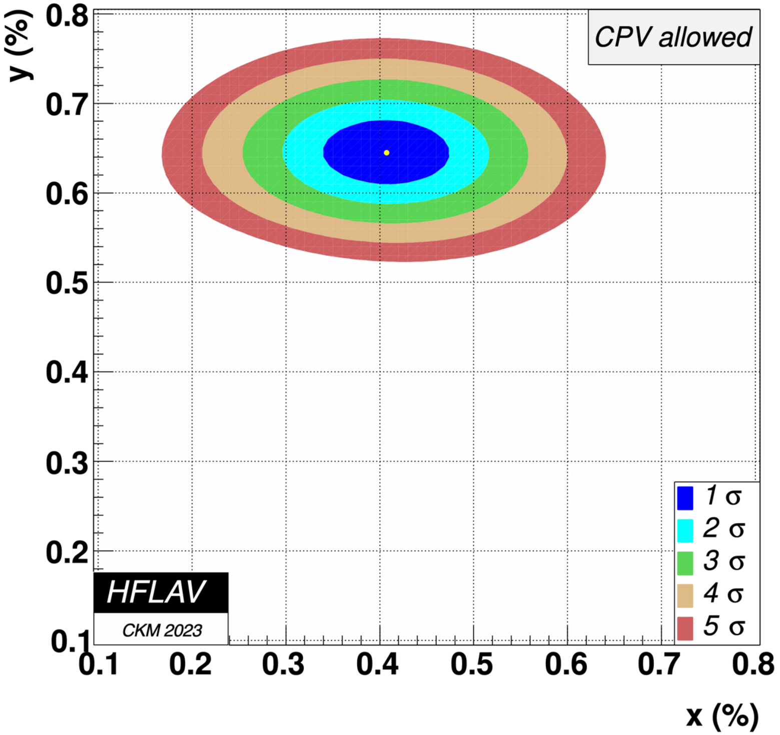
Combination with previous LHCb results

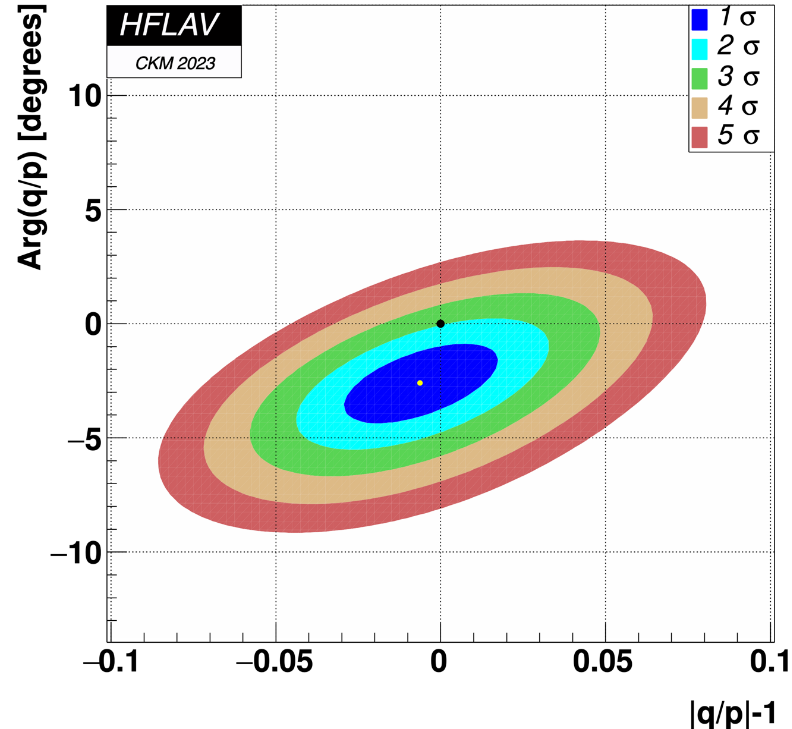
$$
\begin{aligned}
x &= (4.01 \pm 0.49) \times 10^{-3}, \\
y &= (\;5.5 \pm 1.3\;) \times 10^{-3}, \\
|q/p| &= \;\; 1.012\,^{+0.050}_{-0.048}, \\
\phi &= -0.061\,^{+0.037}_{-0.044} \text{ rad.}
\end{aligned}
$$





CP violation in mixing (HFLAV)





$$x = 0.407 \pm 0.044$$

$$y = 0.645^{+0.024}_{-0.023}$$

$$\phi = -2.6^{+1.1}_{-1.2}$$

$$\left|\frac{q}{p}\right| = 0.944^{+0.016}_{-0.015}$$

No sign of CP violation in mixing and interference between mixing and decay

Large impact of LHCb measurements on the world averages

Conclusions

- The LHCb experiment plays an important role in the determination of CP violation in charm decay
- LHCb observed for the first time CP violation in a charm decay
- High precision reached in CP violation mixing parameters
- Several searches are ongoing in LHCb to understand the nature of CP violation with additional decays (two and three bodies)
- The Belle-II experiment has on tape a sample equivalent to BaBar and half of Belle
- Belle-II data-taking will restart soon (early next year) → an important contribution is expected in the following years to complement the LHCb measurements in the charm sector
- Exciting time head for LHCb with the 2024 and 2025 data-taking campaign