Charm Physics at LHCb

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On behalf of the LHCb collaboration

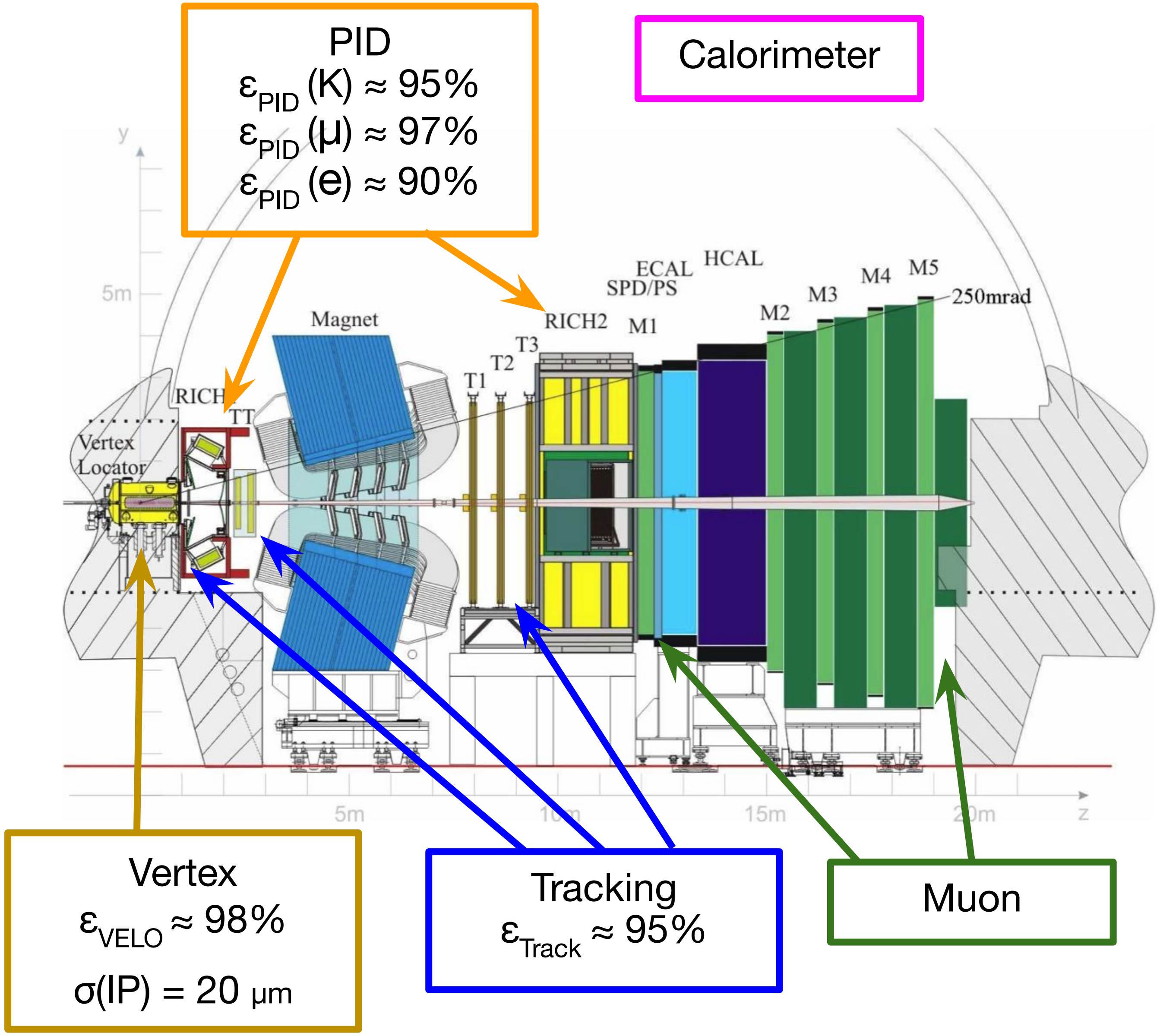
20th Lomonosov Conference on Elementary Particle Physics

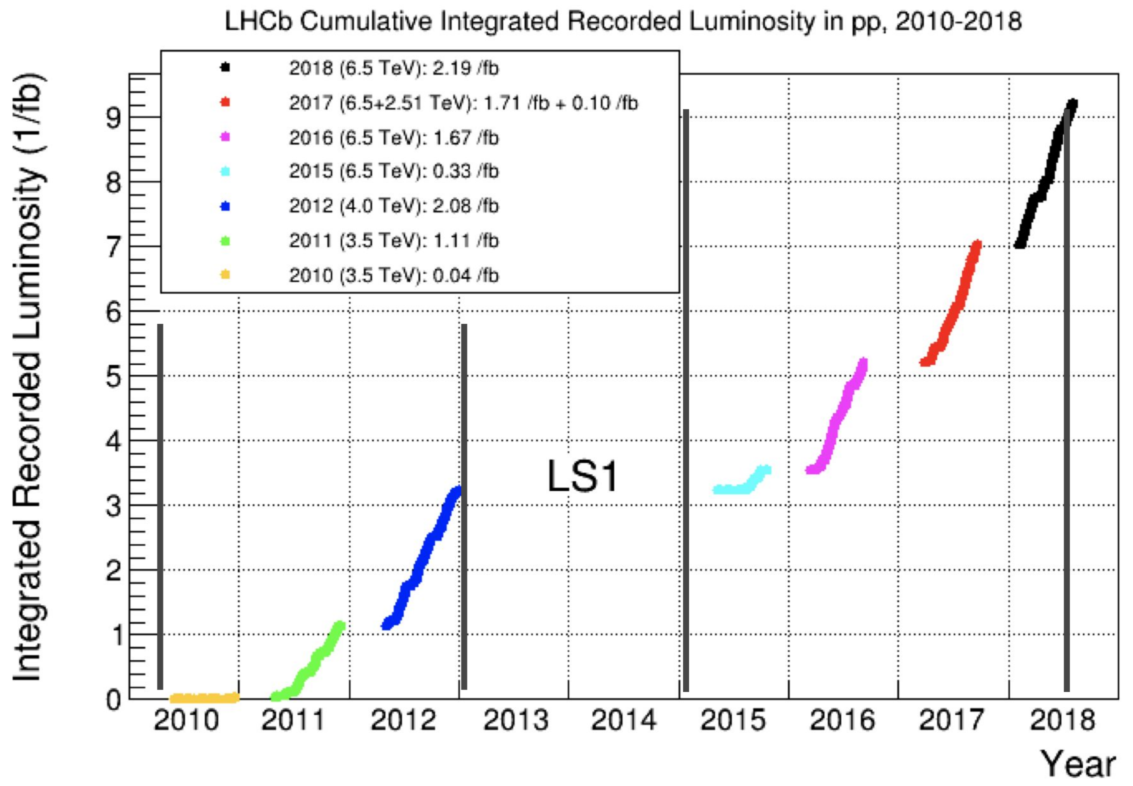
Charm Physics Programme @LHCb

- Mixing and CP violation
  - First observation of a difference between D^0 mass eigenstates [arXiv:2106.03744]
  - Time-dependent CPV search in $D^0 \to K^+K^-$, $\pi^+\pi^-$ [arXiv:2105.09889]
  - Time-integrated CPV search in $D^0 \to K^0_S K^0_S$ [arXiv:2105.01565]
- Production and spectroscopy
  - Lifetime of Ω^0_c [LHCb-PAPER-2021-021(Preliminary)]
- Rare decays
  - Flavour-changing neutral current (FCNC)
  - etc.

LHCb experiment

JINST 3 (2008) S08005



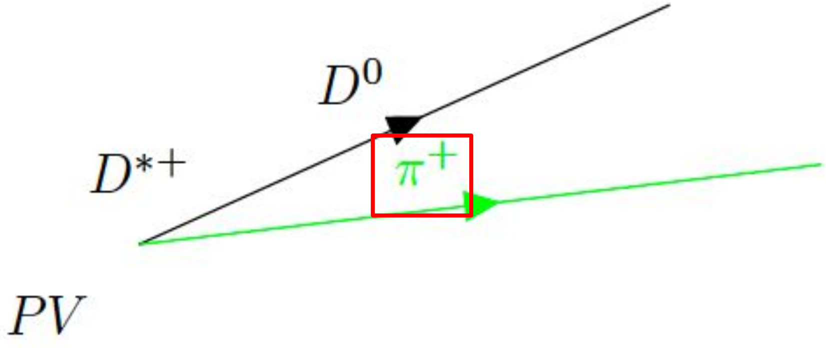


Run 1
3/fb at 7/8 TeV

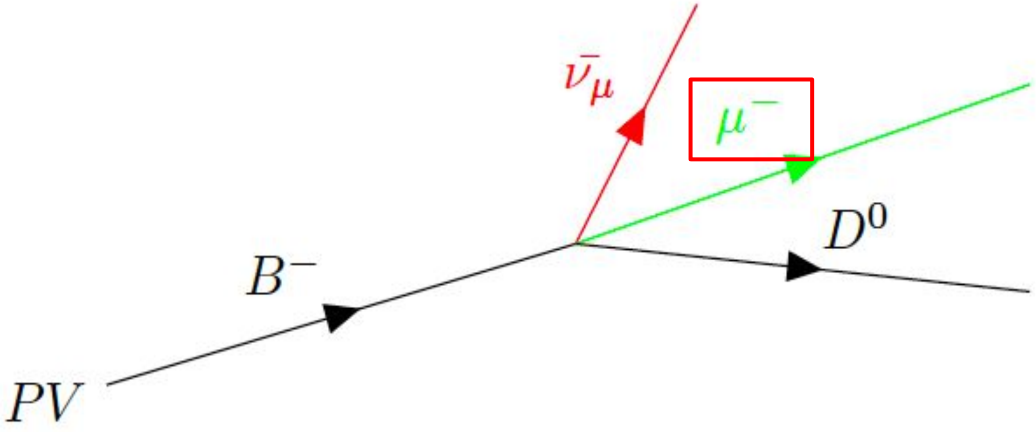
Run 2
6/fb at 13TeV

Charm Productions at the LHCb experiment

- **Unique**
  - Up-type quark decay
  - New physics coupling can be probed
- **Indirect CPV in charm decays**
  - Small mixing, sensitive to CPV
  - Probe high BSM scales (suppressed in SM)
- **Large cross section**
  - Billions of charm hadron decays to be studied at LHCb!



