Mixing and indirect CP violation in charm mesons at LHCb

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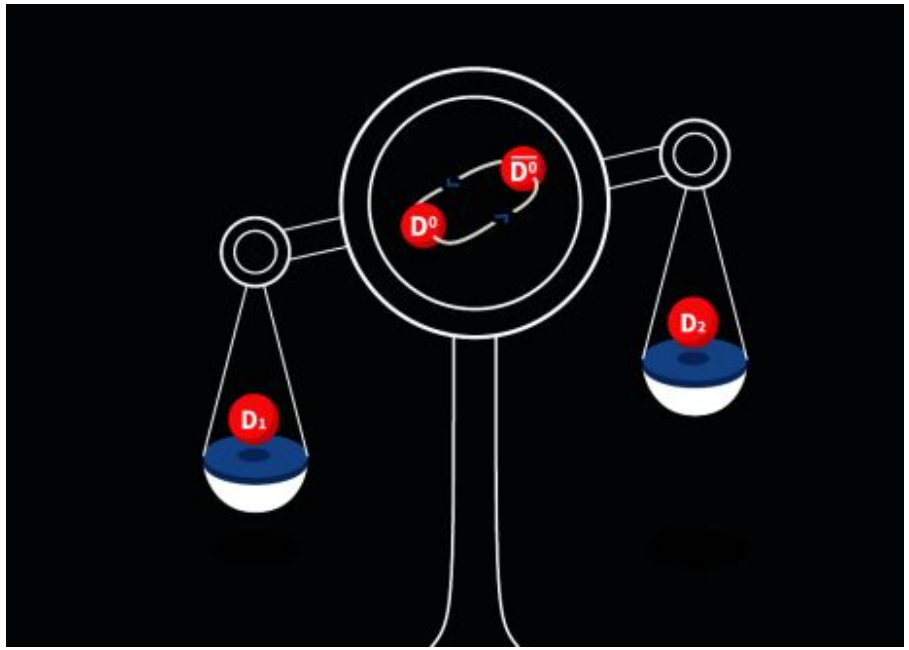
On behalf of the LHCb collaboration

The International Conference on High-Energy Physics (ICHEP) 2022



NEW RESULT

LHCb-PAPER-2022-020

Model-independent measurement of charm mixing parameters in $\overline{B} \to D^0(\to K^0_S\pi^+\pi^-)\mu^-\bar{\nu}_\mu X$ decays

in preparation

Complementary to →

PHYSICAL REVIEW LETTERS **127,** 111801 (2021)

Observation of the Mass Difference between Neutral Charm-Meson Eigenstates

PHYSICAL REVIEW D **105,** 092013 (2022)

Measurement of the charm mixing parameter $y_{CP} - y_{CP}^{K\pi}$ using two-body D^0 meson decays

PHYSICAL REVIEW D **104,** 072010 (2021)

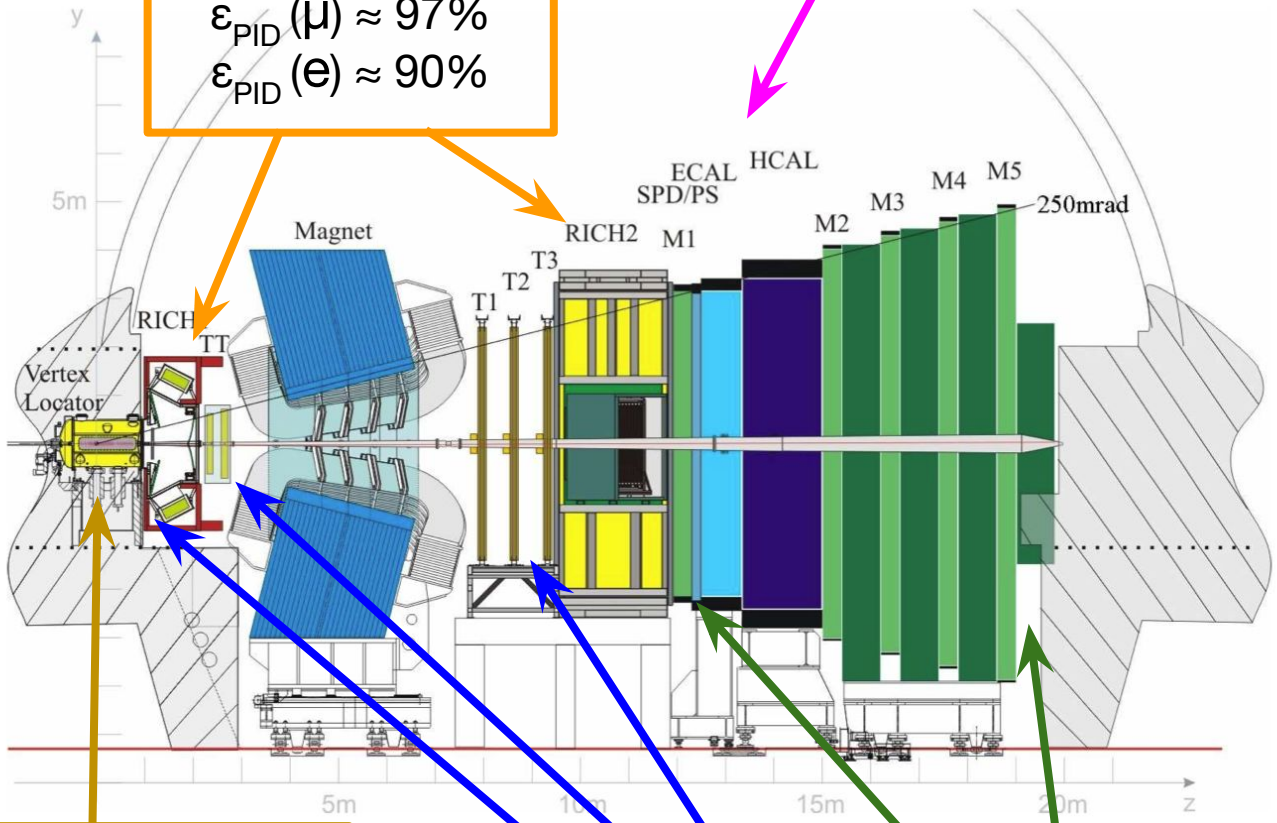
Search for time-dependent *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

