Study of CP violation in charm at LHCb

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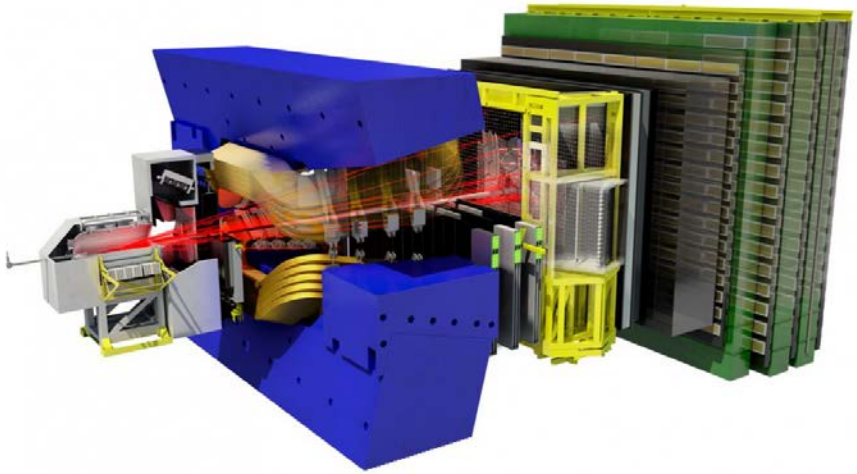

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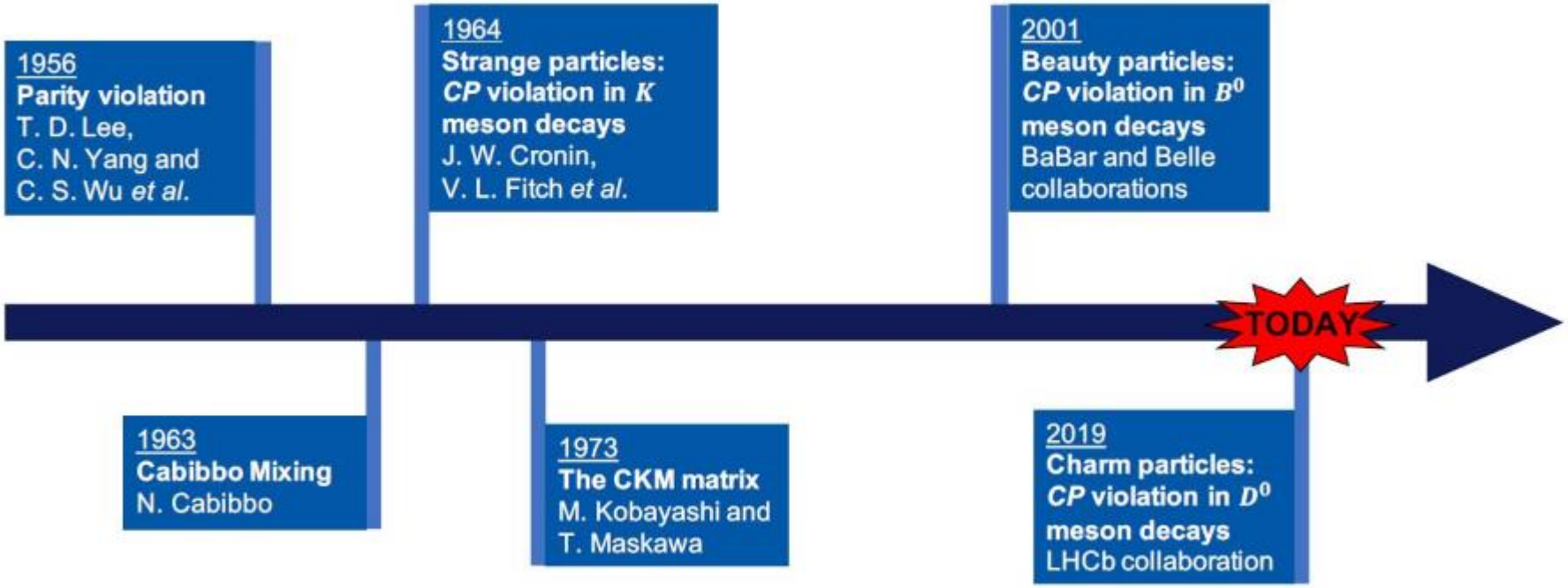
Outline

- CP violation and LHCb
- Charm mixing and indirect CPV violation
- Direct CP violation and first observation
- Future prospects
- Summary

CP Violation

Breaking of combined symmetry of Charge-conjugation and Parity

- **matter/antimatter behaves differently**
- **A necessary condition to explain BAU**



Origin of CPV in SM: $\eta \neq 0$

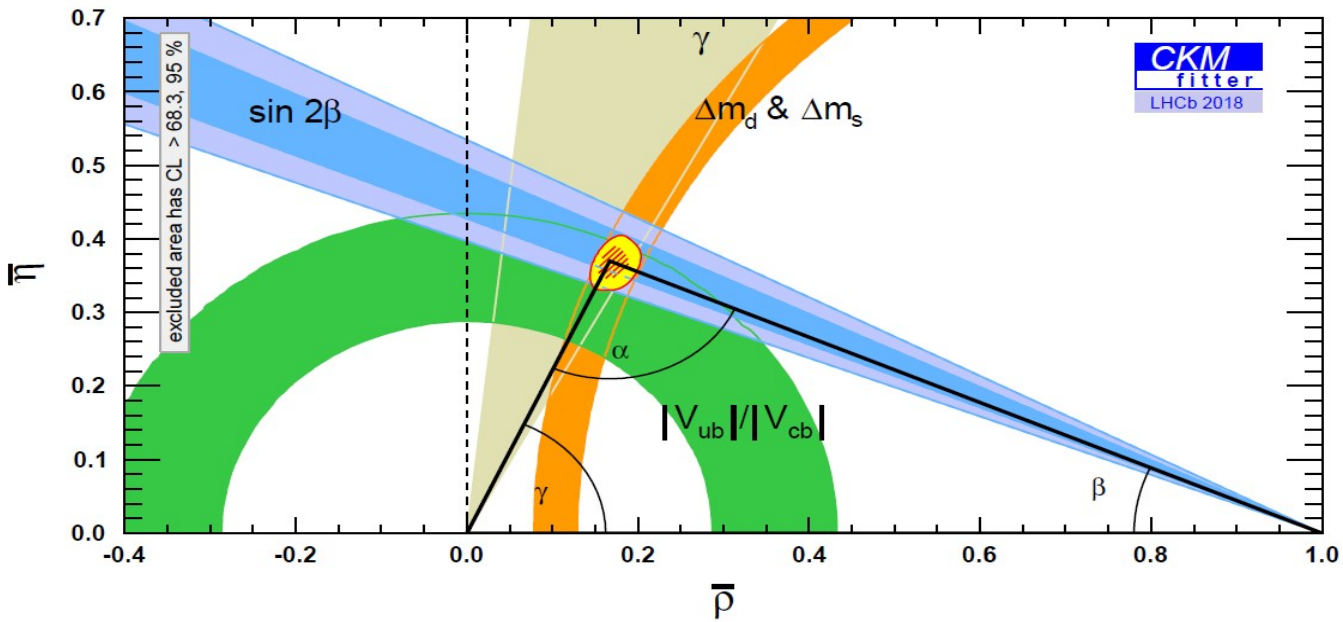
$$V_{CKM} \approx \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \hat{\rho} - i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

small CPV in charm sector

large γ

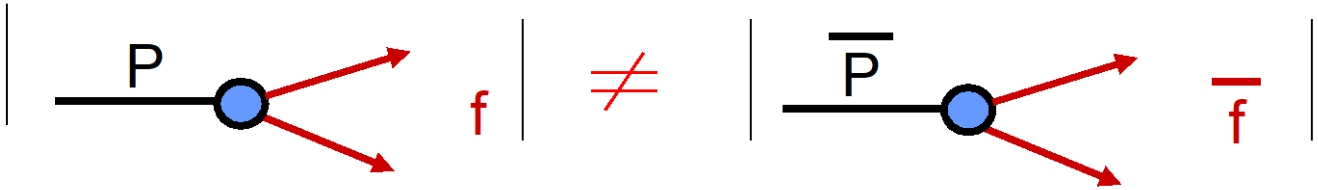
large β

small β_s



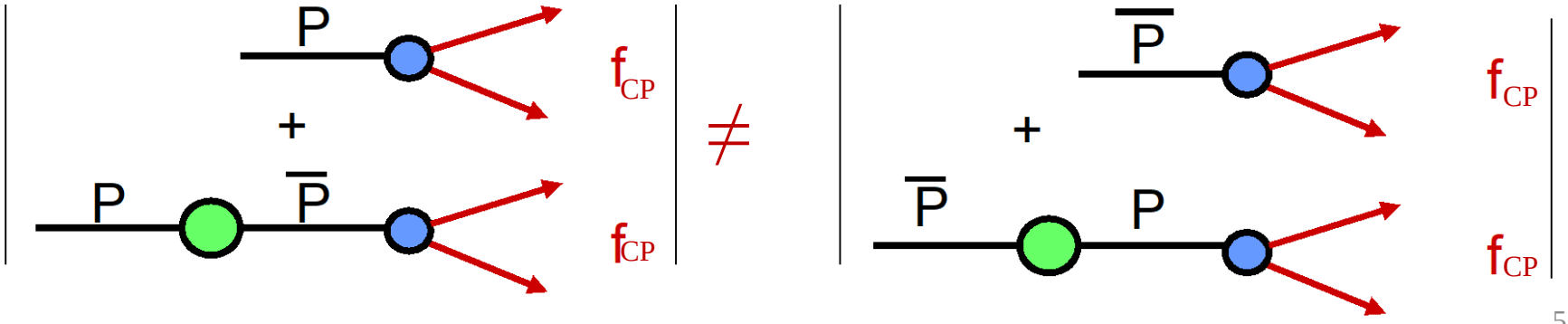
Three types of CPV

~~CP~~ in decay (Interference of 2 or more complex amplitudes)