Prompt [π-tagged]



Semileptonic [μ-tagged]

Mixing and CPV

Mixing parameters

- Flavour mixing is the transition between a neutral flavoured meson and its antiparticle. The time evolution is described by

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

  - Eigenstates of this Hamiltonian are

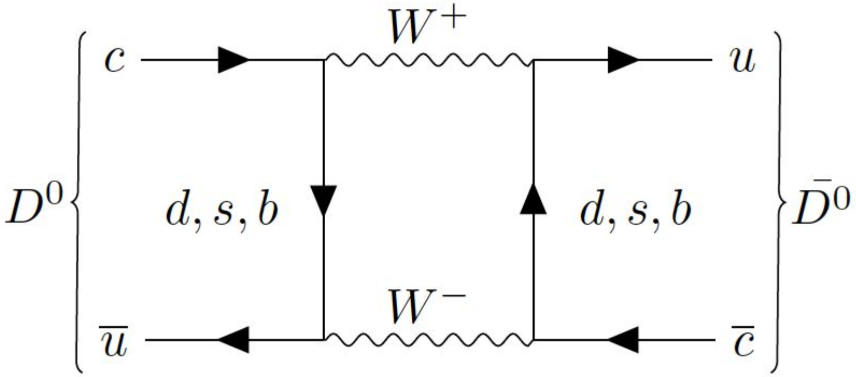
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$ with eigenvalues $$\omega_{1,2} \equiv m_{1,2} - \frac{i}{2}\Gamma_{1,2}$$

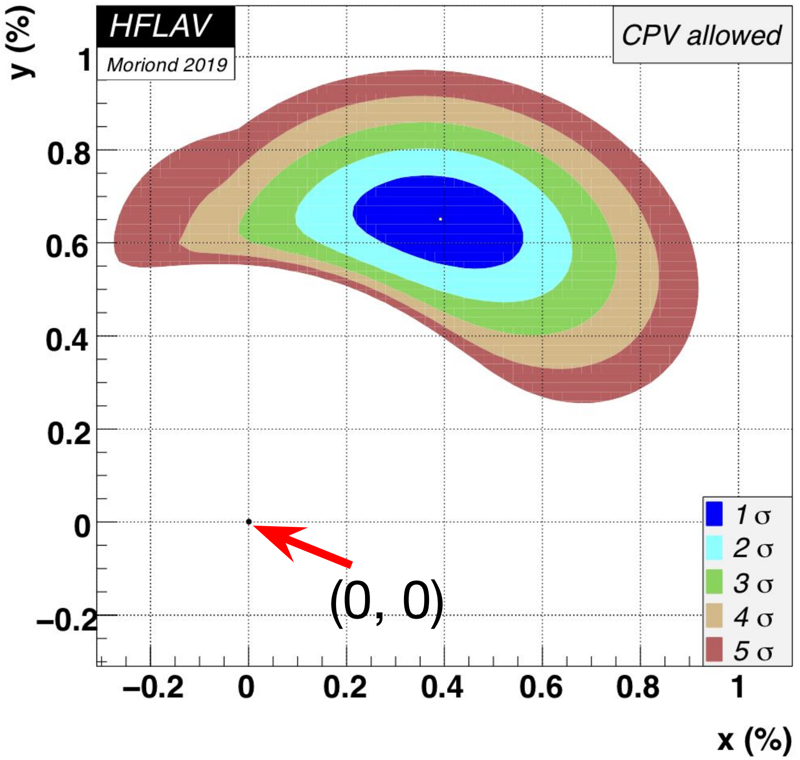
$$\boxed{x \equiv (m_1 - m_2)/\Gamma = \Delta m/\Gamma \qquad y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma = \Delta\Gamma/2\Gamma}$$

- Mixing parameters in charm **have yet to be measured with high precision. [Mixing occurs when x and y ≠ 0]**
- Measurements of these parameters are **sensitive to probe physics beyond the Standard Model (SM).**

SM: $x, y \in [10^{-6}, 10^{-1}]$

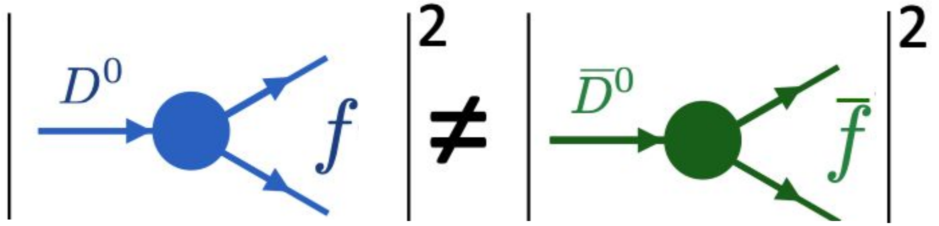
Int.J.Mod.Phys.A21:5686-5693,2006



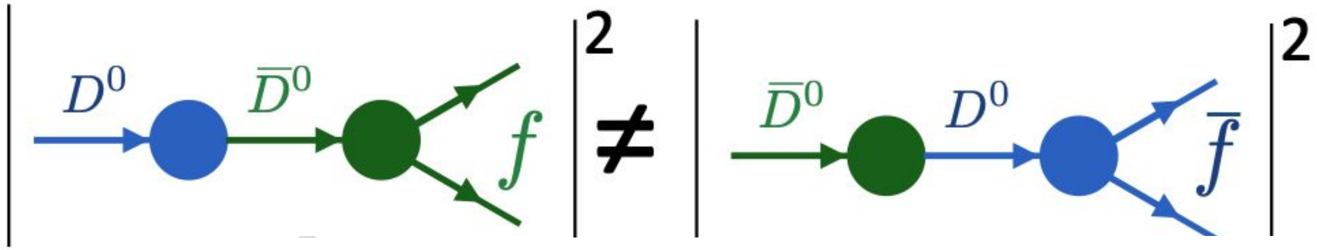


Mixing and CPV

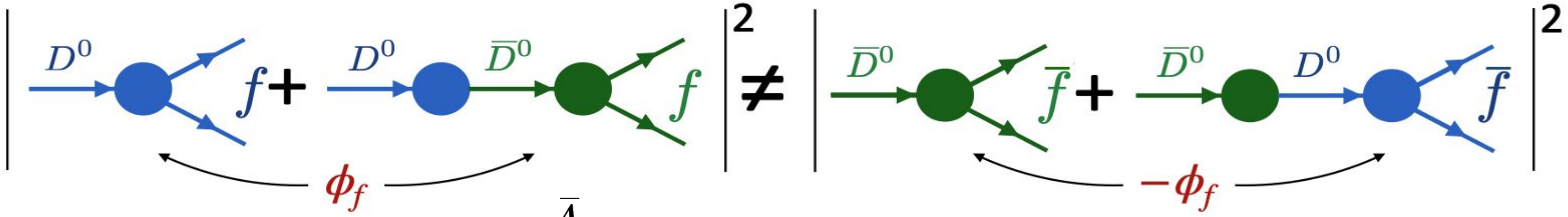
Direct CPV



CPV in mixing



CPV in decay-mixing interference

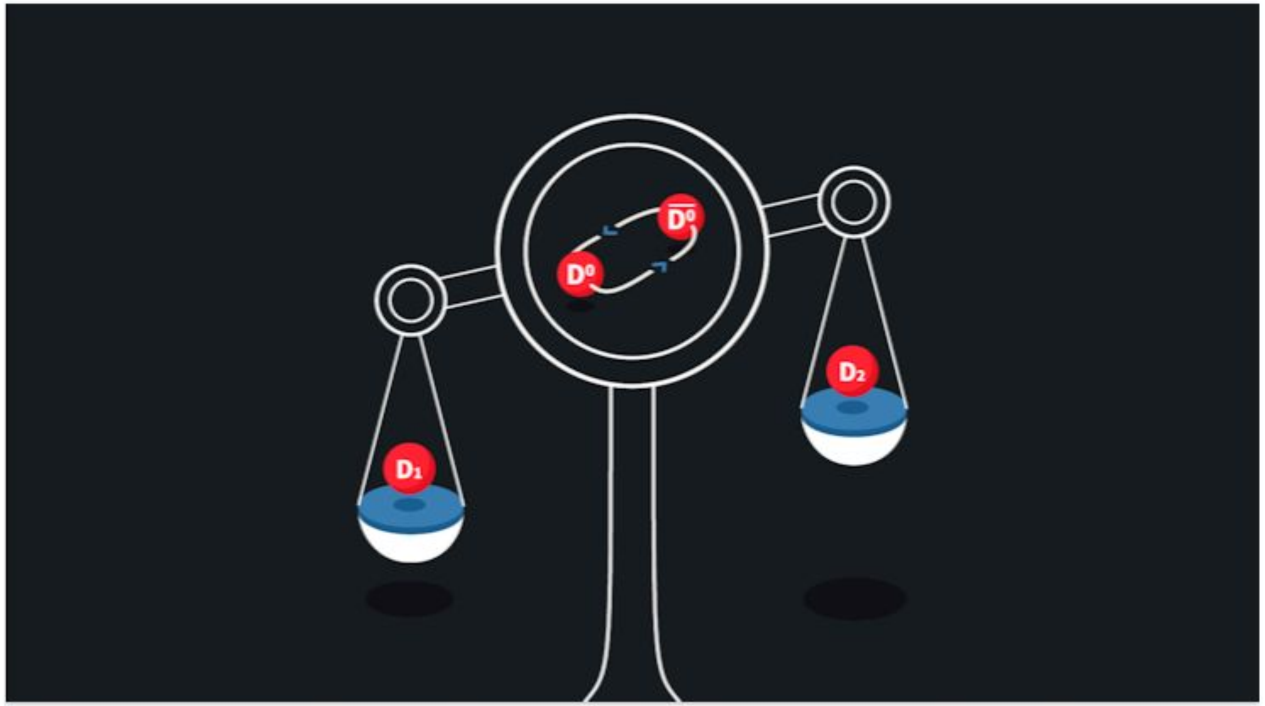


$$\phi_f \equiv \arg\left(\frac{q\bar{A}_f}{pA_f}\right) \qquad \phi_f \neq 0 \rightarrow CPV$$

LHCb measures tiny mass difference between particles

The result is a milestone in the study of how a particle known as a D0 meson changes from matter into antimatter and back

8 JUNE, 2021 | By Ana Lopes



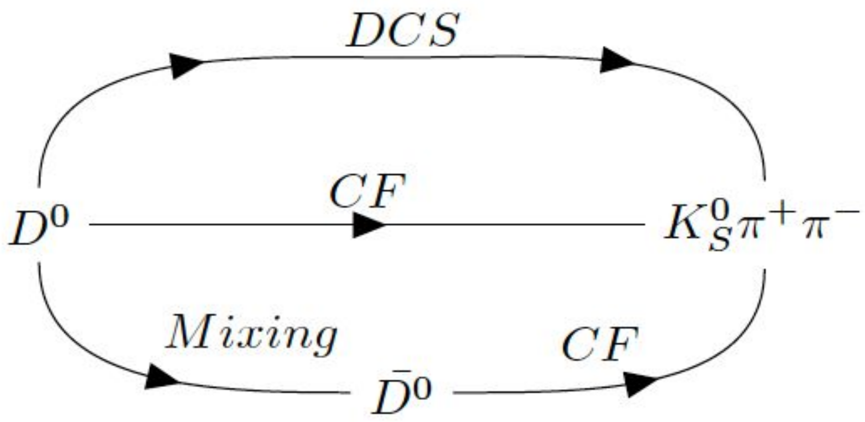
The LHCb collaboration has measured the tiny mass difference between the D1 and D2 mesons, which are a manifestation of the quantum superposition of the D0 particle and its antiparticle. This mass difference controls the speed of the D0 oscillation into its antiparticle and back. (Image: CERN)