LHCb experiment

JINST 3 (2008) S08005

PID
ε_{PID} (K) ≈ 95%
ε_{PID} (μ) ≈ 97%
ε_{PID} (e) ≈ 90%

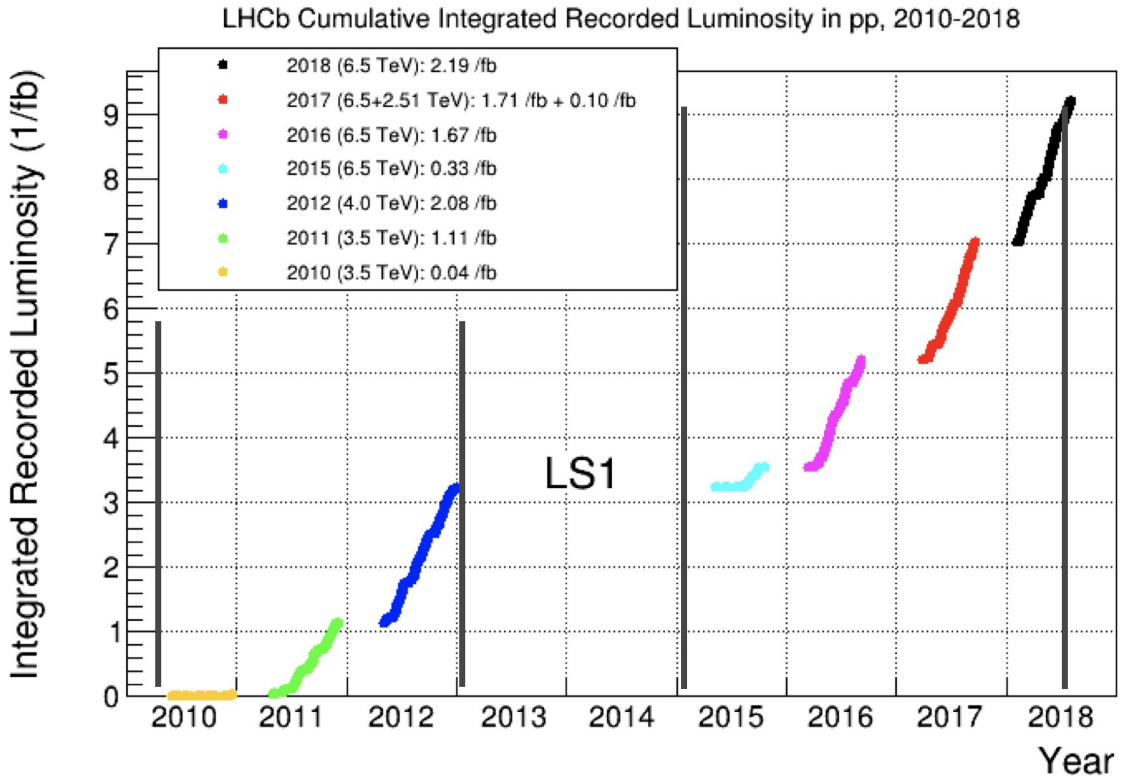
Calorimeter



Vertex
ε_{VELO} ≈ 98%
σ(IP) = 20 μm

Tracking
ε_{Track} ≈ 95%

Muon

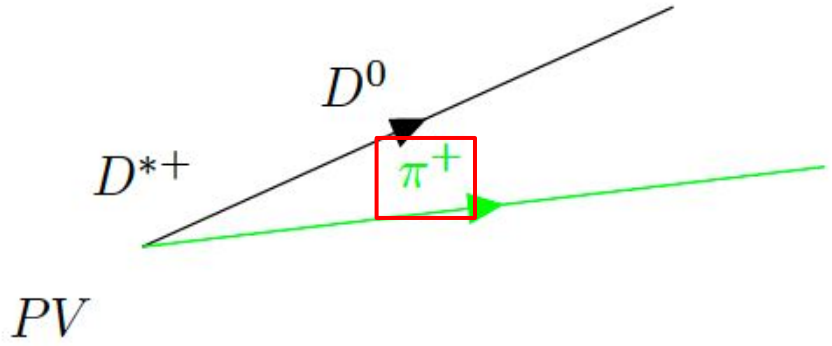


Run 1
3/fb at 7/8 TeV

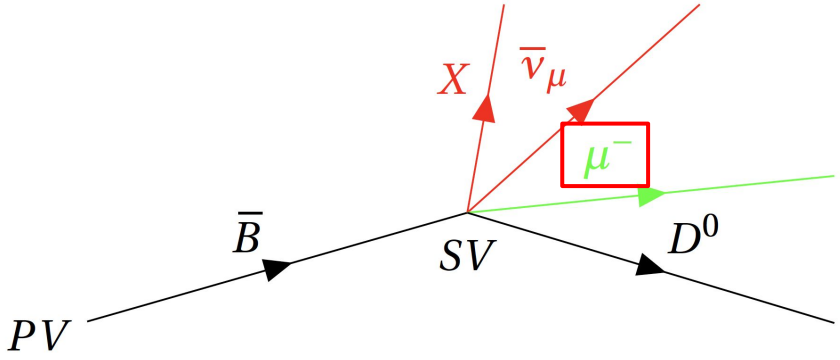
Run 2
6/fb at 13TeV

Charm Physics 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. Mixing is described by