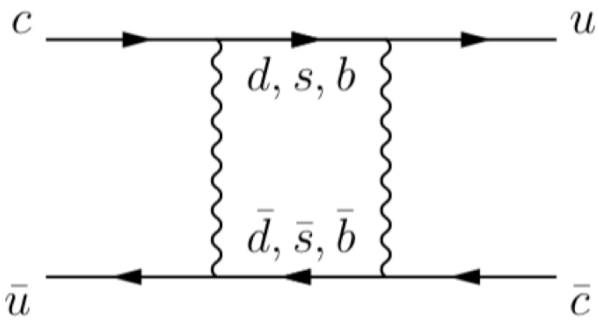
~~CP~~ in mixing ("indirect ~~CP~~")

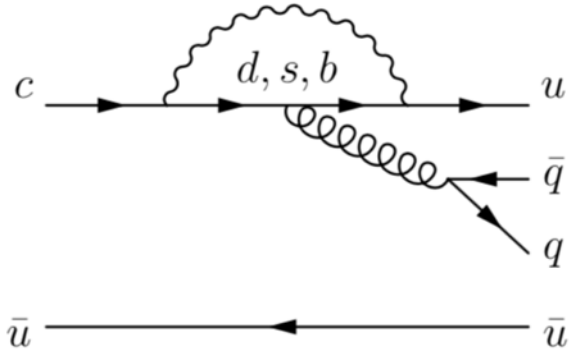
~~CP~~ in interference between mixing and decay ("Mixing induced ~~CP~~")



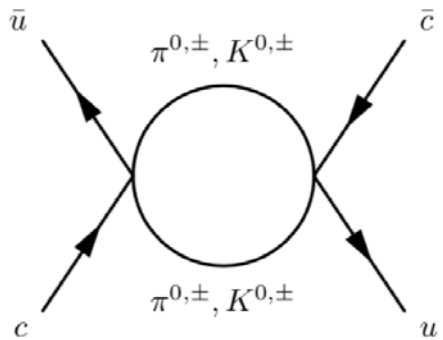
What is special about charm

- **Unique way to probe NP in up-type FCNC**

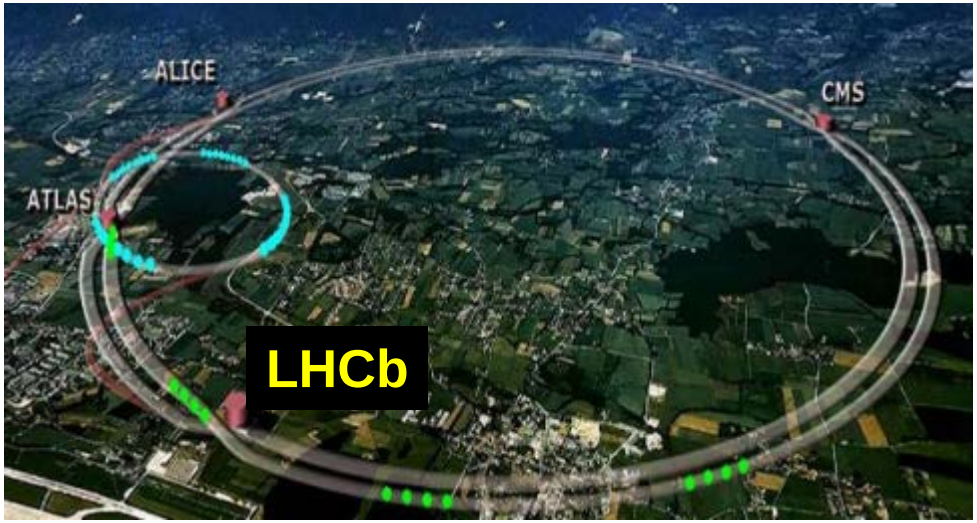


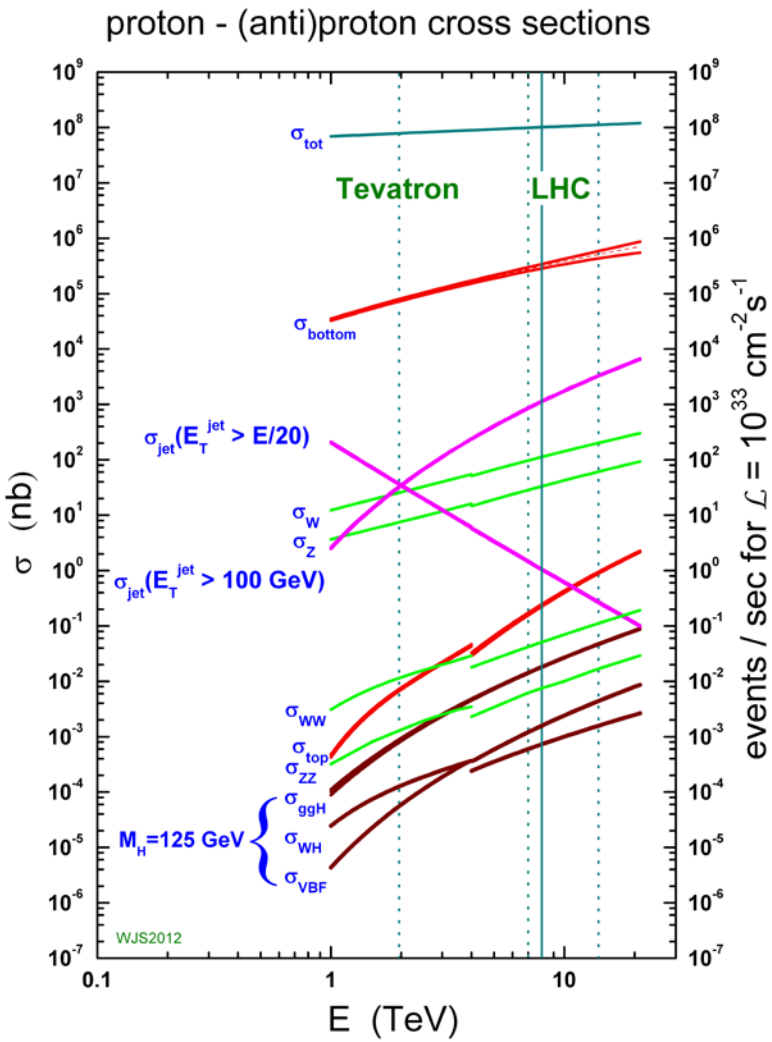


- **D^0 mixing small due to GIM**
- **CPV highly suppressed in SM but no precise estimations**
  - **Indirect CPV $\leq O\,(10^{-4})$**
  - **Direct CPV $\leq\ O(10^{-3})$**
- **Good understanding of long-distance effects essential**



LHC: charm factory





Large production cross sections

$\sigma(c\bar{c}X) \sim 4\% \times \sigma_{pp}^{inesl}$

20 times bigger than $\sigma(b\bar{b}X)$)

Many species of c-hadrons

Open charm: $D^0, D^{\pm}, D_s^{\pm}, \Lambda_c^{\pm}$

Hidden charm: $J/\psi, \Xi_{cc}^{++}, P_c$, ...