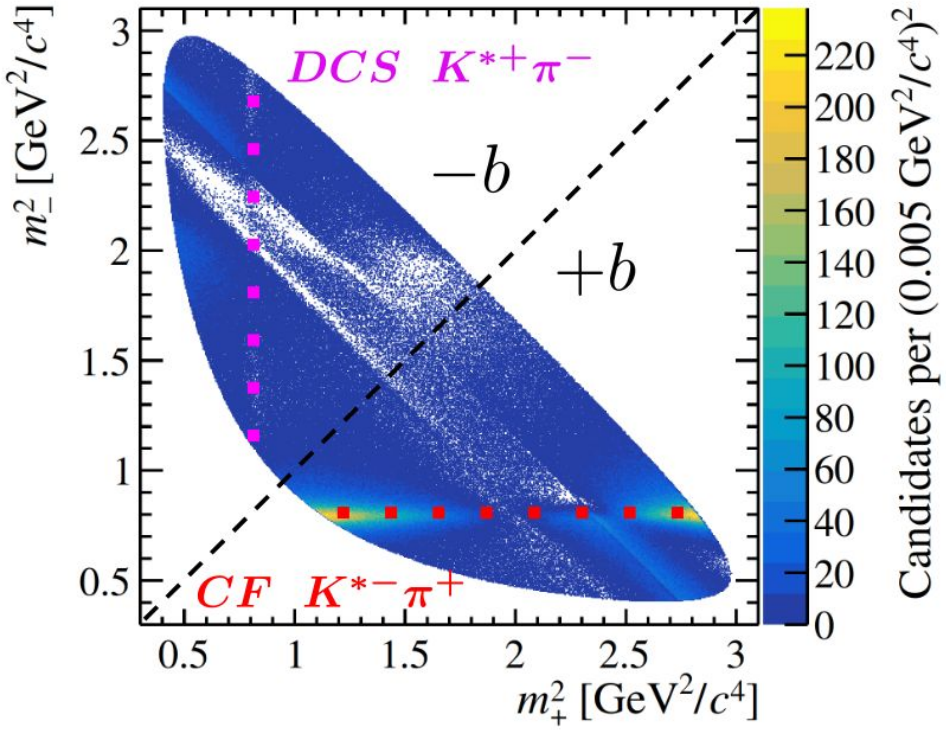
First non-zero measurement of x

$D^0 \to K^0_S \pi^+ \pi^-$

Phys. Rev. D 99, 012007

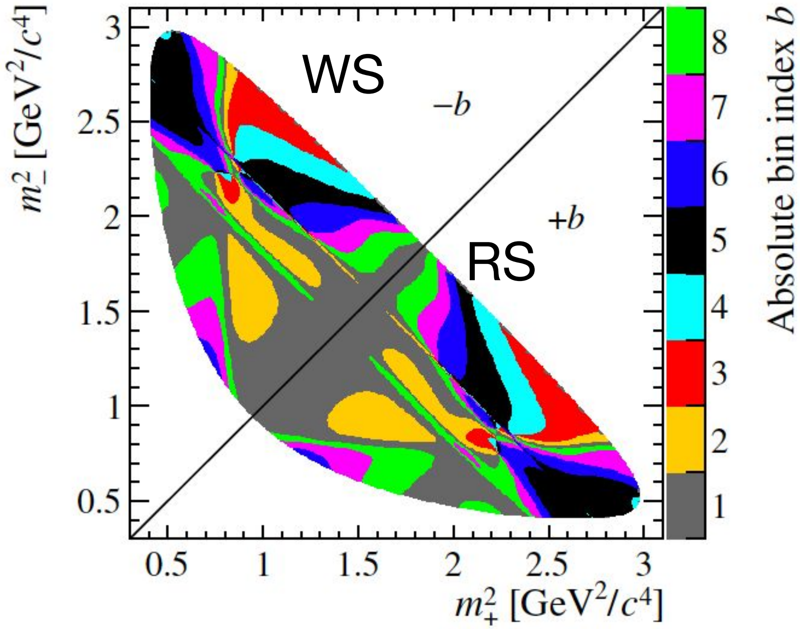
- Self-conjugate decay
  - Reconstruction efficiency is equivalent between D^0 flavours.
  - Decay path: Cabibbo-favored (CF),
    Doubly-Cabibbo-suppressed (DCS)
- Mixing and indirect CPV
  - Sensitive to x, y
  - Indirect CPV measurement of q/p and ϕ_f
- Analysis approaches: Model independent with Binflip method
  - Measure the time-dependent ratio between positive and negative Dalitz bins of constant strong phase difference, which gives access to mixing parameters
  - Suppress biases due to nonuniform event reconstruction efficiencies.
- Analysis on Run 2 dataset π-tagged sample

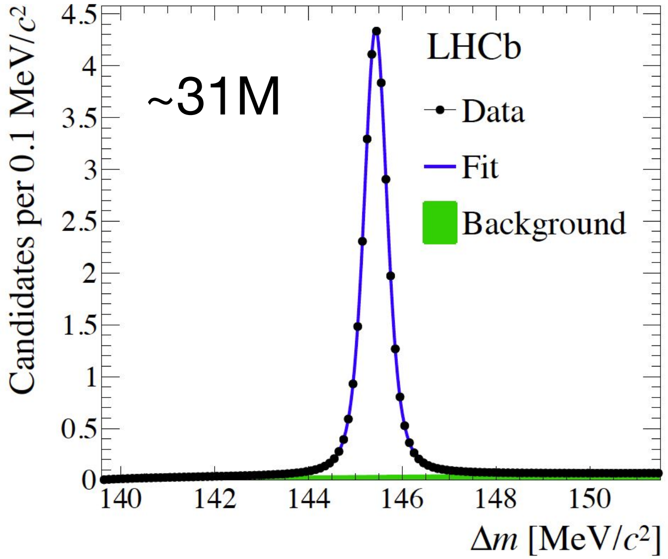




Binflip method

Phys. Rev. D 99, 012007





$$R_{bj} = \frac{N_{-bj}}{N_{+bj}} = \frac{\langle t\rangle_j \sqrt{r_b}\,\mathrm{Re}\left(X_b^* z\right) + \frac{1}{4}\left\langle t^2\right\rangle_j |z|^2 + r_b\left[1 + \frac{1}{4}\left\langle t^2\right\rangle_j \mathrm{Re}\left(z^2\right)\right]}{\langle t\rangle_j \sqrt{r_b}\,\mathrm{Re}\left(X_b z\right) + \frac{1}{4}\left\langle t^2\right\rangle_j |z|^2 r_b + \left[1 + \frac{1}{4}\left\langle t^2\right\rangle_j \mathrm{Re}\left(z^2\right)\right]}$$

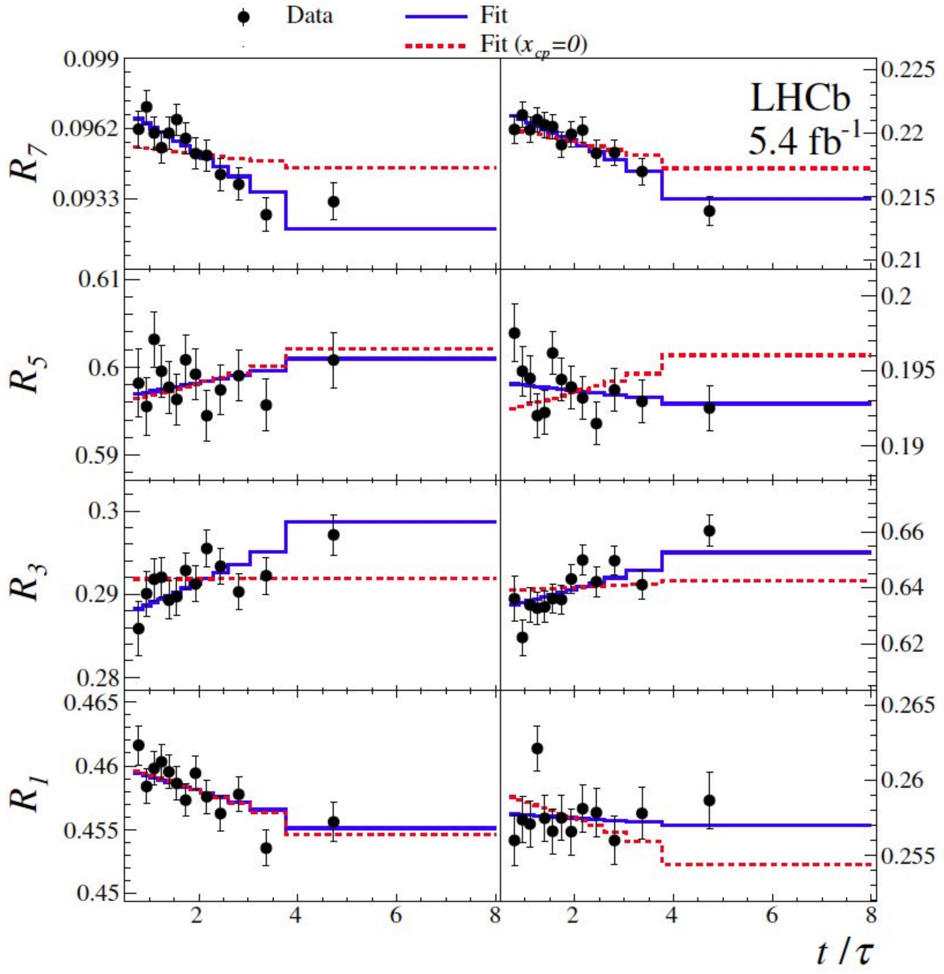
- Measure the ratio of signal yields between Dalitz bins -b and +b, in bins of the decay time j.
- $z = y - ix$ and r_b is the ratio at $t = 0$.
- Strong phase differences: $X_b = c_b - is_b$ [constrained from CLEO and BESIII, arXiv:2003.00091]
- With CP conservation (q/p = 1):