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

  - With parameters

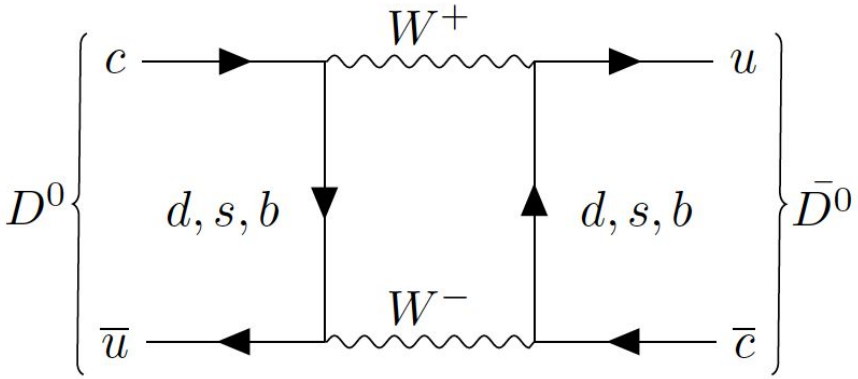
$$x \equiv (m_1 - m_2)/\Gamma = \Delta m/\Gamma \qquad y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma = \Delta\Gamma/2\Gamma$$

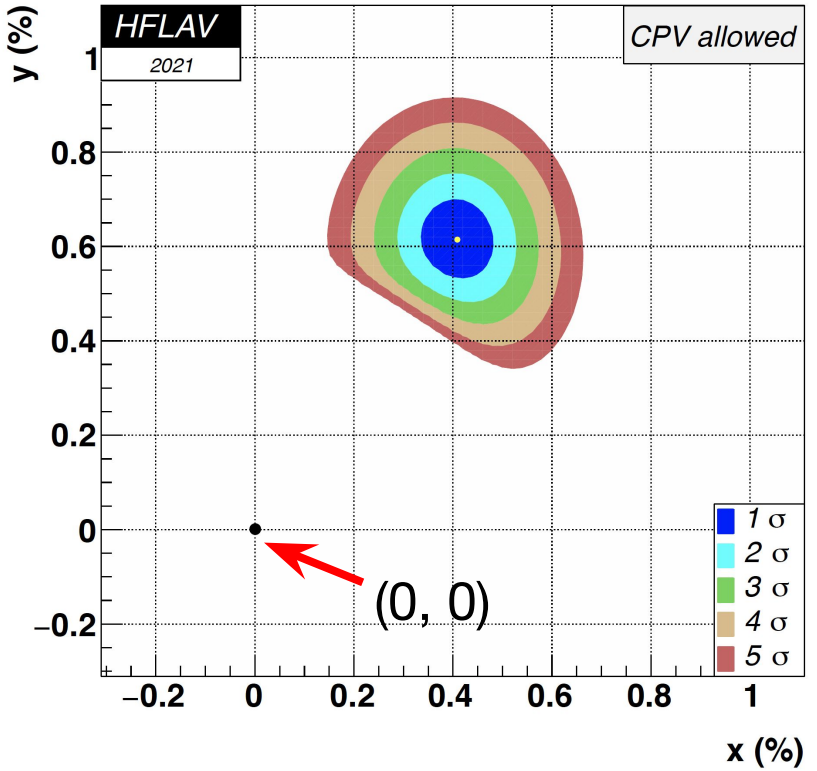
- Charm mixing parameter *x* has been recently observed to be > 0 in promptly produced $D^0 \to K^0_S\pi^+\pi^-$ from LHCb.