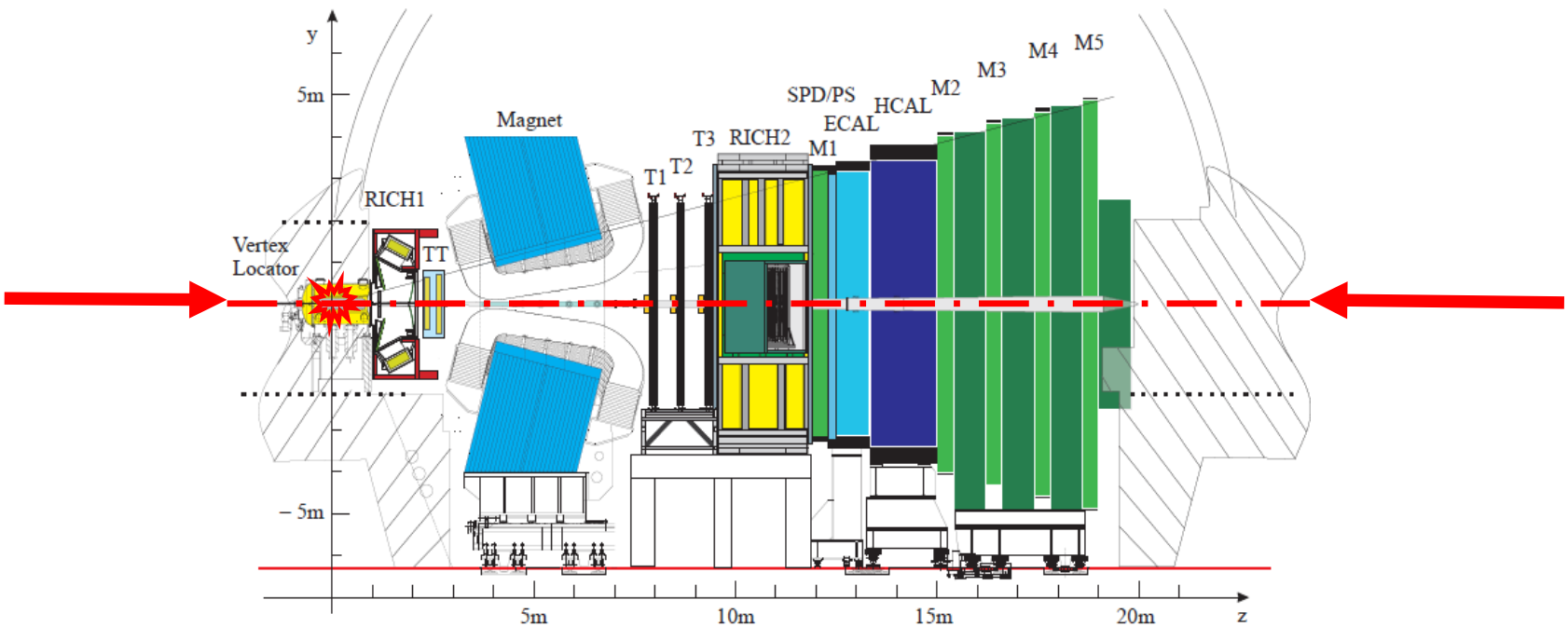
LHCb detector

Single arm forward spectrometer covering rapidity range

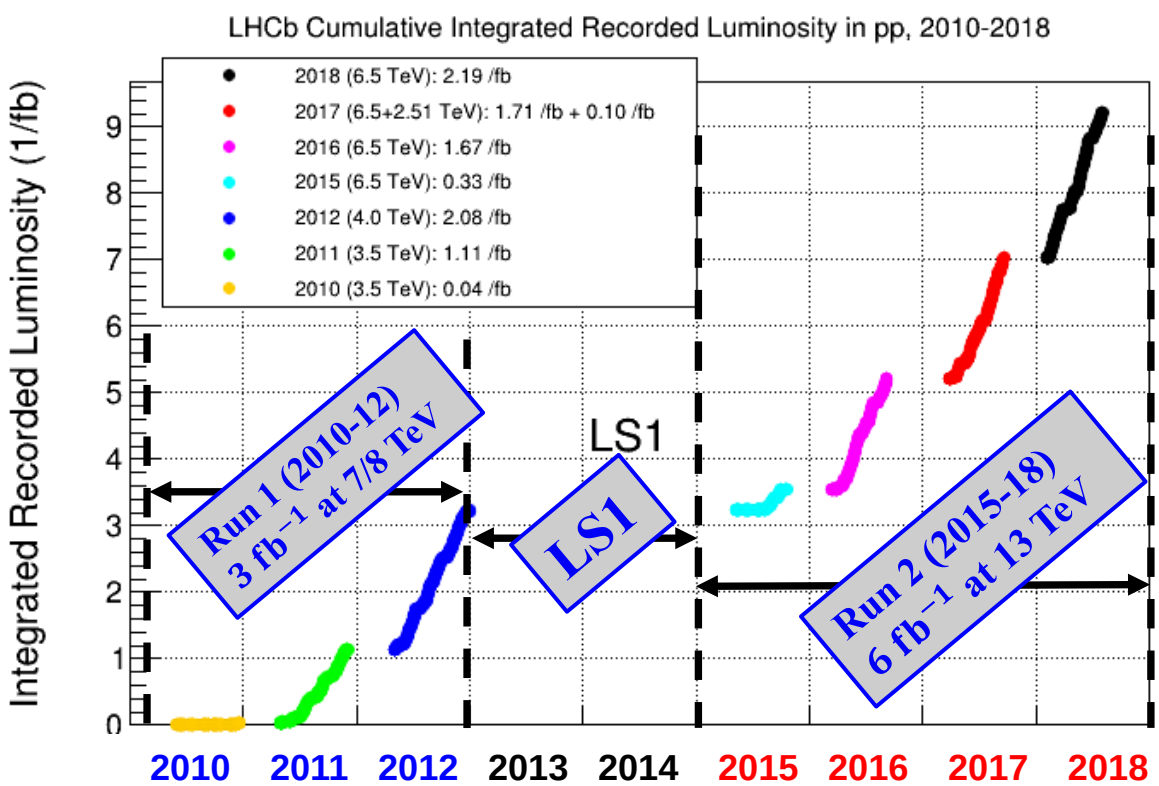
$2 < \eta < 5$

Excellent performance in

tracking, vertexing and particle identification



Data samples



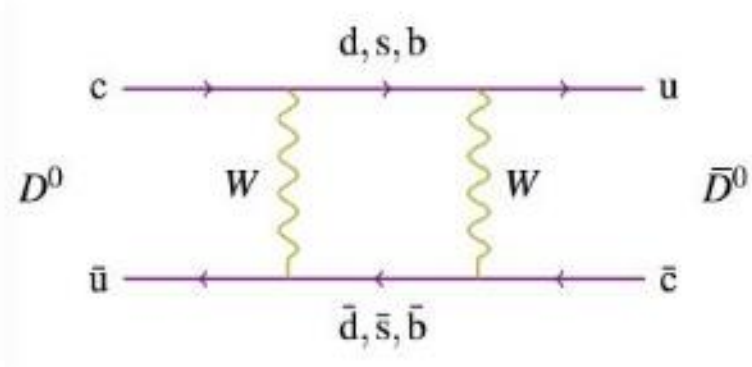
More than 9 fb^{-1} accumulated in Run1+Run 2

$\sim 10^{13}$ $c\bar{c}$ have been produced

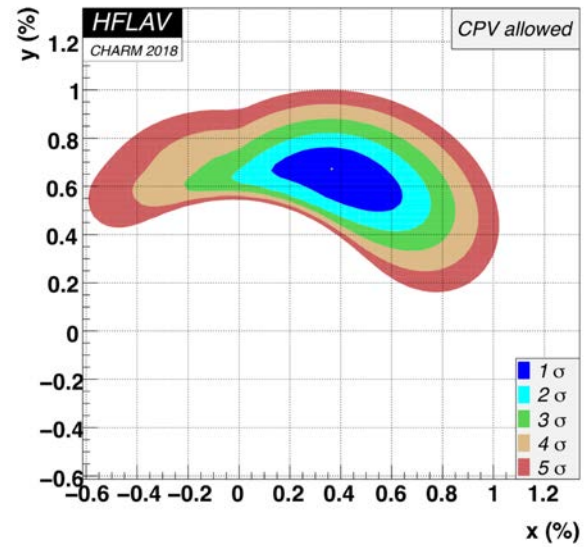
59 publications on charm: mixing, CPV, lifetimes, spectroscopy, masses, rare decays, ⋯

$D^0 - \overline{D}^0$ mixing and indirect CPV

Mixing and CP parameters

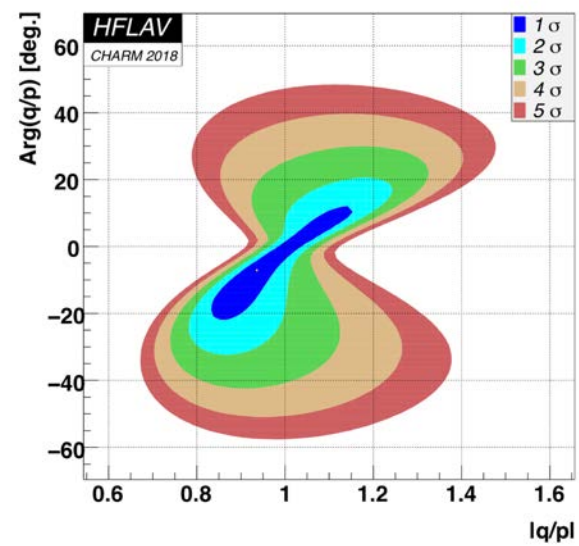


$$|D_{1,2}> = p|D^0> \pm q|\bar{D}^0>$$



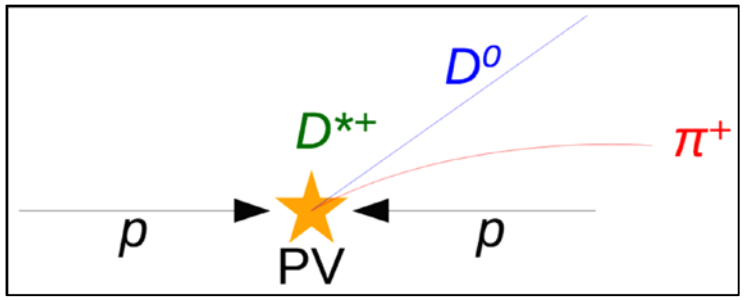
- **Mixing very small (<1%)**
  - $x \equiv \frac{M_1 - M_2}{\Gamma}, \; y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$
- **CP violation highly suppressed**
  - $\left|\frac{q}{p}\right| \neq 1$ **: CPV in mixing**
  - $\phi_f \equiv \arg\left(\frac{q\bar{A}_f}{pA_f}\right) \neq 0$**: mixing induced CPV**

  ($\phi \equiv \arg\left(\frac{q}{p}\right) \approx \phi_f$ **if no CPV in decay)**

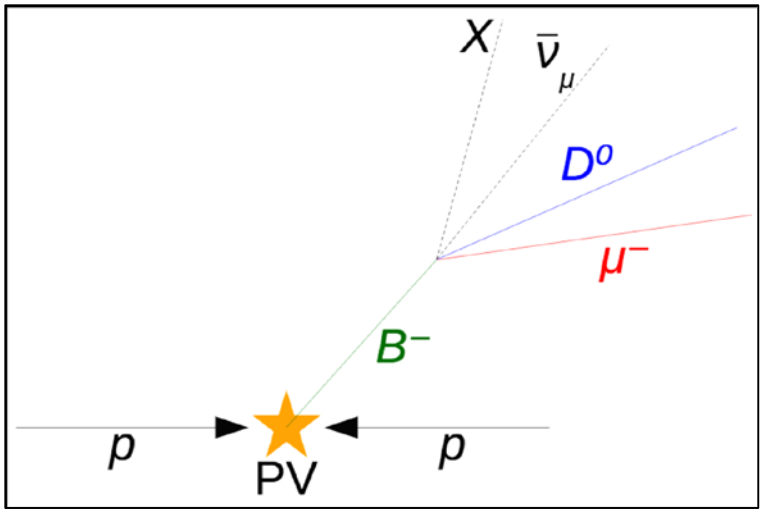


D^0 flavour tagging

- π-tagged prompt sample
  - $D^{*\pm} \rightarrow D^0\pi^\pm$
  - D^0 points to PV



- μ-tagged semileptonic sample
  - $B \rightarrow D^0\mu^\pm X$
  - D^0 doesn't point to PV
  - Factor of 4 lower yields