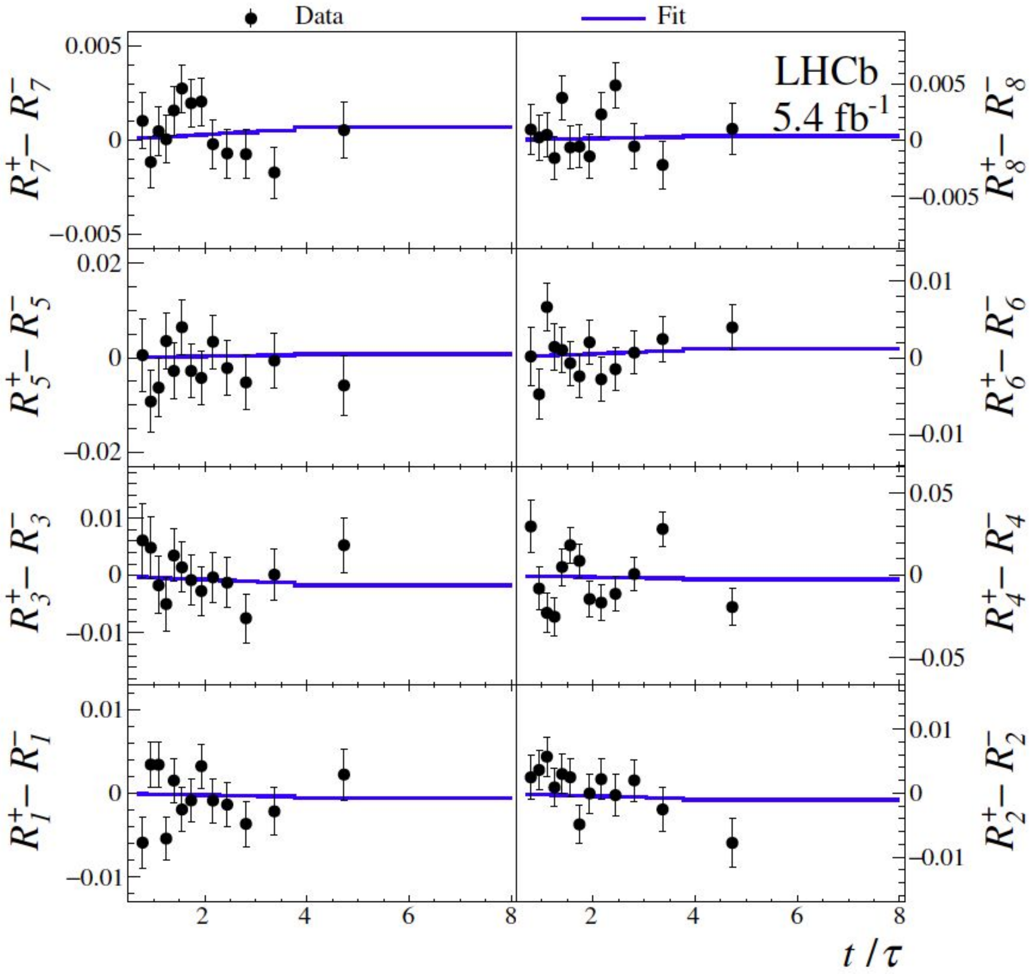
$$R_{bj}^{\pm} \approx r_b - \langle t\rangle_j \sqrt{r_b}\left[(1 - r_b)c_b\, y - \boxed{(1 + r_b)s_b\, x}\right]$$

  - Sensitive to both *x* and *y* parameters!

$D^0 \to K^0_S\pi^+\pi^-$ Binflip Results

arXiv:2106.03744



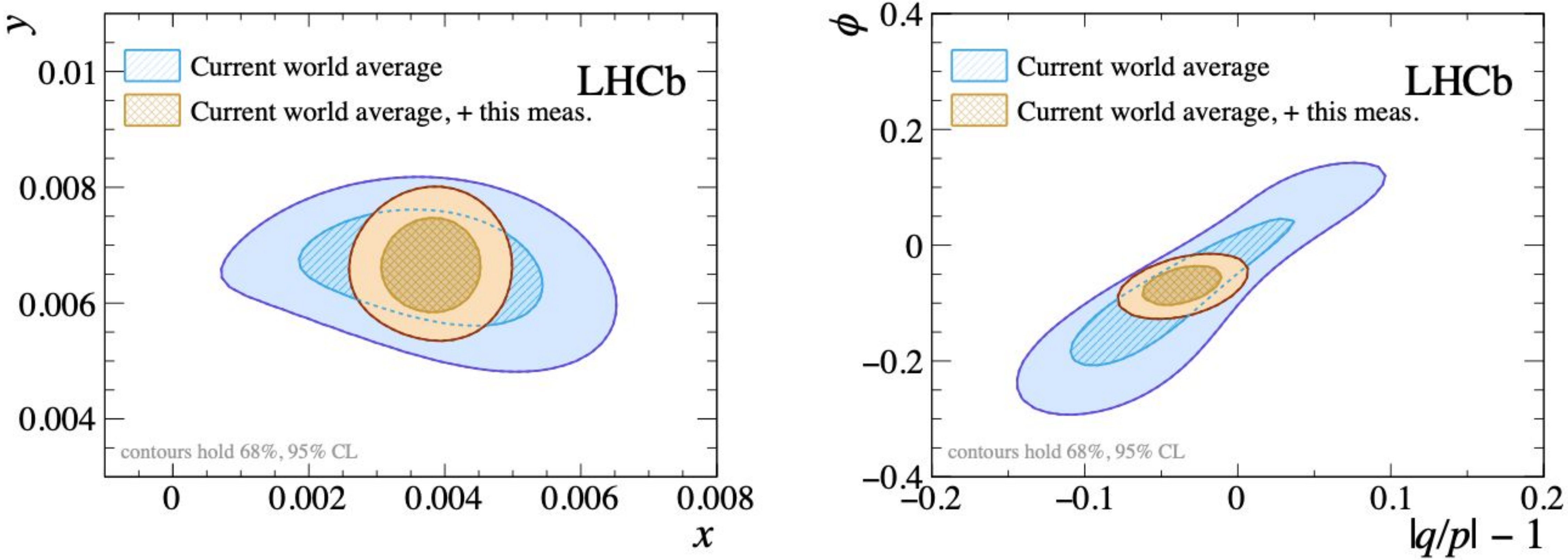


$$x_{CP} = (\ \ 3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$$
$$y_{CP} = (\ \ 4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$$

$$\Delta x = (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3}$$
$$\Delta y = (\ \ 0.20 \pm 0.36 \pm 0.13) \times 10^{-3}$$

$D^0 \to K^0_S \pi^+ \pi^-$ Binflip Results

arXiv:2106.03744



" First observation of a difference between D^0 mass eigenstates (> 7σ significance) "

However, no significant CPV is observed.

$D^0 \to K^0_S\pi^+\pi^-$ Binflip Upcoming Results

Semileptonic [μ-tagged]

- Model independent Binflip Method
  - Cover wider decay time distribution because events are selected with muon candidate
  - Combination with prompt sample
- Model dependent amplitude model
  - Perform amplitude fit with parameterized Dalitz and decay time efficiencies

Time-dependent CPV in $D^0 \to h^+h^- \quad (h = K, \pi)$

arXiv:2105.09889

- Search for CPV in two-body decay
  - Measure the time-dependent decay rate asymmetry

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

Final state dependent CPV ~ 10^{-5}

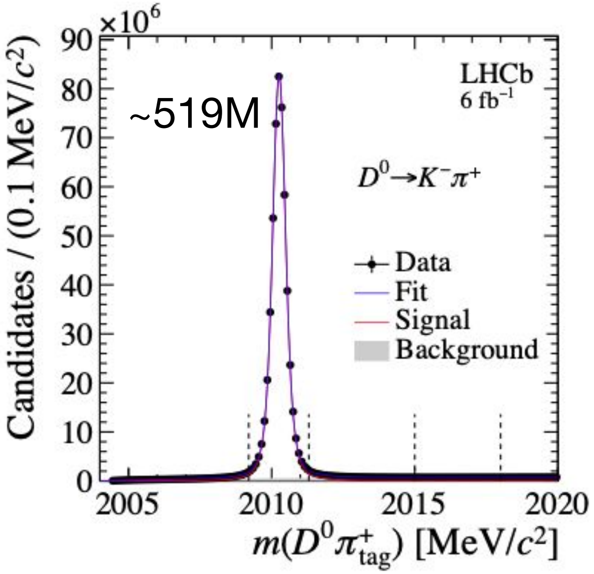
$$\Delta Y_f = -A_{\Gamma,f}$$

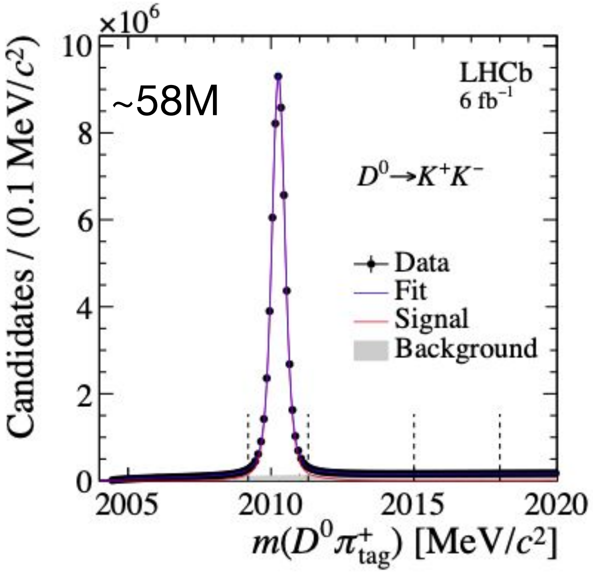
$$\approx x\phi - y\left(\left|\frac{q}{p}\right| - 1\right)$$

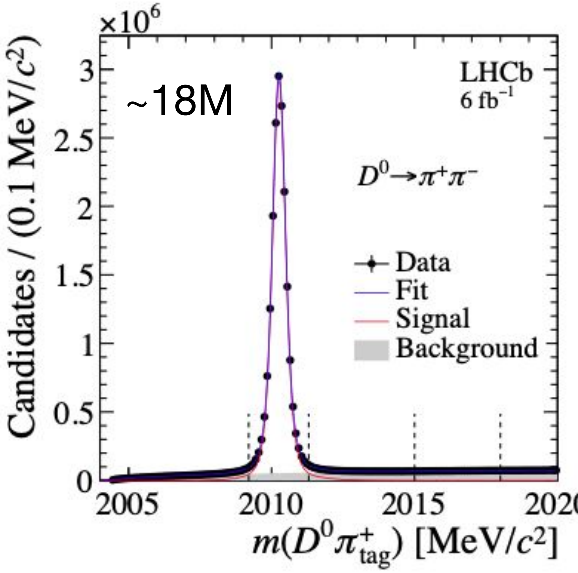
- The raw asymmetry can be factored to

$$A_{\text{raw}}(f,t) \approx A_{CP}(f,t) + A_{\text{det}}(\pi^+_{\text{tag}}) + A_{\text{prod}}(D^{*+})$$