$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3}$$

PRL 127, 111801 (2021)

- An analysis on $\overline{B} \to D^0\mu^-\overline{\nu}_\mu X$ sample is conducted and complements the prompt measurement, probing additionally low D^0 decay times.





Mixing and CPV

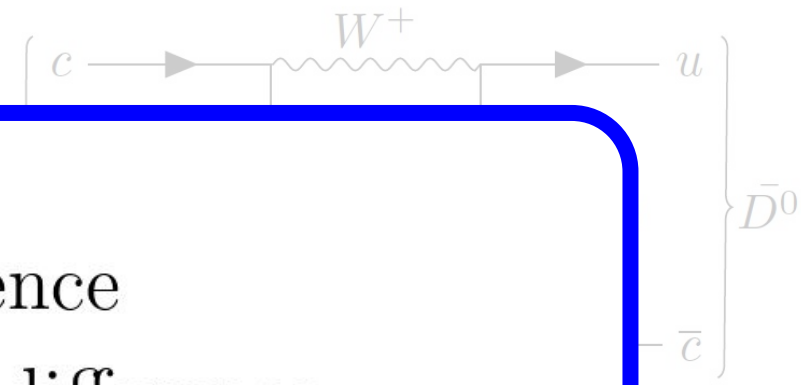
Mixing parameters

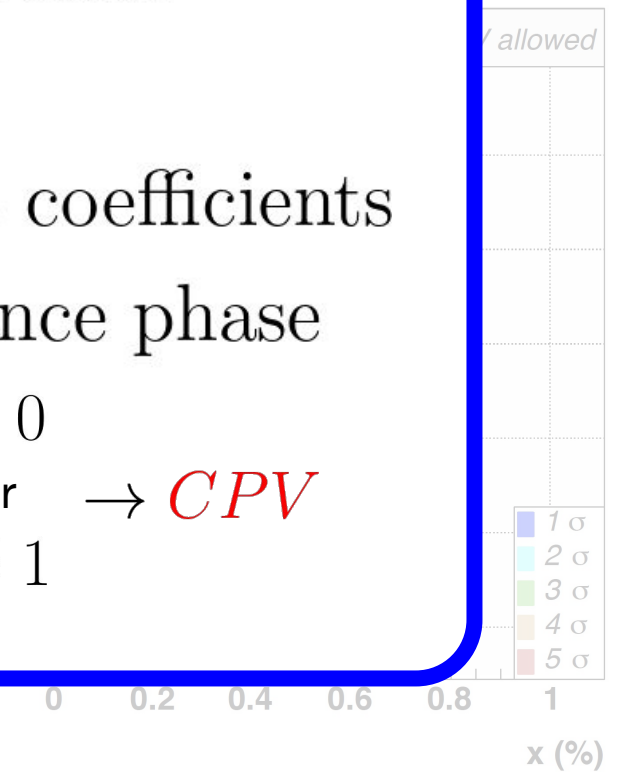
$$\text{Mixing parameters} \begin{cases} x & : \text{mass difference} \\ y & : \text{decay-time difference} \end{cases}$$

$$CP\text{-violating parameters} \begin{cases} |q/p| & : \text{flavour state coefficients} \\ \phi & : CP\text{-interference phase} \end{cases}$$