Mixing analysis with $D^0 \to K^{\pm}\pi^{\mp}$

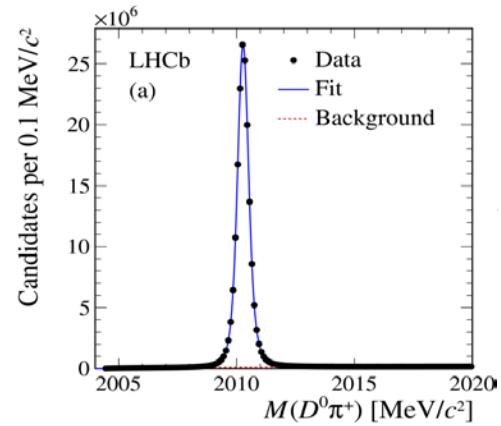
- First observation by LHCb with 2011 data [PRL 110 (2013) 101802]
- Updated using 2011-2016 data [PRD 97 (2018) 031101]
- Ratio of WS to RS decay rates changes with decay time *t*

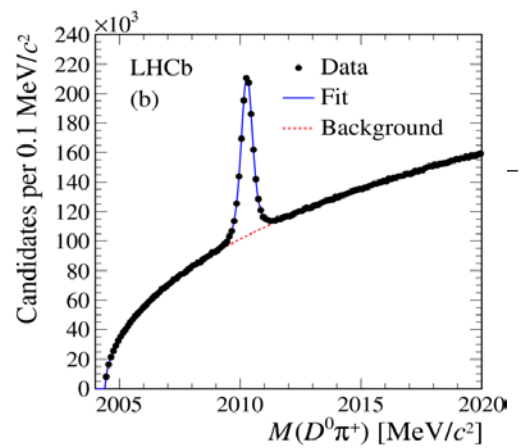
$$R(t) \approx R_D + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

$$x' = x\cos\delta + y\sin\delta$$

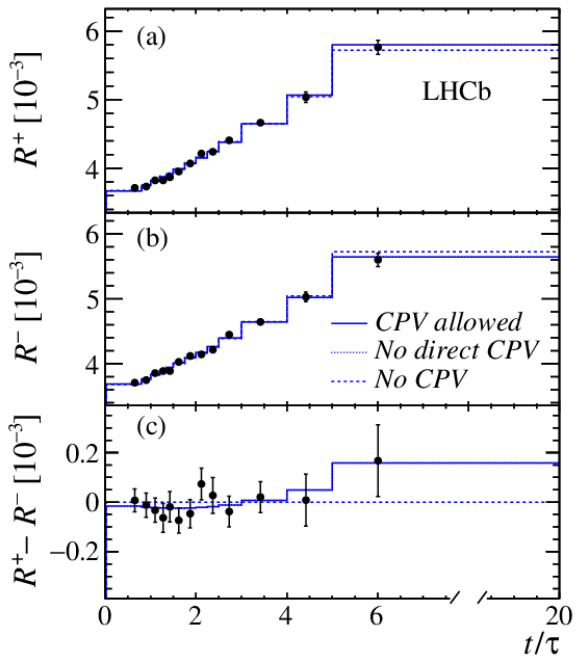
$$y' = y\cos\delta - x\sin\delta$$

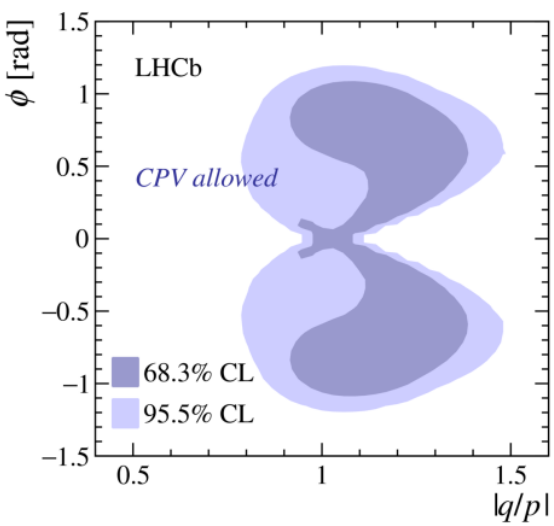
$$\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)} = -\sqrt{R_D}e^{-i\delta}$$





WS/RS fit results





[PRD 97 (2018) 031101]

Run I 3 fb^{-1}, Run II 2 fb^{-1}

- **Assuming CP invariance**

$$x'^2 = (3.9 \pm 2.7) \times 10^{-5}$$

$$y' = (5.28 \pm 0.52) \times 10^{-3}$$

- **Direct CP asymmetry ~ 0**

$$A_D = \frac{R_D^+ - R_D^+}{R_D^+ + R_D^+} = (-0.1 \pm 9.1) \times 10^{-3}$$

- **Weak constraint on indirect CPV**

$$0.82 < \left|\frac{q}{p}\right| < 1.45 \text{ @95\% CL}$$

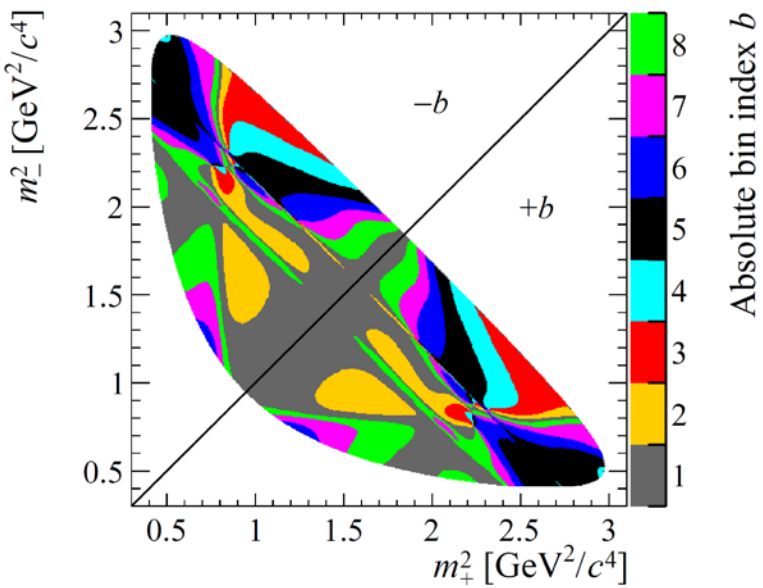
Mixing analysis with $D^0 \to K_S\pi^+\pi^-$

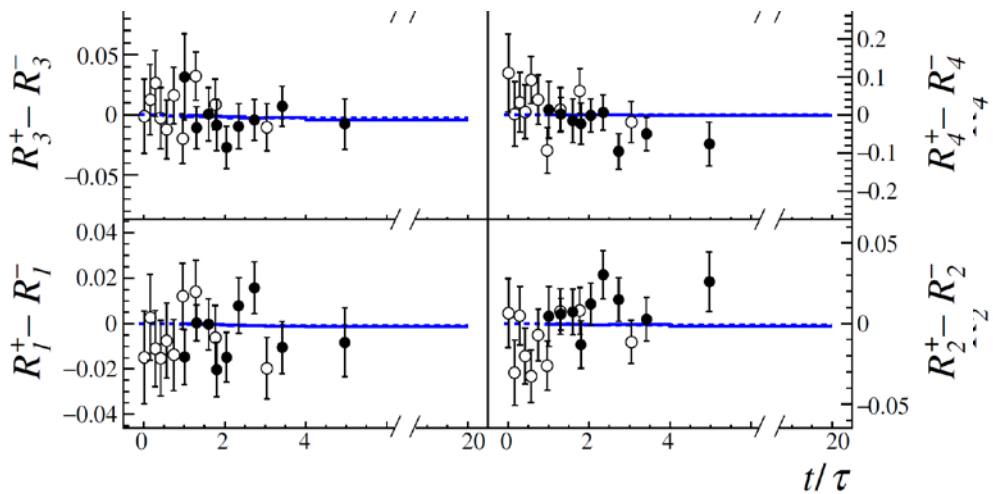
[PRL 122 (2019) 231802]

- Use $D^0 \to K_S\pi^+\pi^-$ in run 1
  - Most precise determination of x from yield ratio between $\pm b$ bins as a function of decay time

    $$x_{CP} = (2.7 \pm 1.6 \pm 0.4) \times 10^{-3}$$
  - No difference observed between initial D^0 and $\bar{D}^0$

    $$\Delta x = (-0.53 \pm 0.70 \pm 0.22) \times 10^{-3}$$

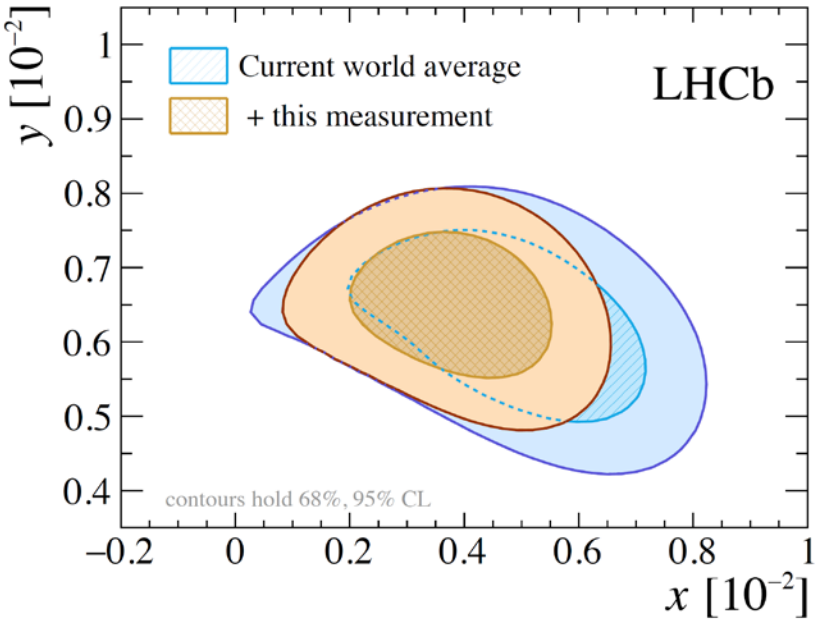


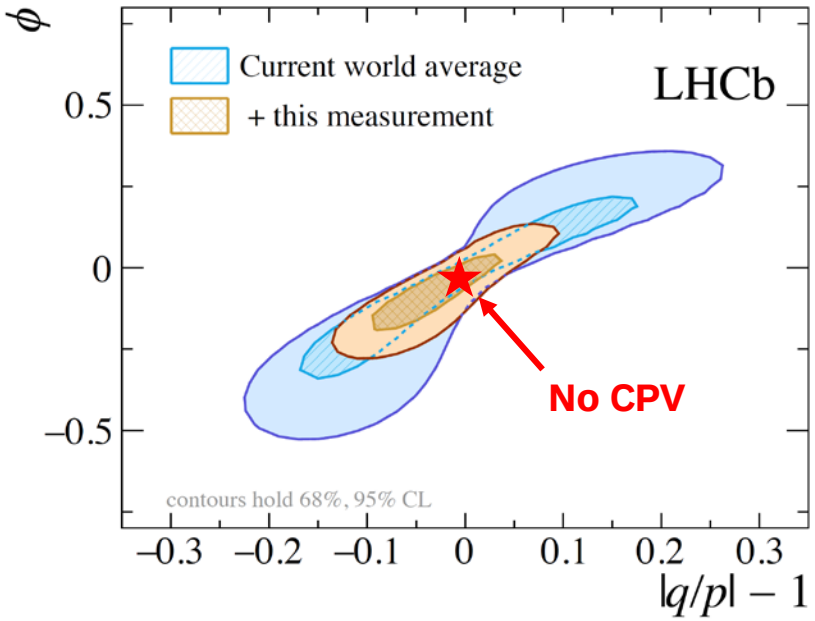


Impact on W.A.