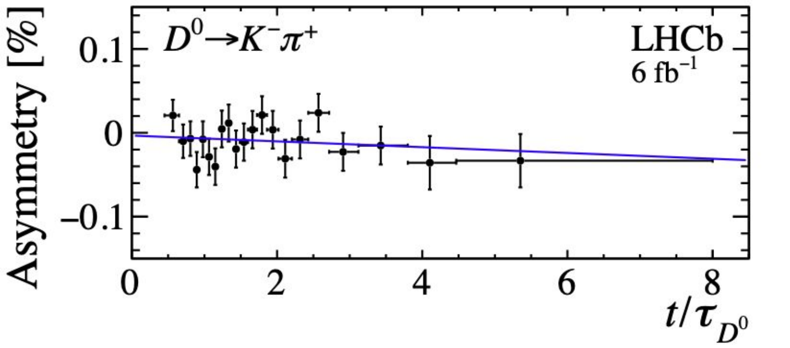
- Analysis on Run2 dataset π-tagged sample







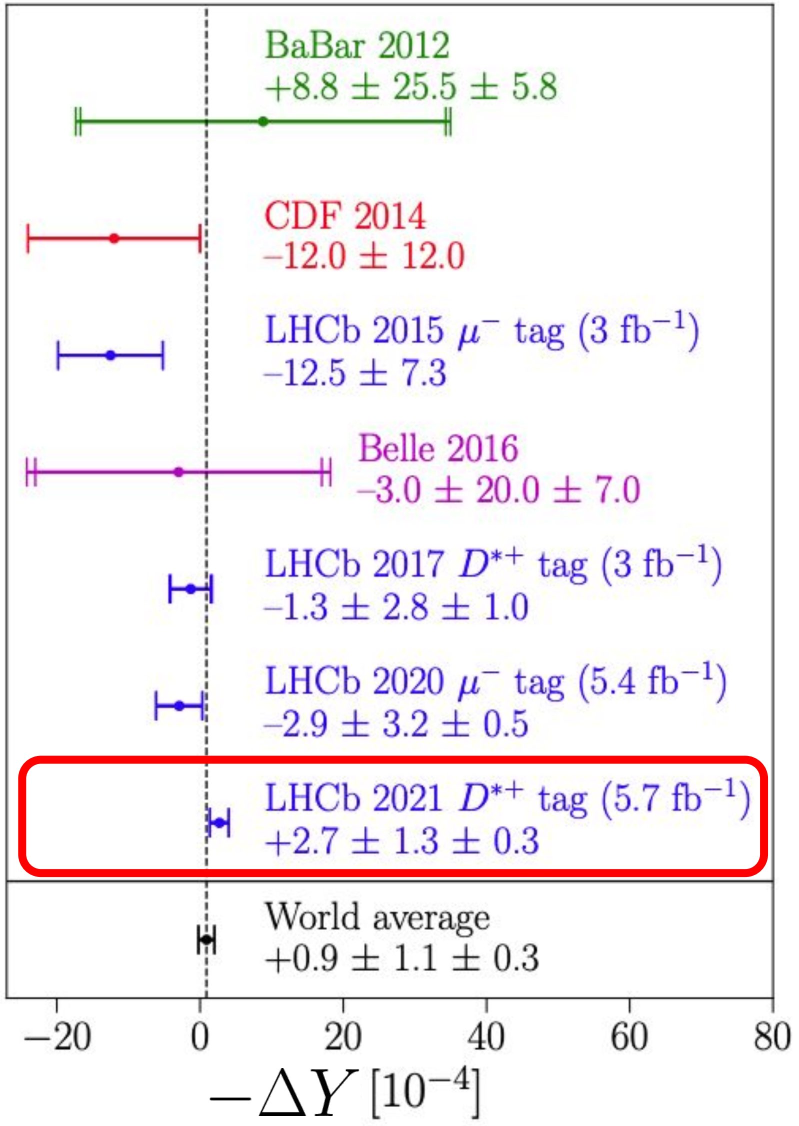
$$\Delta Y_{K^-\pi^+} = (-0.4 \pm 0.5 \pm 0.2) \times 10^{-4}$$



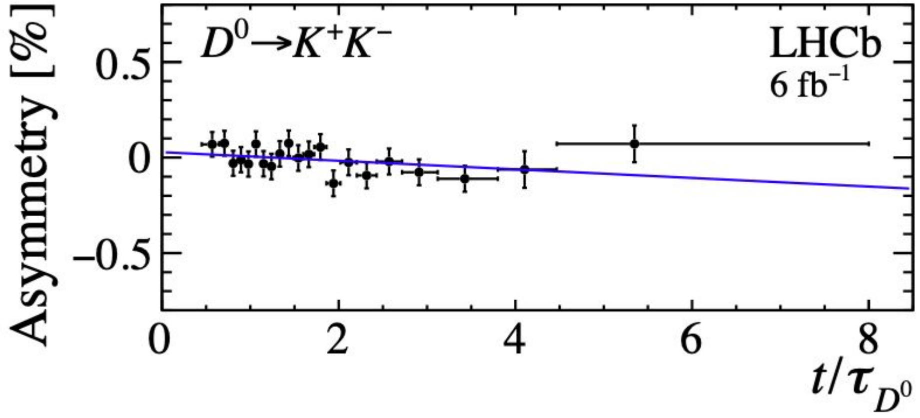
Control sample
No significant CPV

Time-dependent CPV in $D^0 \to h^+h^-$ $(h = K, \pi)$

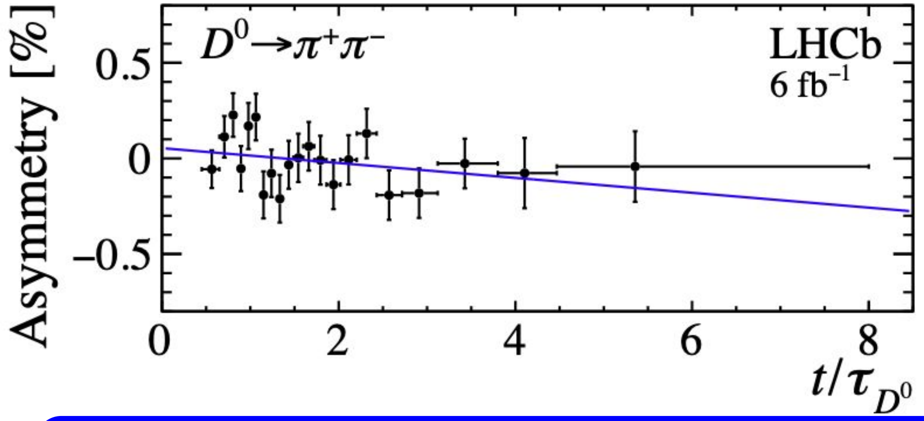
arXiv:2105.09889



$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4}$



$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}$



$$\Delta Y = (-2.7 \pm 1.3 \pm 0.3) \times 10^{-4}$$

Measurement of CPV in $D^0 \to K^0_S K^0_S$

arXiv:2105.01565

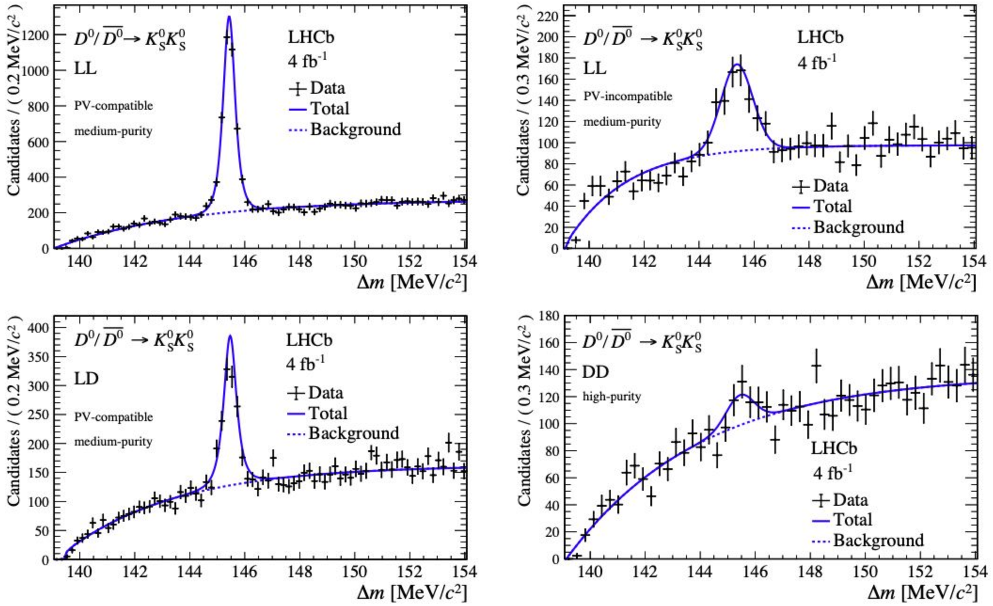
- Time-integrated CPV search
  - Measure decay width difference between D^0 flavours

$$\mathcal{A}^{CP}(K^0_S K^0_S) = \frac{\Gamma(D^0 \to K^0_S K^0_S) - \Gamma(\overline{D}^0 \to K^0_S K^0_S)}{\Gamma(D^0 \to K^0_S K^0_S) + \Gamma(\overline{D}^0 \to K^0_S K^0_S)}$$

- This quantity can be large up to around 1%

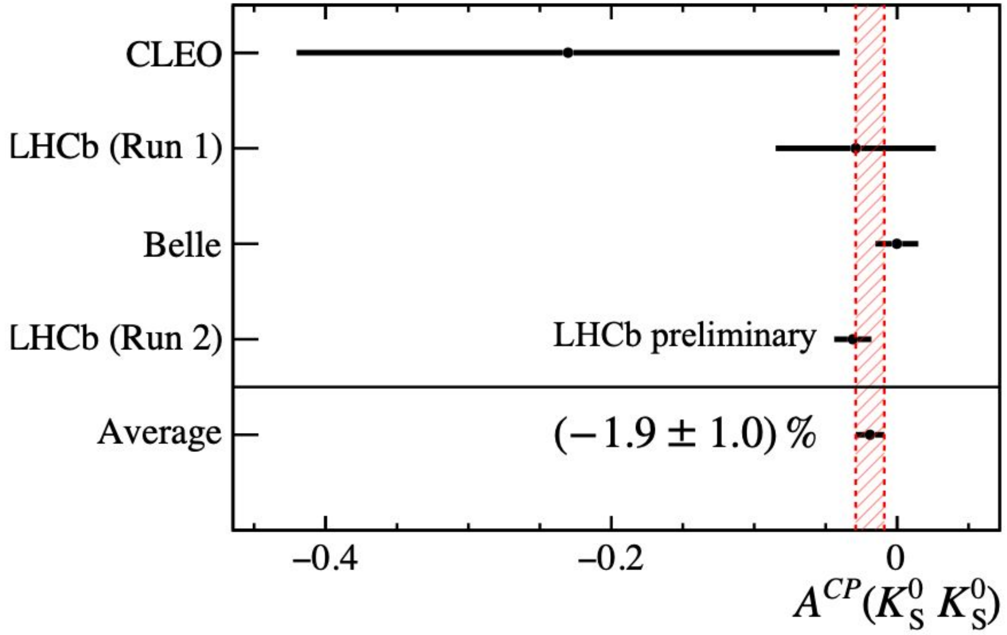
Phys. Rev. D 92, 054036

- Analysis on Run 2 dataset π-tagged sample



$$\mathcal{A}^{CP}(K^0_S K^0_S) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$$

- Consistent with no CPV at 2.4σ
- Most precise measurement up to date!