$$\phi \equiv \arg\left(\frac{q\overline{A}}{pA}\right)$$

$$\phi \neq 0 \quad \text{or} \quad |q/p| \neq 1 \rightarrow CPV$$



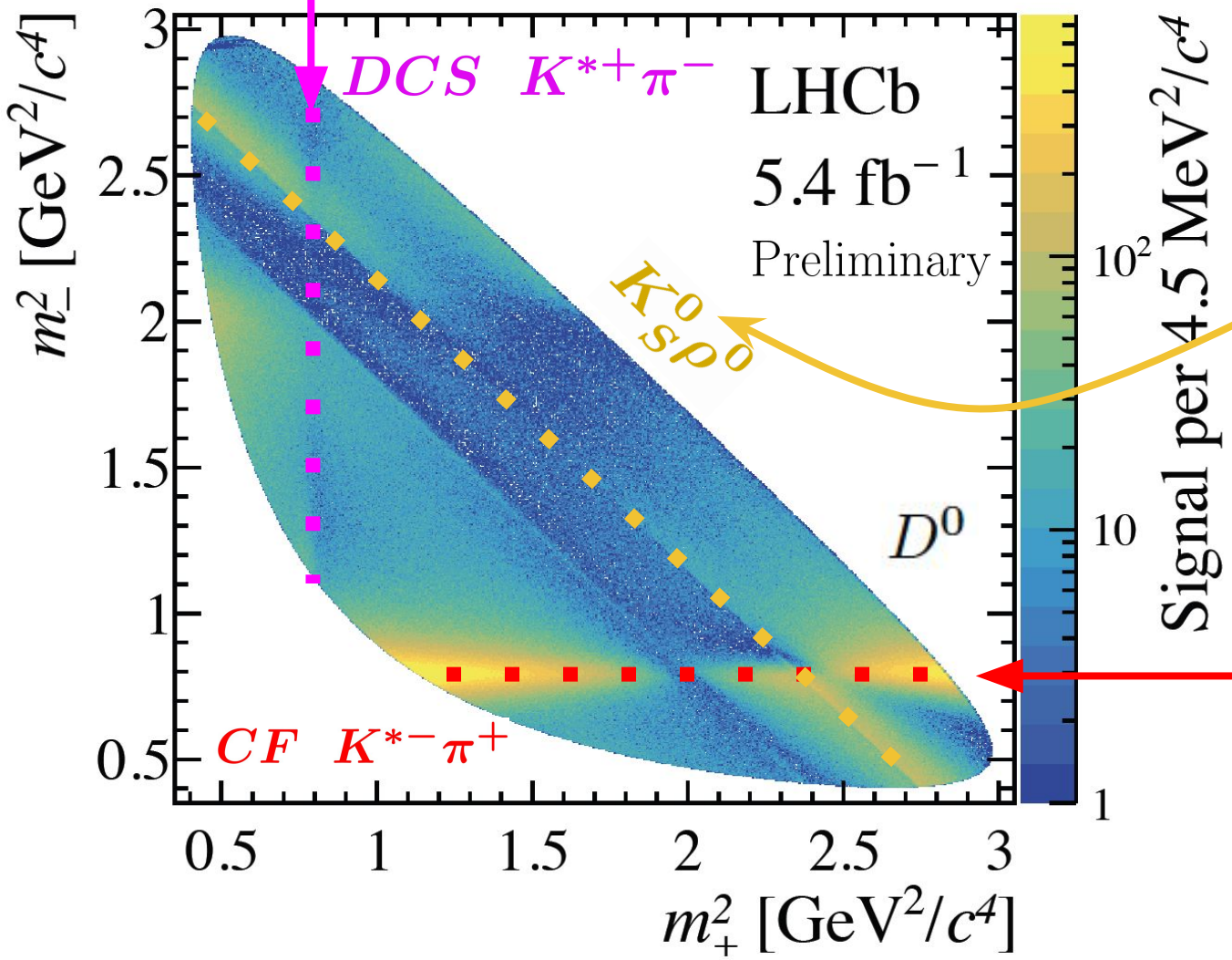


$D^0 \to K^0_S \pi^+ \pi^-$

$K^*(892)^+ \pi^-$, $K^{*+} \to K^0_S \pi^+$

Doubly-Cabibbo-Suppressed (DCS)

$m^2_\pm \equiv m^2(K^0_S \pi^\pm)$



$K^0_S \rho^0$
$K^0_S \omega$, $\omega \to \pi^+\pi^-$
$K^0_S(\pi^+\pi^-)_{S-wave}$
$K^0_S f_0(980)$, $f_0 \to \pi^+\pi^-$
$K^0_S f_0(1370)$, $f_0 \to \pi^+\pi^-$
$K^0_S f_2(1270)$, $f_2 \to \pi^+\pi^-$

Cabibbo-Favoured (CF)