[PRL 122 (2019) 231802]

$x\ [10^{-2}]$	$0.27^{+0.17}_{-0.15}$
$y\ [10^{-2}]$	0.74 ± 0.37
$\lvert q/p \rvert$	$1.05^{+0.22}_{-0.17}$
ϕ	$-0.09^{+0.11}_{-0.16}$





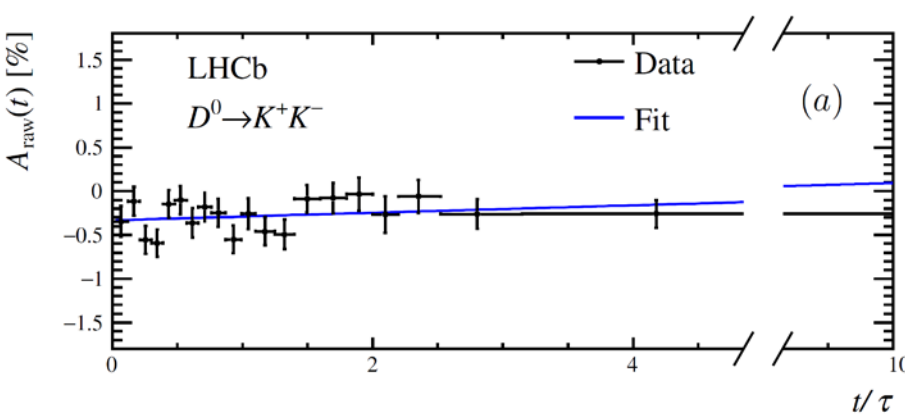
Consistent with CP symmetry

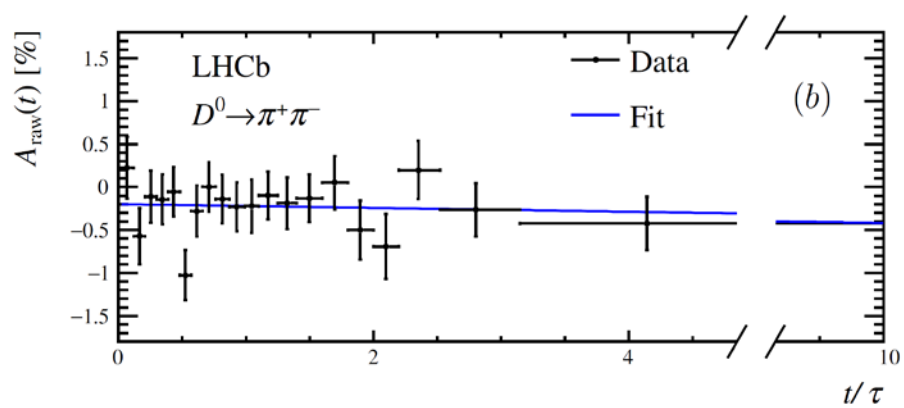
Golden probe of indirect CPV: A_Γ

$$A_{CP}(t) \equiv \frac{\Gamma(D^0(t)\to f) - \Gamma(\overline{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\overline{D}^0(t)\to f)} \simeq a^f_{\rm dir} - \boxed{A_\Gamma}\frac{t}{\tau_D}$$

$$A_\Gamma(f) \approx -x\phi_f + y\left(|q/p| - 1\right) - y\mathcal{A}^{\rm dir}_{CP}(f)$$

	Run 1 PRL 118 (2017) 261803	Run 2 update (5.4 fb^{-1}) arXiv: 1911.01114
$A_\Gamma(K^+K^-)\times 10^{-3}$	$-0.30 \pm 0.32 \pm 0.10$	$-0.44 \pm 0.23 \pm 0.06$
$A_\Gamma(\pi^+\pi^-)\times 10^{-3}$	$+0.46 \pm 0.58 \pm 0.12$	$+0.25 \pm 0.43 \pm 0.07$
Average	-0.29 ± 0.28	-0.29 ± 0.21

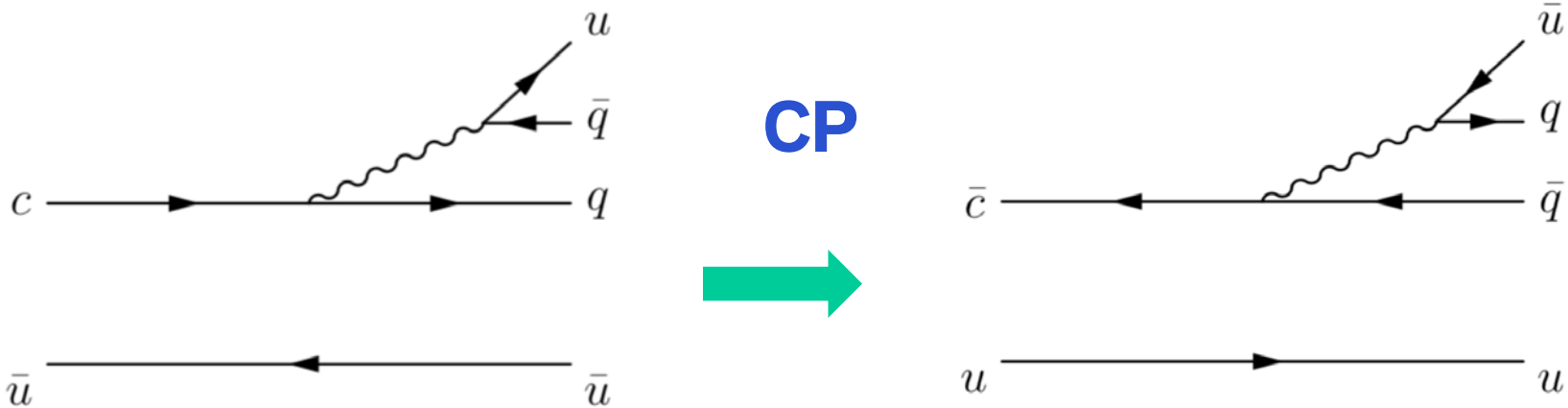




Consistent with no CPV within a few $\times 10^{-4}$

Direct CP violation

CP transformation



$$A = \rho\, e^{i\delta}\, e^{i\theta}$$

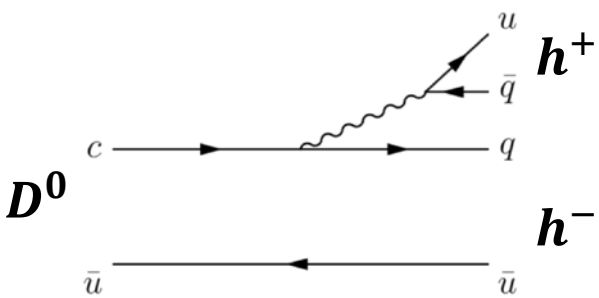
$$\bar{A} = \rho\, e^{i\delta}\, e^{-i\theta}$$

A CP transformation

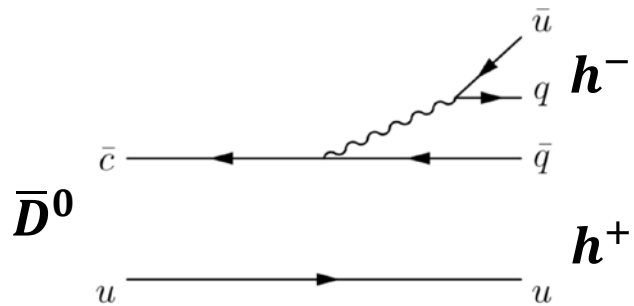
- **change sign of the weak phase θ**
- **leaves the strong phase δ unchanged**

CP violation in decay

Tree level

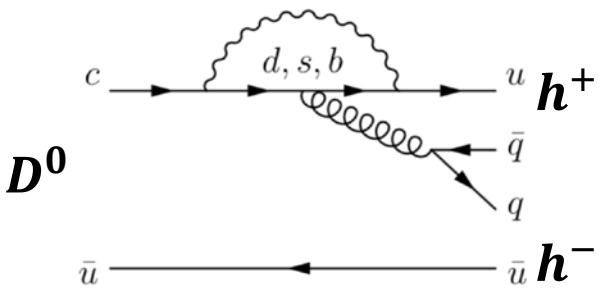


$$A_T = \rho_T e^{-i\delta_T}\, e^{-i\theta_T}$$

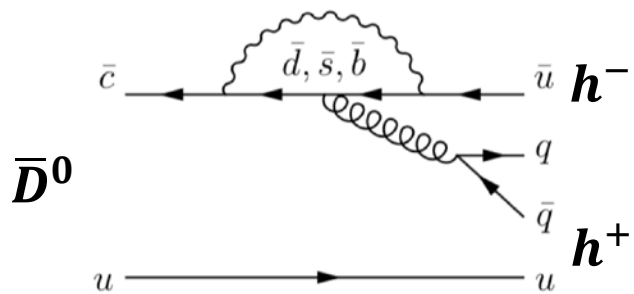


$$A_T = \rho_T e^{-i\delta_T}\, e^{+i\theta_T}$$

Loop level



$$A_P = \rho_P e^{-i\delta_P}\, e^{-i\theta_P}$$



$$A_P = \rho_P e^{-i\delta_P}\, e^{+i\theta_P}$$

$$|\bar{A}_T + \bar{A}_P|^2 - |A_T + A_P|^2 = 4\rho_T\rho_P \sin(\delta_T - \delta_P)\, \sin(\theta_T - \theta_P) \neq 0$$