Lifetime of Ω_c^0 baryon

LHCb-PAPER-2021-021

Charm hadron hierarchy

- On PDG 2018

$$\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \boxed{\tau_{\Omega_c^0}}$$

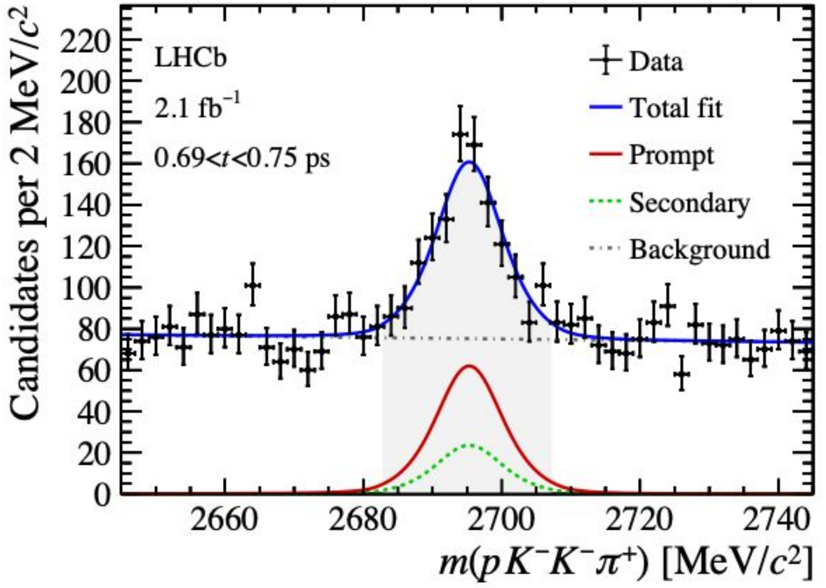
PRD 98, 030001 (2018)

- In 2018, LHCb measured longer Ω_c^0 lifetime in semileptonic b-baryon decays

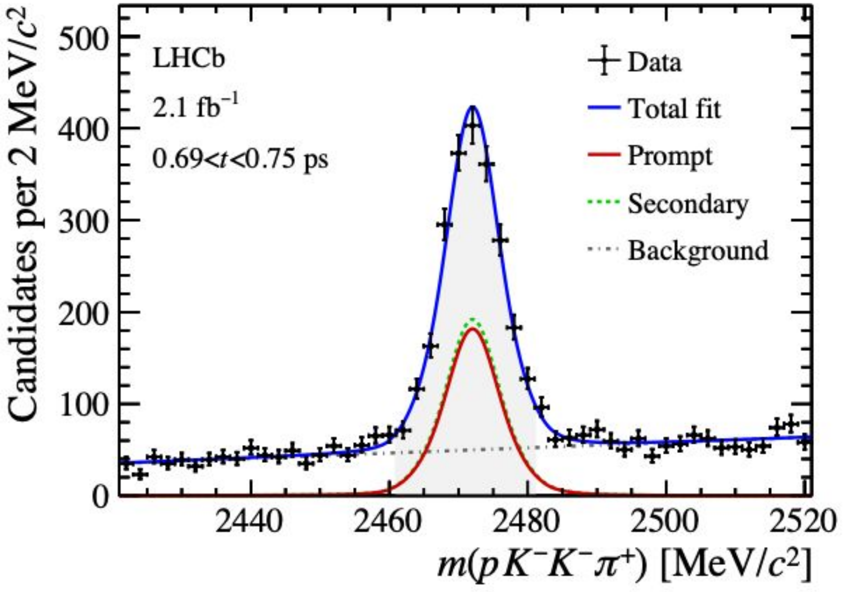
$$\tau_{\Xi_c^+} > \boxed{\tau_{\Omega_c^0}} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$$

PRL 121, 092003(2018)

- Cross-check the result with an independent sample
  - Run 2 dataset on promptly produced $\Omega^0_c/\Xi^0_c \rightarrow pK^-K^-\pi^+$ final state
  - Use prompt $D^0 \rightarrow K^-K^+\pi^-\pi^+$ decays as control mode
- Estimate lifetime with least squares fits to decay time



Ω_c^0



Ξ_c^0

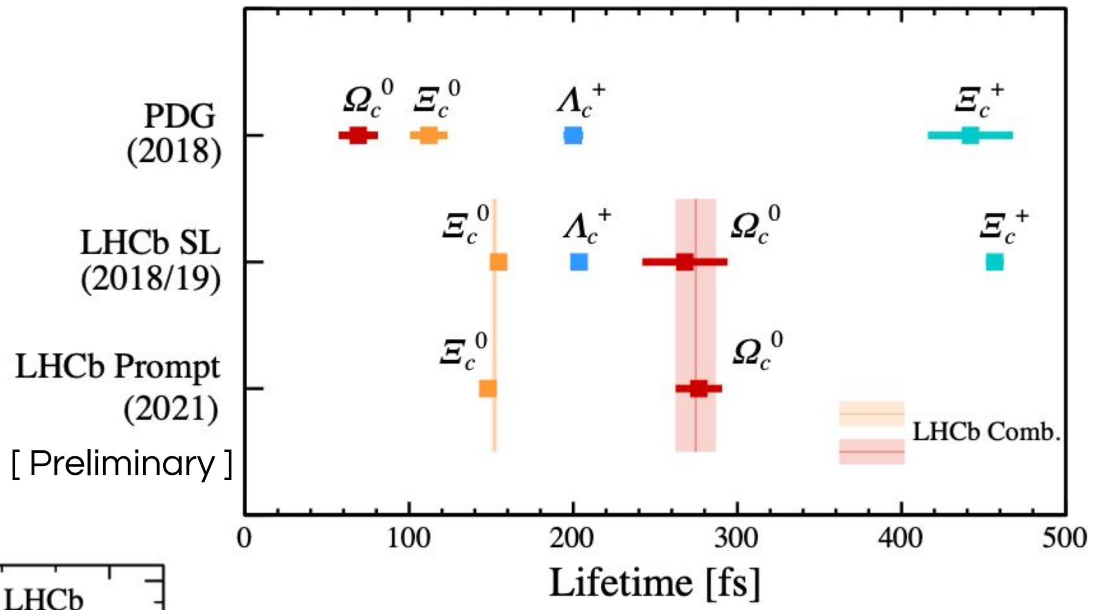
Lifetime of Ω_c^0 baryon

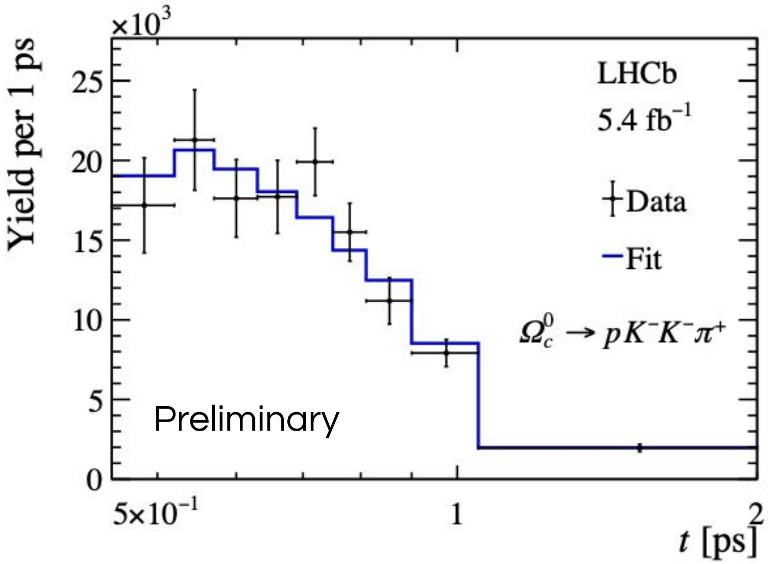
LHCb-PAPER-2021-021

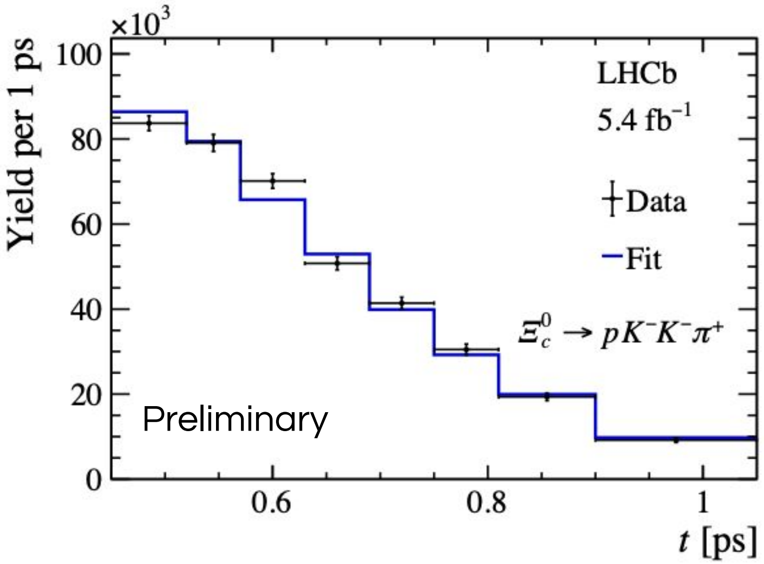
- Measure the lifetimes to be

$$\tau_{\Omega_c^0} = 276.5 \pm 13.4 \pm 4.4 \pm 0.7\,\text{fs}$$

$$\tau_{\Xi_c^0} = 148.0 \pm 2.3 \pm 2.2 \pm 0.2\,\text{fs}$$







$$\boxed{\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}}$$

CONFIRMED

Conclusions

- LHCb has produced the largest dataset of charm hadrons.
  - This leads to new interesting results and provides often world-best measurements
  - More results are coming soon!
- However, the measurements are limited by statistics
  - This is expected to be improved in Run 3 which is starting next year with luminosity up to 50/fb by 2030
  - Working on preparing upgraded detector as well as upgraded online trigger

Thank you!
Any questions?