$K^*(892)^- \pi^+$, $K^{*-} \to K^0_S \pi^-$

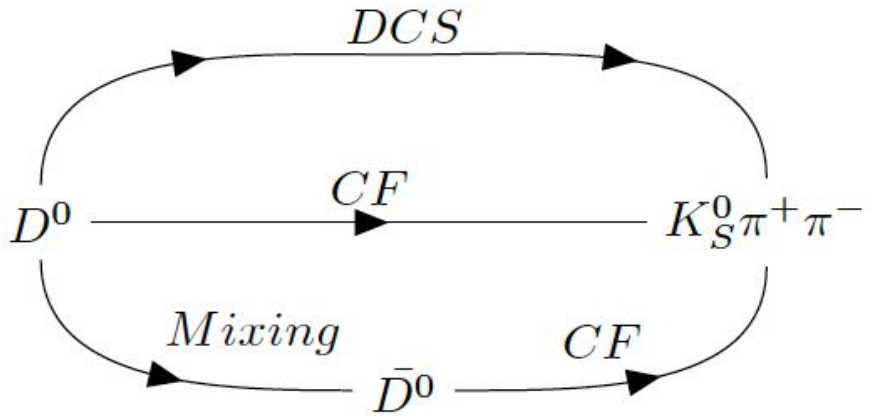
$K^*_0(1430)^- \pi^+$, $K^{*-}_0 \to K^0_S \pi^-$
$K^*_2(1430)^- \pi^+$, $K^{*-}_2 \to K^0_S \pi^-$
$K^*(1680)^- \pi^+$, $K^{*-} \to K^0_S \pi^-$

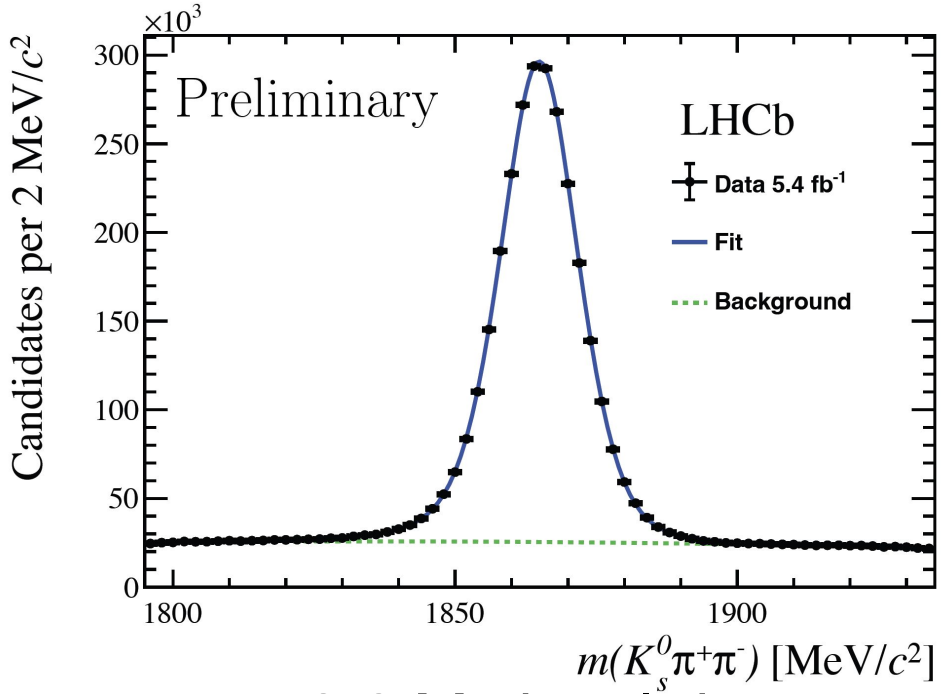
[PDG 2022 - PTEP 2022, 083C01 (2022)]

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

- Self-conjugate decay
  - Reconstruction efficiency is **equivalent** between D^0 flavours.
- Mixing and indirect CPV
  - Sensitive to x, y
  - Indirect CPV measurement of q/p and ϕ_f
- Binflip method [PRD 99, 012007 (2019)]
  - Model independent
  - Access to mixing parameters through the time-dependent ratio between positive and negative Dalitz bins of constant strong phase difference
  - **Suppress biases due to nonuniform event reconstruction efficiencies.**
- Analysis on Run 2 dataset μ-tagged [LHCb-PAPER-2022-020*].

*in preparation





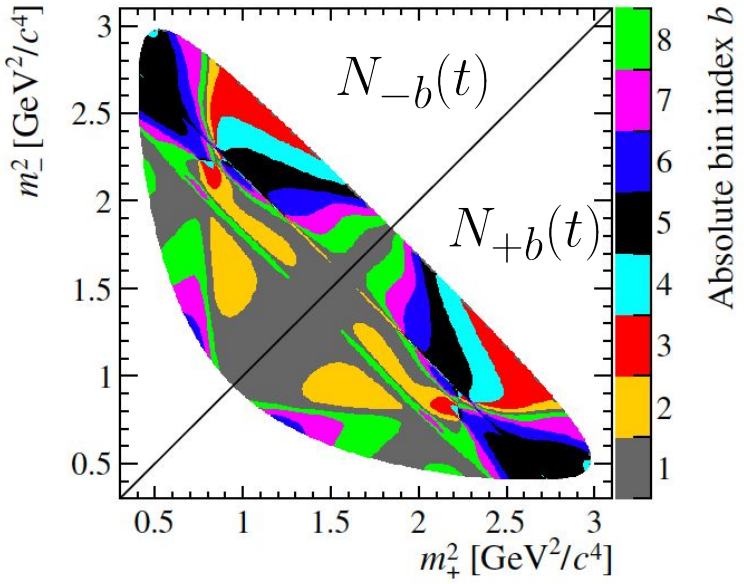
~ 3.6 M signal decays

Binflip method

PRD 99, 012007 (2019)

- Measure the ratio *R* of signal yields between Dalitz bins -b and +b, in bins of the decay time j.
  - Fit the ratio as a function of decay time.