No CPV in many LHCb searches

- SM expectation of A_{CP}^{dir} small, but "how small" is uncertain

$$A_{CP}^{dir} \equiv \frac{|A(D \to f)|^2 - |A(\bar{D} \to \bar{f})|^2}{|A(D \to f)|^2 + |A(\bar{D} \to \bar{f})|^2} \leq O(10^{-3})$$

- Two-body decays (precision ~10^{-3})

[PRL 122 (2019) 191803]

$$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) = (\ \ 1.3 \ \pm 1.9\ \ (\text{stat}) \pm 0.5\ \ (\text{syst})) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to K_S^0 K^+) = (-0.09 \pm 0.65\,(\text{stat}) \pm 0.48\,(\text{syst})) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (\ \ 0.05 \pm 0.42\,(\text{stat}) \pm 0.29\,(\text{syst})) \times 10^{-3}$$

$$A_{CP}(D^0 \to K^+K^-) = (0.04 \pm 0.12 \pm 0.10)\%$$
$$A_{CP}(D^0 \to \pi^+\pi^-) = (0.07 \pm 0.14 \pm 0.11)\%$$

[PLB 767 (2017) 177] (run 1)

- Multibody decays

✓ $A_{CP}(\Lambda_c^+ \to pK^+K^-) - A_{CP}(\Lambda_c^+ \to p\pi^+\pi^-)$ [JHEP 03 (2018) 182]

✓ CPV in phase space of $D^0 \to \pi^+\pi^-\pi^+\pi^-$ [PLB 769 (2017) 345]

✓ $A_{CP}(D^0 \to h^+h^-\mu^+\mu^-)$ [PRL 121 (2018) 091801]

ΔA_{CP} strategy for $D^0 \to h^+h^-$

$$A_{raw}(f) = \frac{N(D^0 \to f) - N(\bar{D}^0 \to \bar{f})}{N(D^0 \to f) + N(\bar{D}^0 \to \bar{f})}$$

Detection asymmetry , zero for symmetric $f = h^+h^-$

$$A_{raw}(f) = A_{CP}(f) + \cancel{A_D(f)} + A_T(f)$$

Physical CP asymmetry

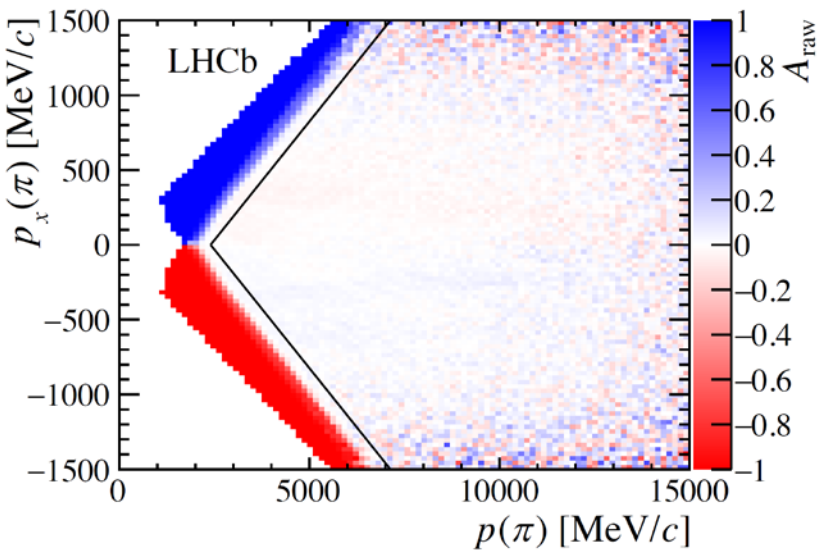
Production and detection asymmetry related to D^0 flavour tagging

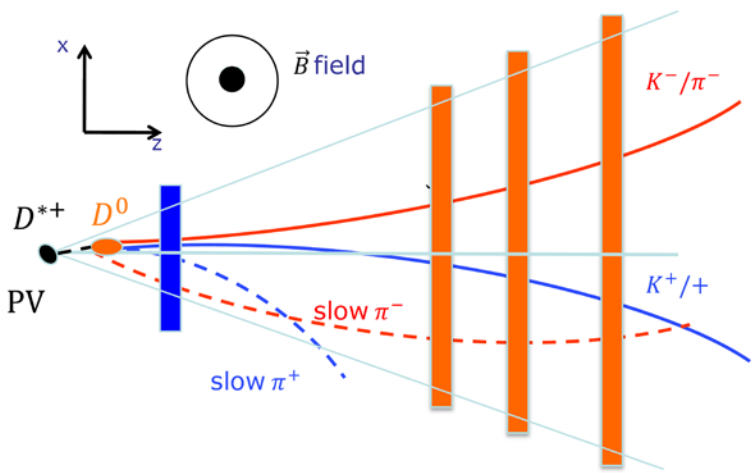
A_T cancels in the asymmetry difference

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$
$$\approx A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-)$$

Event selection

- **Use full run 2 sample**
- **Requirements on**
  - **Quality, p_T and PID of tracks**
  - **Vertex quality, p_T and impact parameter of D^0**
- **Remove soft pion (or muon) kinematic regions where raw asymmetry is large**





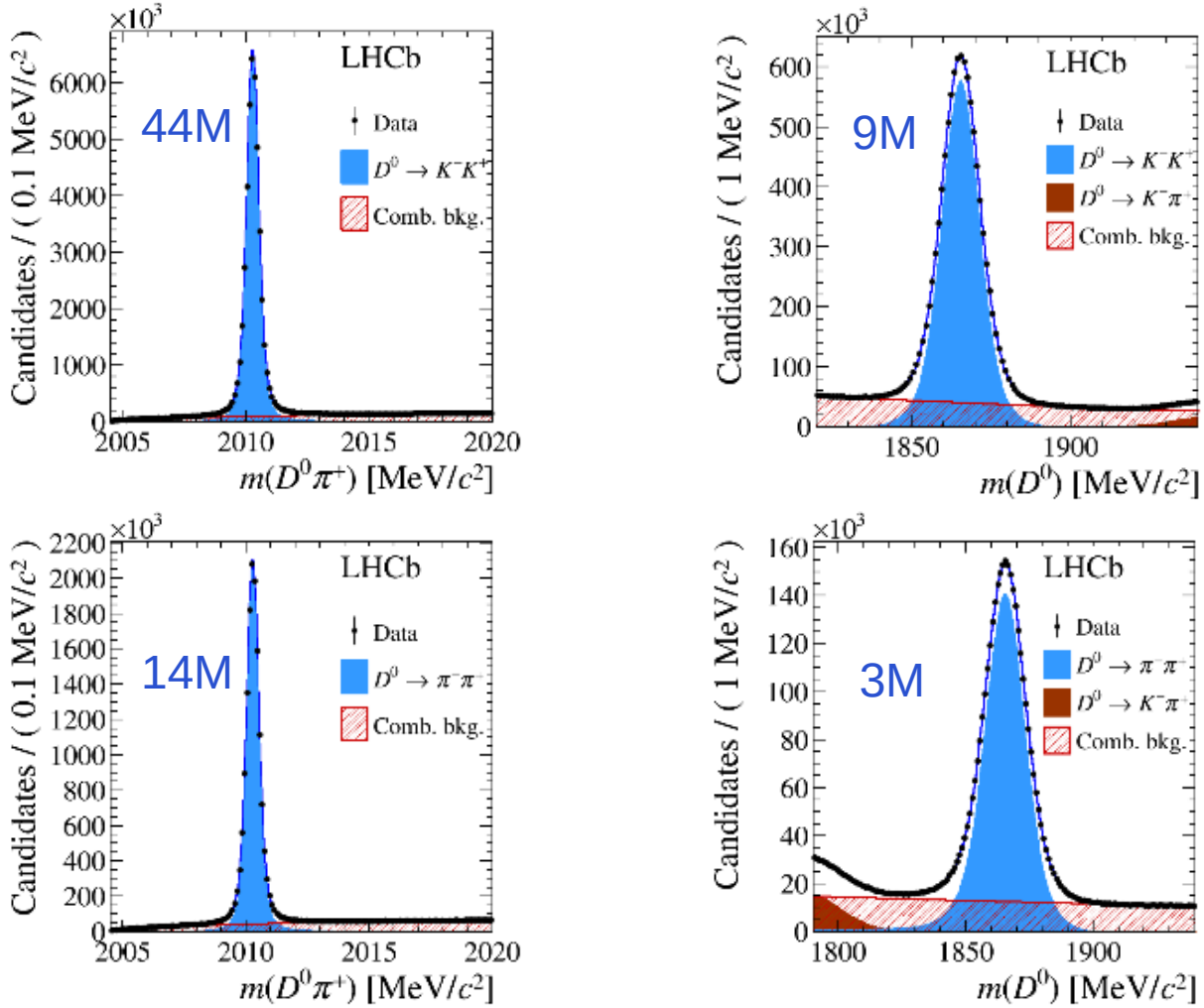
Signal samples

[PRL 122 (2019) 211803]