BACKUP

Mixing and CPV

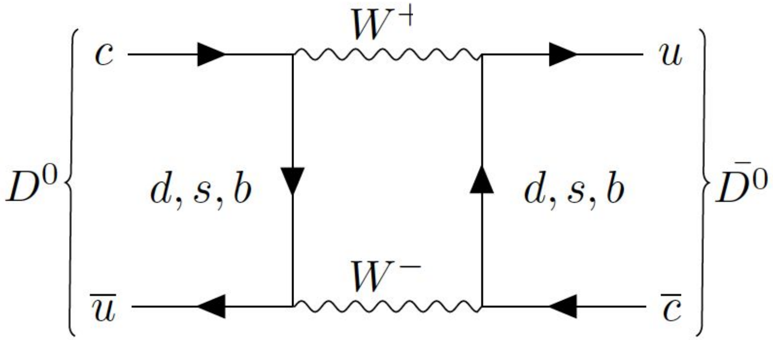
- Mass eigenstates of neutral meson mixing

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

- Usually described by mixing parameters *x, y*

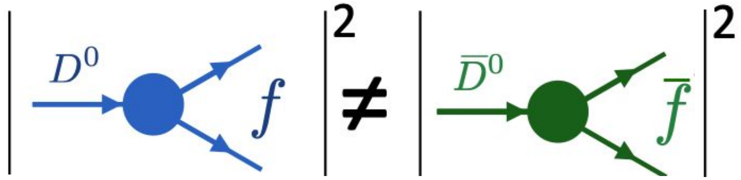
$$x = \frac{m_2 - m_1}{\Gamma}, \; y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}, \; \Gamma = \frac{\Gamma_2 + \Gamma_1}{2}$$

- and interference parameter $\phi_f \equiv \arg(\frac{q\bar{A}_f}{pA_f})$
- Mixing occurs when x and y ≠ 0

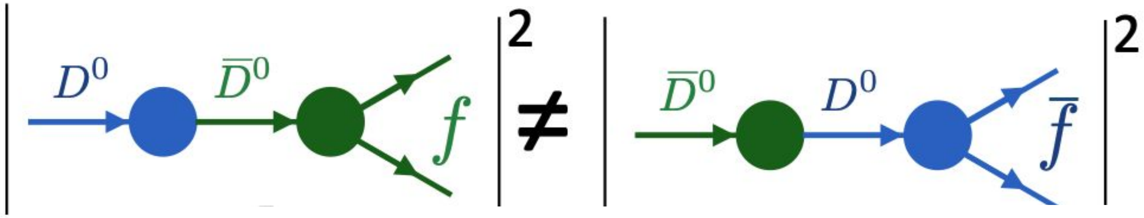


- There are different scenarios of CPV

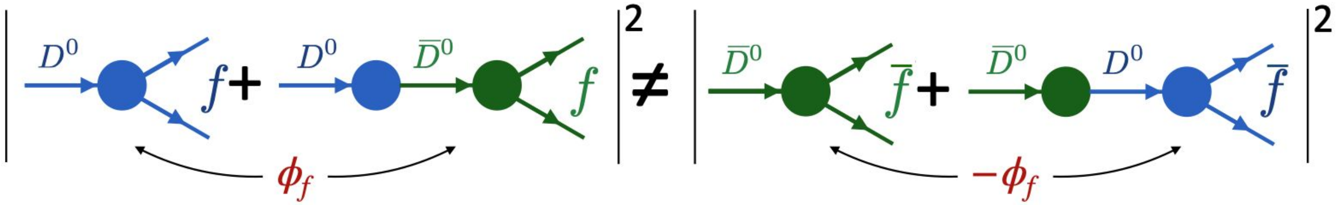
Direct CPV



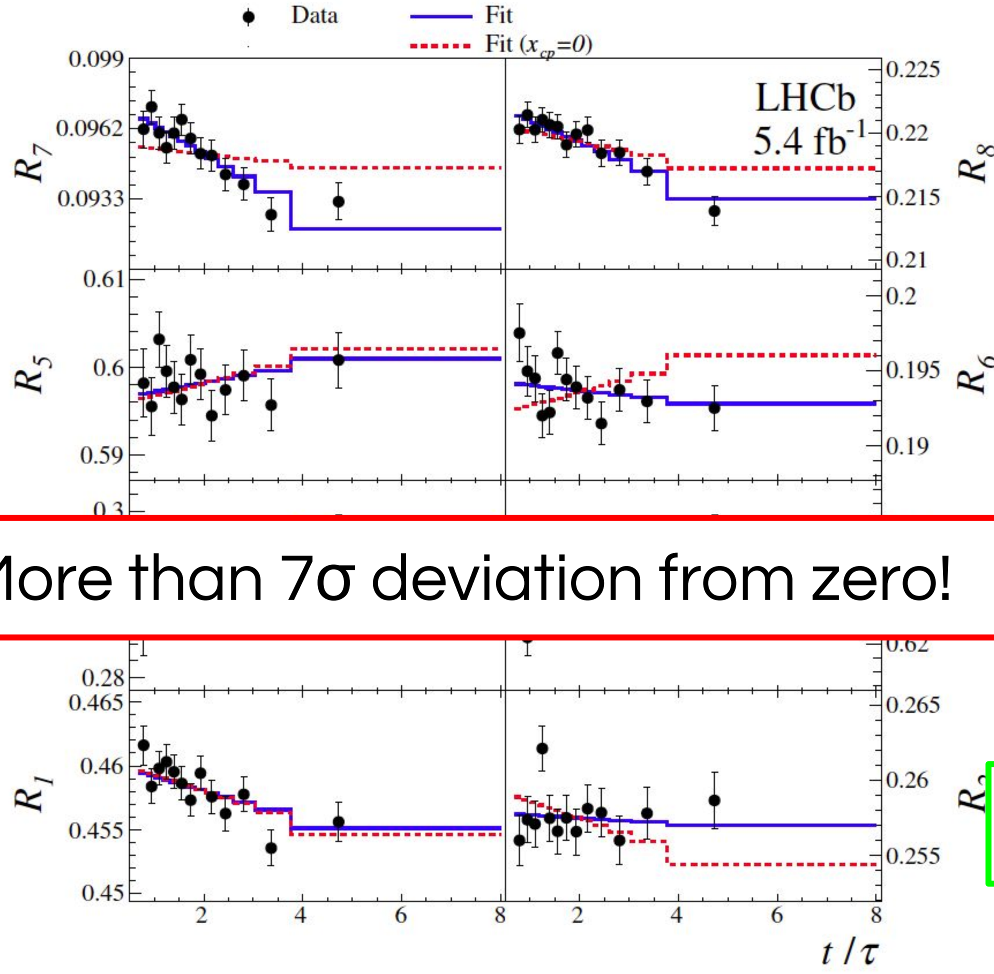
CPV in mixing

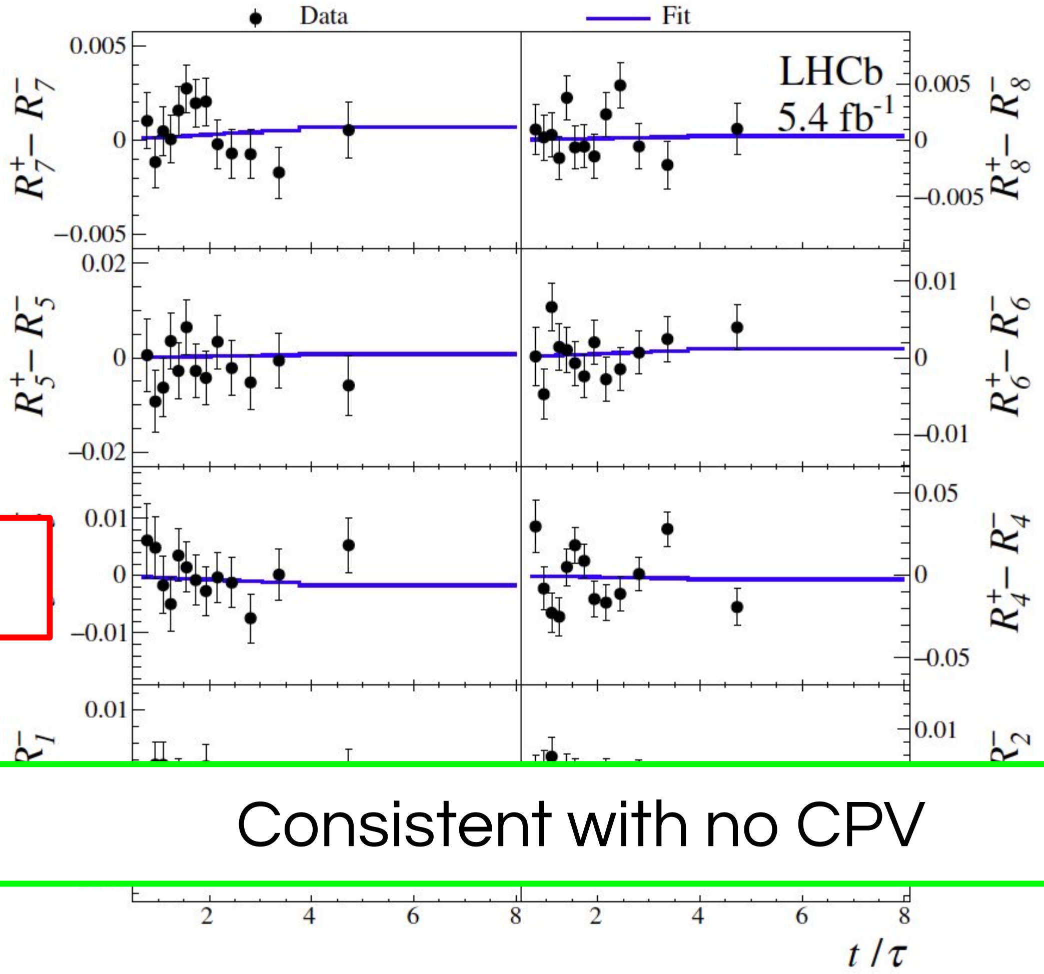


CPV in decay-mixing interference



$D^0 \to K_S^0\pi^+\pi^-$ Binflip Results





More than 7σ deviation from zero!

Consistent with no CPV

$$x_{CP} = (\ \ 3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$$

$$y_{CP} = (\ \ 4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$$

$$\Delta x = (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3}$$

$$\Delta y = (\ \ 0.20 \pm 0.36 \pm 0.13) \times 10^{-3}$$

$D^0 \to K^0_S\pi^+\pi^-$ Binflip Results

$$
\begin{aligned}
x_{CP} &= (3.97 \pm 0.46 \pm 0.29) \times 10^{-3} \\
y_{CP} &= (4.59 \pm 1.20 \pm 0.85) \times 10^{-3} \\
\Delta x &= (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3} \\
\Delta y &= (0.20 \pm 0.36 \pm 0.13) \times 10^{-3}
\end{aligned}
$$

$\longrightarrow$

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

“ First observation of a difference between *D⁰* mass eigenstates with significance of more than 7σ. ”

However, no significant of CPV is observed.