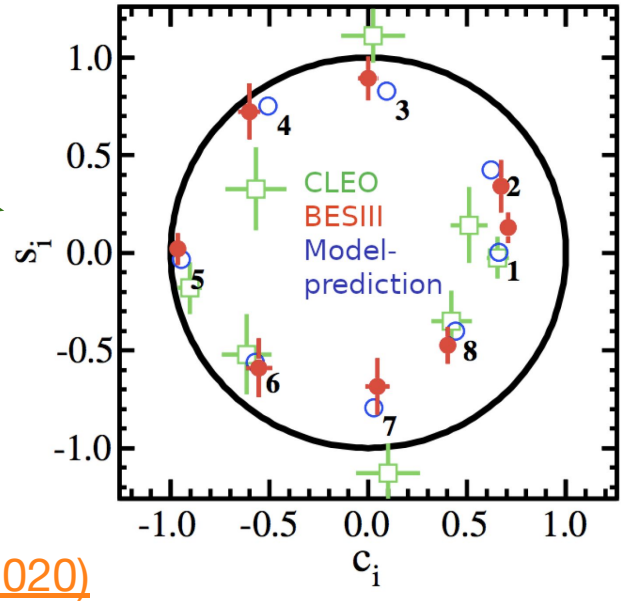
$$R_b(t) = \frac{N_{-b}(t)}{N_{+b}(t)}$$



- If mixing occurs, this ratio **changes as a function of D^0 decay time.**
- Strong phase $X_b = (c_b - i\,s_b)$ by CLEO, BESIII
- With CP conservation (q/p = 1):

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

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



PRD 82, 112006 (2010) , PRD 101, 112002 (2020)

Binflip method - Parametrisation

PRD 99, 012007 (2019)

Sign refers to the flavour of D^0

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

Converge to x and y
If $\phi = 0$ and $|q/p| = 1$

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

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

"slope differences"
If unequal to 0
→ CPV

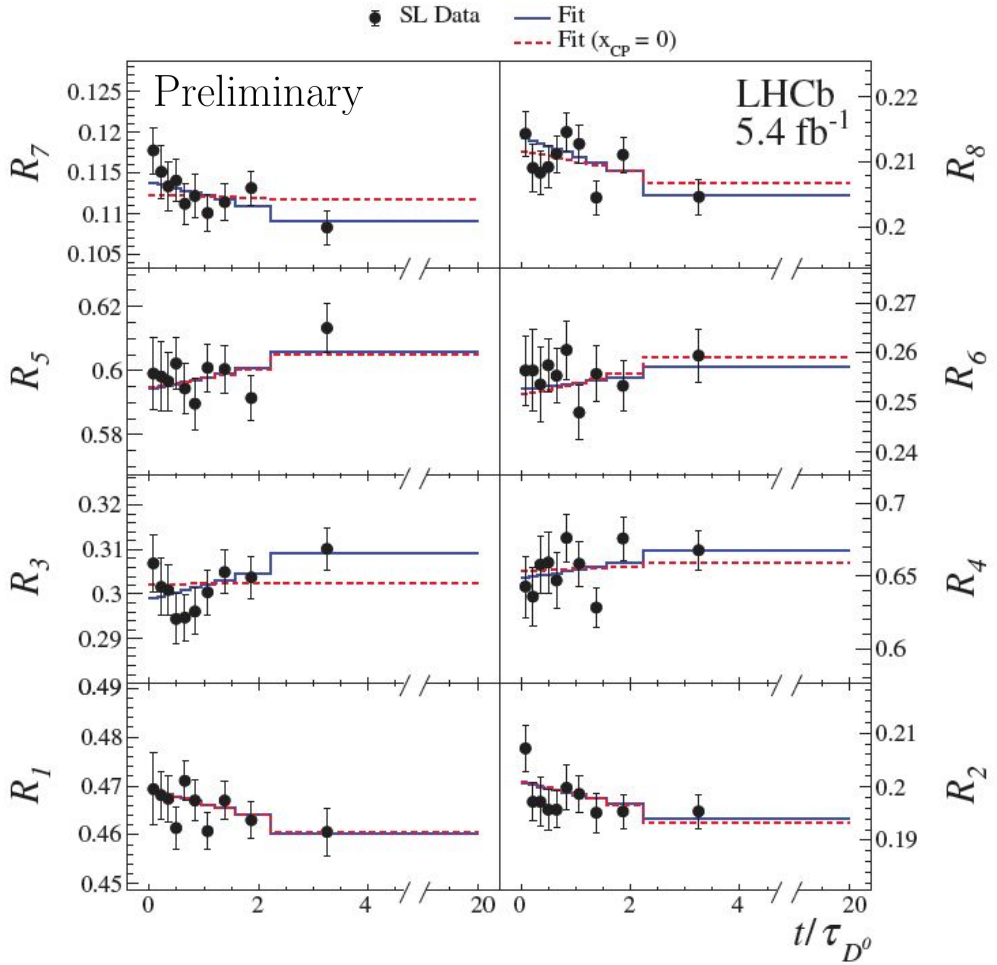
$$\Delta x = -\mathrm{Im}(\Delta z) = \frac{1}{2}\left[x \cos\phi \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) + y \sin\phi \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