π-tagged **μ-tagged**

K^+K^-

$\pi^+\pi^-$

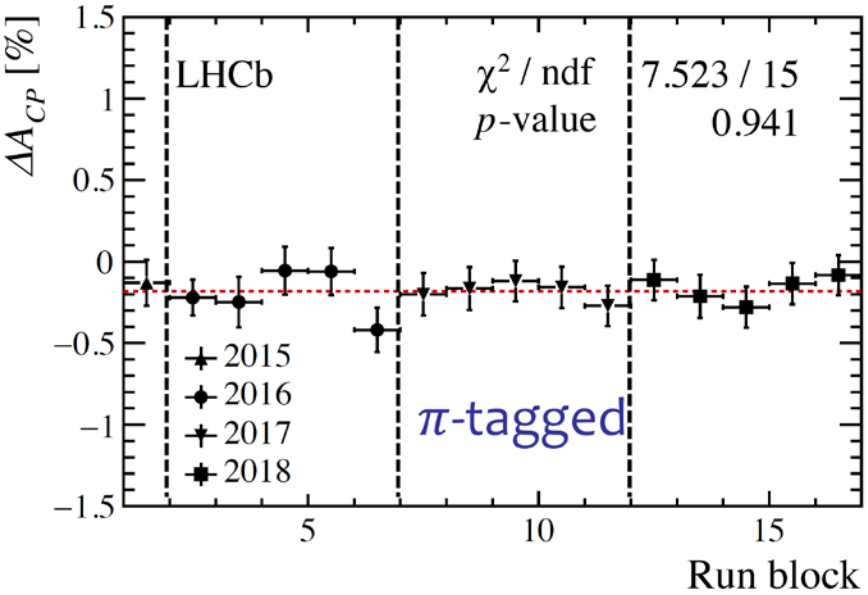


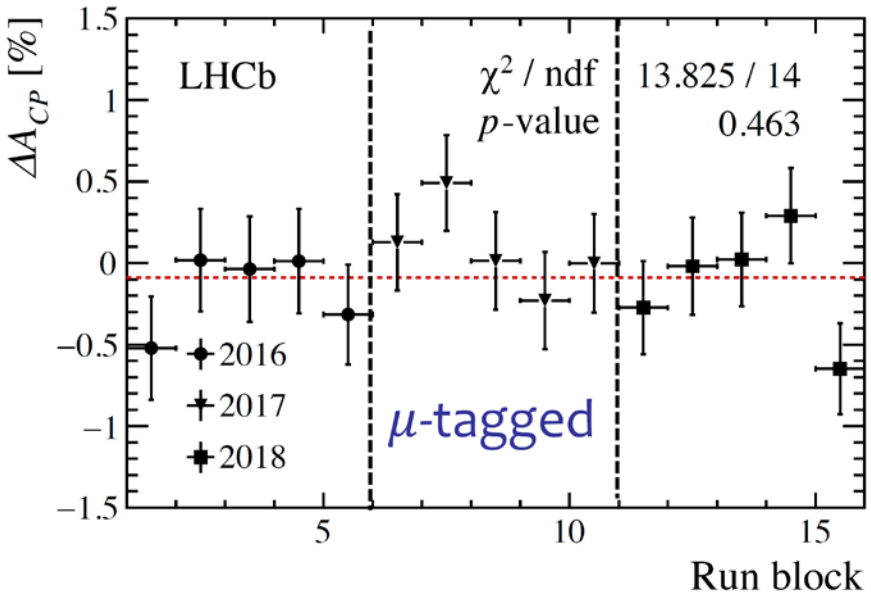
A_{raw} is obtained for each sample

Stability

[PRL 122 (2019) 211803]

- **Samples split according to year, magnet polarity and kinematic variables**
- **No evidence for unexpected dependencies are seen**





Systematics

[PRL 122 (2019) 211803]

Systematic effects well under control

Source (10^{-4})	π-tagged	μ-tagged
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
Peaking background	0.5	–
B fractions	–	1
B reco. efficiency	–	2
Total	0.9	5

ΔA_{CP} results

[PRL 122 (2019) 211803]

$$\Delta A_{CP}^{\pi-tag} = (-1.82 \pm 0.32 \pm 0.09) \times 10^{-3}$$

$$\Delta A_{CP}^{\mu-tag} = (-0.9 \pm 0.8 \pm 0.5) \times 10^{-3}$$

Compatible with previous LHCb results and WA

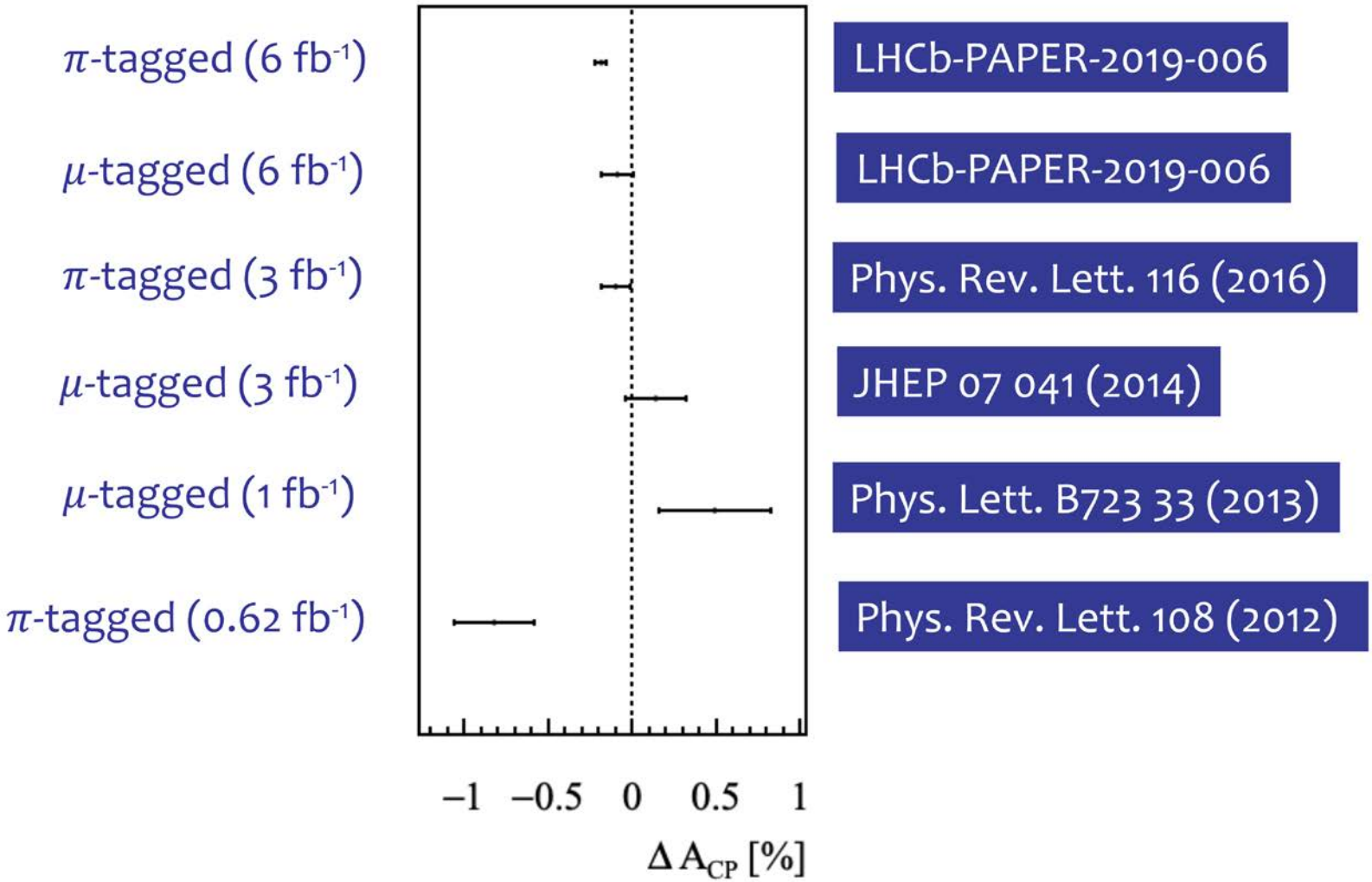
LHCb combination (full run1 + run 2)

$$\Delta A_{CP} = (-1.54 \pm 0.29) \times 10^{-3}$$

CP violation in charm observed at 5.3σ !

At the upper end of the SM expectations

History of ΔA_{CP} at LHCb



Interpreting time-integrated ΔA_{CP}

$$\Delta A_{CP} \approx \Delta a_{CP}^{dir}\left(1 + \frac{\overline{<t>}}{\tau(D^0)} y_{CP}\right) + \frac{\Delta<t>}{\tau(D^0)} a_{CP}^{ind}$$

- **Using LHCb averages**
  - $a_{CP}^{ind} \approx -A_{\Gamma} = (+0.29 \pm 0.28) \times 10^{-3}$ [PRL 118 (2017) 261803]
  - $y_{CP} = (5.7 \pm 1.5) \times 10^{-3}$ [PRL 122 (2019) 011802]
- **For the data sample**