$D^0 \to K_S^0\pi^+\pi^-$ Binflip Results

Source	x_{CP}	y_{CP}	Δx	Δy
Reconstruction and selection	0.199	0.757	0.009	0.044
Secondary charm decays	0.208	0.154	0.001	0.002
Detection asymmetry	0.000	0.001	0.004	0.102
Mass-fit model	0.045	0.361	0.003	0.009
Total systematic uncertainty	0.291	0.852	0.010	0.110

Strong phase inputs	0.23	0.66	0.02	0.04
Detection asymmetry inputs	0.00	0.00	0.04	0.08
Statistical (w/o inputs)	0.40	1.00	0.18	0.35
Total statistical uncertainty	0.46	1.20	0.18	0.36

$D^0 \to K_S^0\pi^+\pi^-$ Binflip Results

- Oscillation parameters

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

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

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

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

- Sensitivity to *x*

$$\begin{aligned} R_{bj}^{\pm} &\approx \frac{r_b + \langle t\rangle_j \sqrt{r_b}\operatorname{Re}(X_b^* z)}{1 + \langle t\rangle_j \sqrt{r_b}\operatorname{Re}(X_b z)} \\ &\approx r_b + \langle t\rangle_j \sqrt{r_b}\left[\operatorname{Re}(X_b^* z) - r_b \operatorname{Re}(X_b z)\right] \\ &= r_b - \langle t\rangle_j \sqrt{r_b}\left[(1 - r_b)c_b\, y - (1 + r_b)s_b\, x\right], \end{aligned}$$

Time-dependent CPV in $D^0 \to h^+h^- \quad (h = K, \pi)$

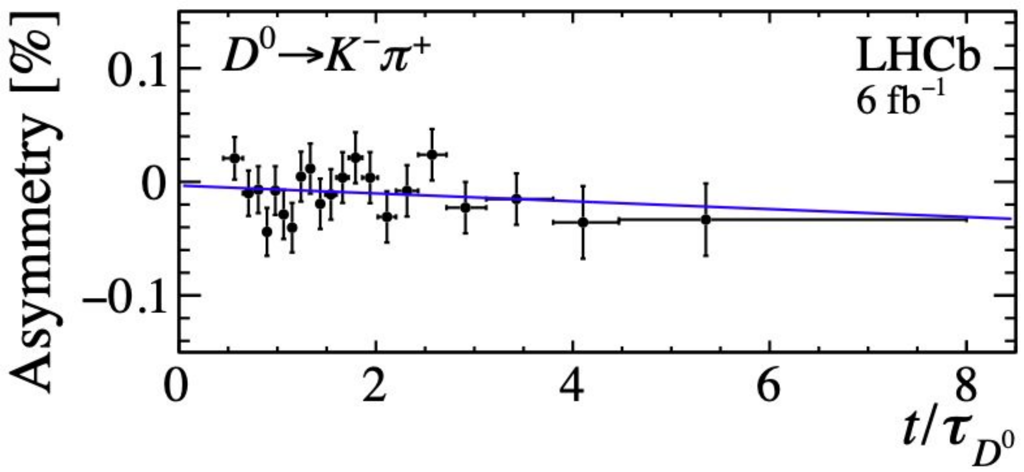
Systematic source	$\Delta A_\Gamma(K^-\pi^+)$ $[10^{-4}]$	$\Delta A_\Gamma(K^+K^-)$ $[10^{-4}]$	$\Delta A_\Gamma(\pi^+\pi^-)$ $[10^{-4}]$
$m(h^+h^-)$ background	0.00	0.06	0.03
Subtraction of the $m(D^0\pi^+_{\text{tag}})$ background	0.12	0.24	0.34
Flavour dependent shift of $m(D^{*+})$ peak	0.14	0.14	0.14
Secondary decays	0.08	0.08	0.08
Kinematic weighting	0.05	0.05	0.05
Total systematic	0.23	0.32	0.39
Statistical	0.50	1.52	2.81

Time-dependent CPV in $D^0 \to h^+h^- \quad (h = K, \pi)$

arXiv:2105.09889

- The analysis procedure is controlled on Kπ channel where CPV is not expected.
- We found no significant CPV in the channel, and the analysis is not affected significantly by the systematics.

$$\Delta Y_{K^-\pi^+} = (-0.4 \pm 0.5 \pm 0.2) \times 10^{-4}$$



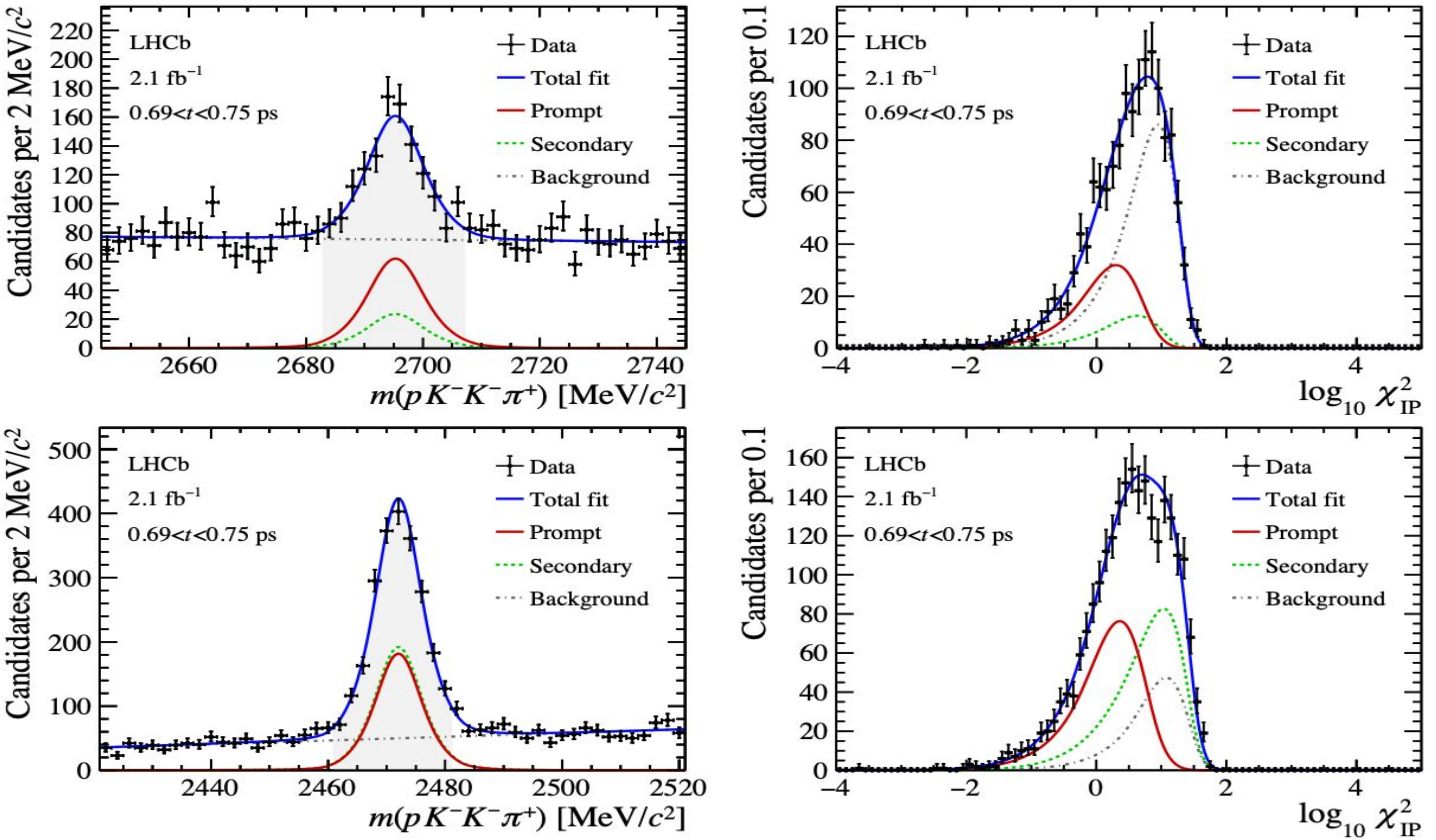
Source	$\Delta Y_{K^+K^-}$ $[10^{-4}]$	$\Delta Y_{\pi^+\pi^-}$ $[10^{-4}]$
Subtraction of the $m(D^0\pi^+_{\text{tag}})$ background	0.2	0.3
Flavour-dependent shift of D^*-mass peak	0.1	0.1
D^{*+} from B-meson decays	0.1	0.1
$m(h^+h^-)$ background	0.1	0.1
Kinematic weighting	0.1	0.1
Total systematic uncertainty	0.3	0.4
Statistical uncertainty	1.5	2.8

Measurement of CPV in $D^0 \to K_S^0 K_S^0$

arXiv:2105.01565

Sample	2015 + 2016 ($2\ \text{fb}^{-1}$)		2017 + 2018 ($4\ \text{fb}^{-1}$)	
	Yield	$\mathcal{A}^{CP}$ [%]	Yield	$\mathcal{A}^{CP}$ [%]
LL PV-comp.	1388 ± 41	$0.3 \pm 2.5 \pm 0.6$	4056 ± 77	$-4.3 \pm 1.6 \pm 0.4$
LL PV-incomp.	178 ± 31	$-11 \pm 17 \pm 2$	430 ± 41	$-3.0 \pm 7.9 \pm 1.1$
LD PV-comp.	411 ± 25	$-7.2 \pm 5.8 \pm 1.1$	1145 ± 49	$-2.9 \pm 3.8 \pm 0.7$
LD PV-incomp.	58 ± 18	$-10 \pm 31 \pm 4$	349 ± 64	$-5 \pm 17 \pm 2$
DD	–	–	87 ± 28	$-35 \pm 47 \pm 6$

Lifetime of Ω_c^0 baryon



Lifetime of Ω_c^0 baryon

Sources	$\tau_{\Omega_c^0}$ [fs]	$\tau_{\Xi_c^0}$ [fs]
Fit model	2.2	1.0
Calibration sample size	0.1	0.1
Kinematic correction	3.4	0.4
Decay-time resolution	1.3	1.8
χ^2_{IP} scaling	1.1	0.5
Decay-length scale	0.1	0.1
D^0–$\overline{D}^0$ mixing	0.8	0.6
Total systematic uncertainty	4.4	2.2
D^0 lifetime	0.7	0.2
Statistical uncertainty	13.4	2.3