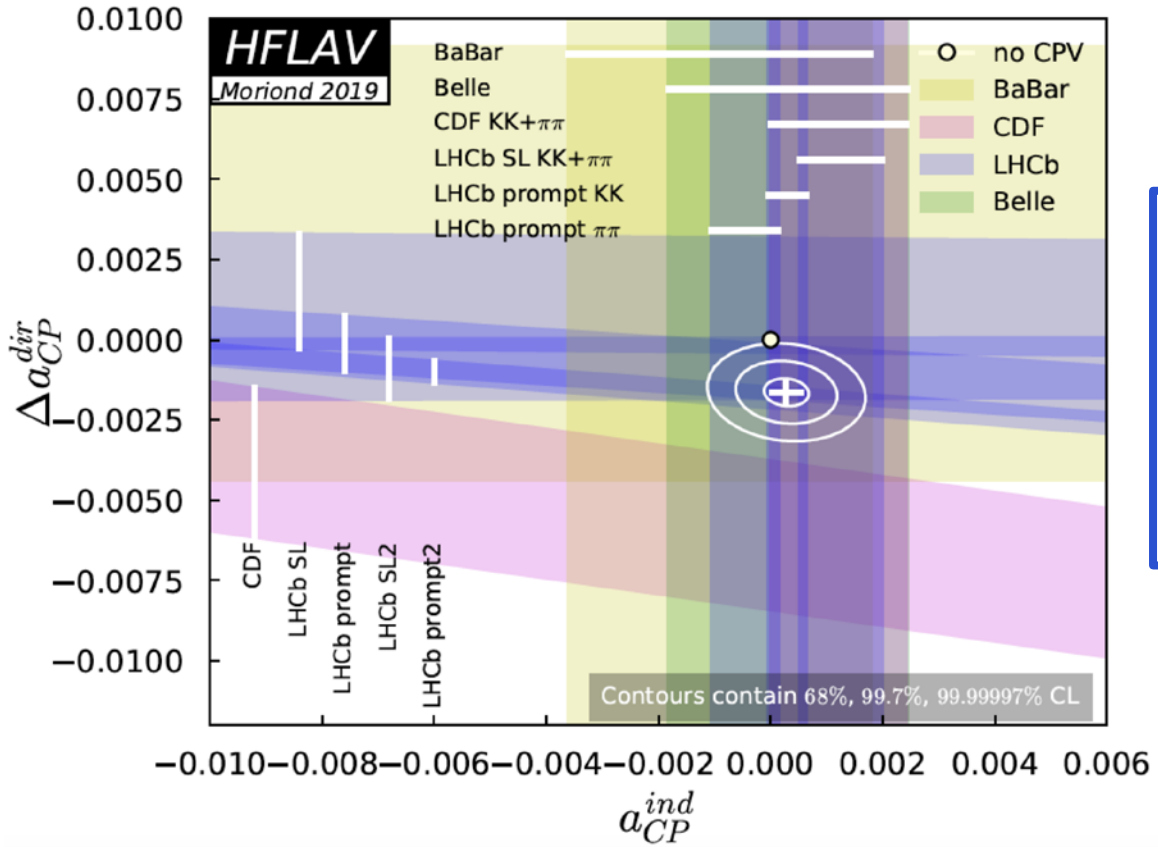
$$\Delta\langle t\rangle/\tau(D^0) = 0.115 \pm 0.002,\ \overline{\langle t\rangle}/\tau(D^0) = 1.71 \pm 0.10$$

$$\boxed{\Delta a_{CP}^{dir} = (-15.6 \pm 2.9) \times 10^{-4}}$$

[PRL 122 (2019) 211803]

ΔA_{CP} dominated by direct CP violation

HFLAV combination



$a_{\mathrm{CP}}^{ind} = (0.028 \pm 0.026)\%$

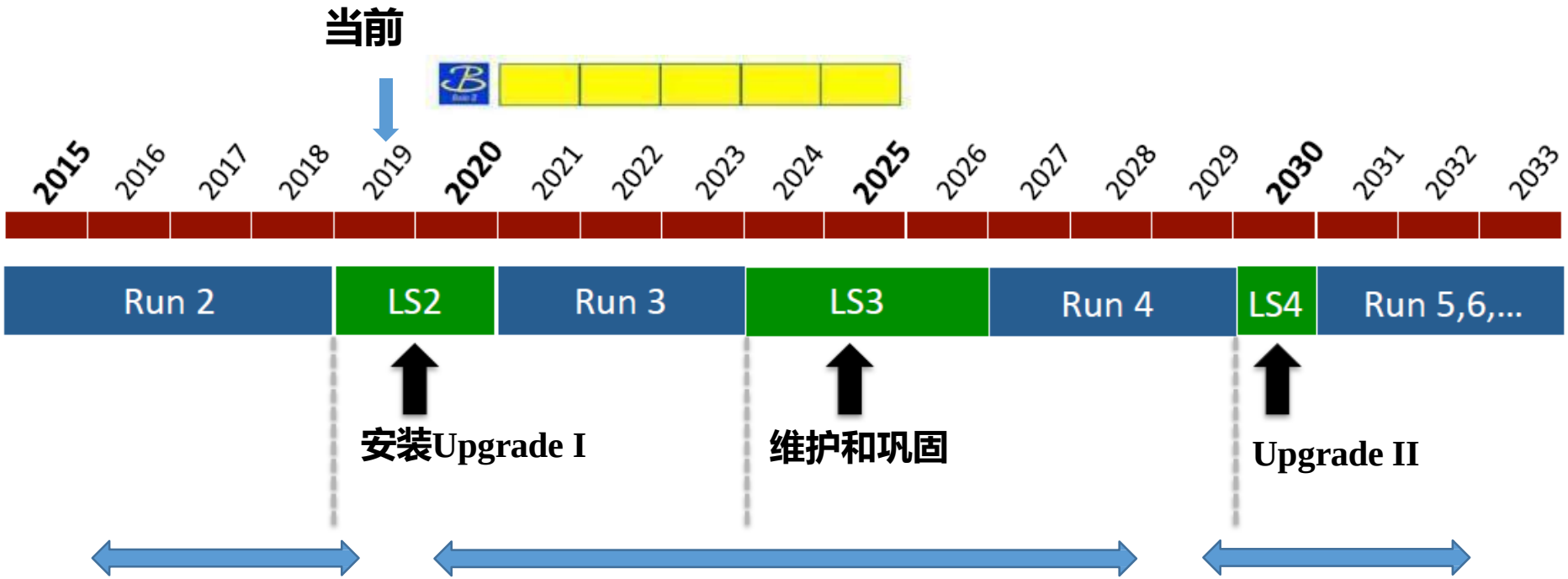
$\Delta a_{\mathrm{CP}}^{dir} = (-0.164 \pm 0.028)\%$

p-value of CP invariance hypothesis: 5×10^{-8} (5.44σ)

World average dominated by LHCb results

Future prospects

LHCb upgrades



$L = 4 \times 10^{32}\ cm^{-2}s^{-1}$

已采集9 fb^{-1}

$L = 2 \times 10^{33}\ cm^{-2}s^{-1}$

计划积累50 fb^{-1}

$L = 2 \times 10^{34}\ cm^{-2}s^{-1}$

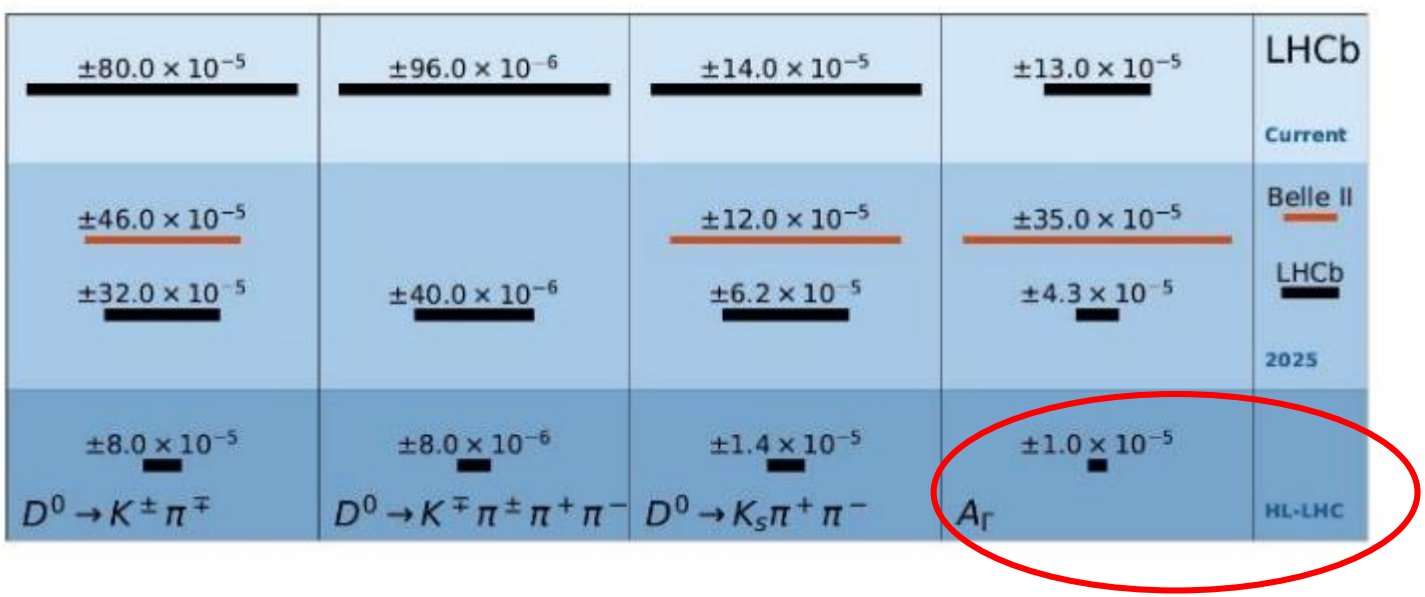
计划积累300 fb^{-1}

Charm CPV outlook

Direct CPV: can reach 10^{-4} precision with 50 fb^{-1} (~2029), posing serious challenges to theorists

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^-K^+$	Yield $D^0 \to \pi^-\pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.01	0.03
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

Indirect CPV: theoretically much more clean, chance for observation with 10^{-5} precision after ~2035



Summary

- **LHCb as a charm factory has produced a series of exciting results**
- **Charm mixing: very well established**
- **Direct CP violation**
  - **Observed for the first time**

    $$\Delta A_{CP} = (-1.54 \pm 0.29) \times 10^{-3}$$
  - **Theoretical interpretation challenging**
- **Indirect CP violation**
  - **Theoretically cleaner than direct CPV**
  - **Current precision of a few $\times 10^{-4}$ is insufficient for observation**
- **Observation of indirect CP will be the next milestone in charm physics and requires LHCb upgrade II**

Backup slides

Charm mixing

- **Mass eigenstates are combinations of D^0 and $\bar{D}^0$**

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

$$x \equiv \frac{\Delta M}{\Gamma}, \quad \Delta M \equiv M_1 - M_2$$
$$y \equiv \frac{\Delta \Gamma}{2\Gamma}, \quad \Delta \Gamma \equiv \Gamma_1 - \Gamma_2$$

$$|\langle \bar{D}^0 | D^0(t) \rangle|^2 = \frac{1}{2}\left|\frac{p}{q}\right|^2 e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

$$|\langle D^0 | \bar{D}^0(t) \rangle|^2 = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

ΔA_{CP} status before 2019