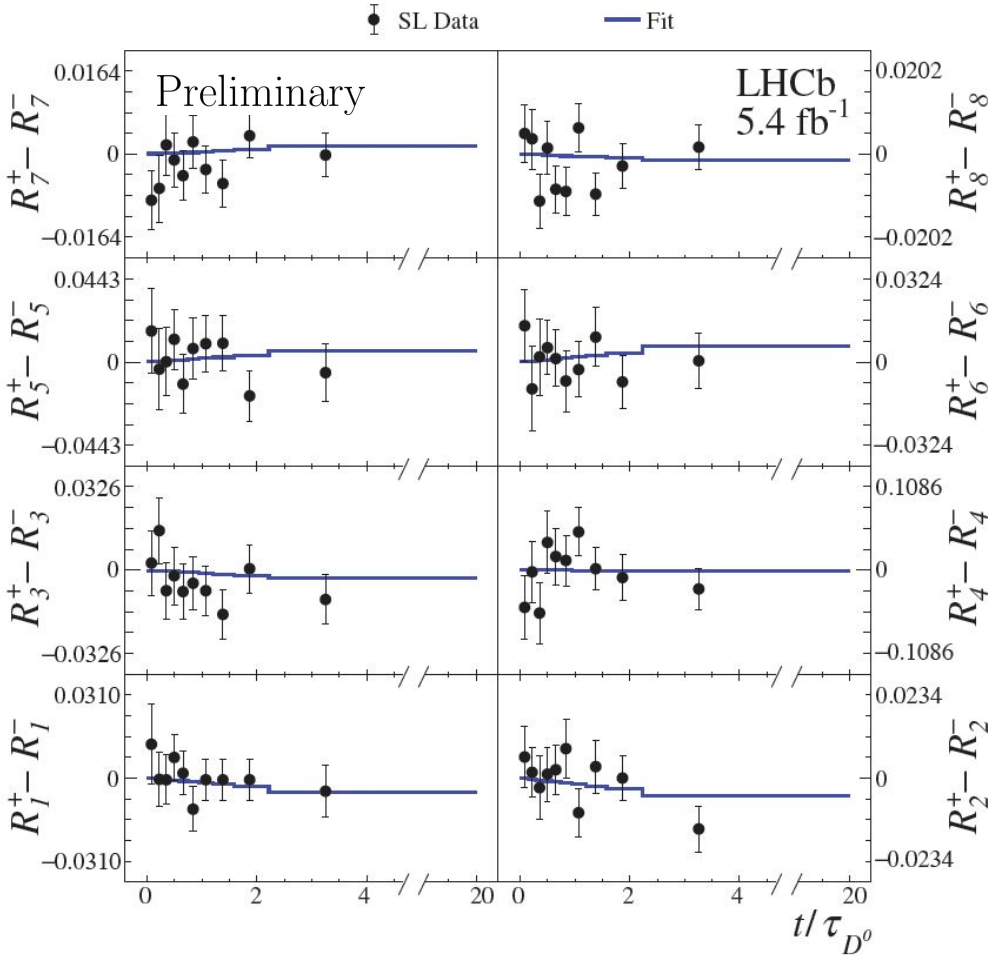
$$\Delta y = -\mathrm{Re}(\Delta z) = \frac{1}{2}\left[y \cos\phi \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - x \sin\phi \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

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

LHCb-PAPER-2022-020*

*in preparation





$$x_{CP} = [\ +4.29 \pm 1.48 \pm 0.26] \times 10^{-3}$$
$$y_{CP} = [+12.61 \pm 3.12 \pm 0.83] \times 10^{-3}$$

$$\Delta x = [\ -0.77 \pm 0.93 \pm 0.28] \times 10^{-3}$$
$$\Delta y = [\ +3.01 \pm 1.92 \pm 0.26] \times 10^{-3}$$

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

LHCb-PAPER-2022-020*

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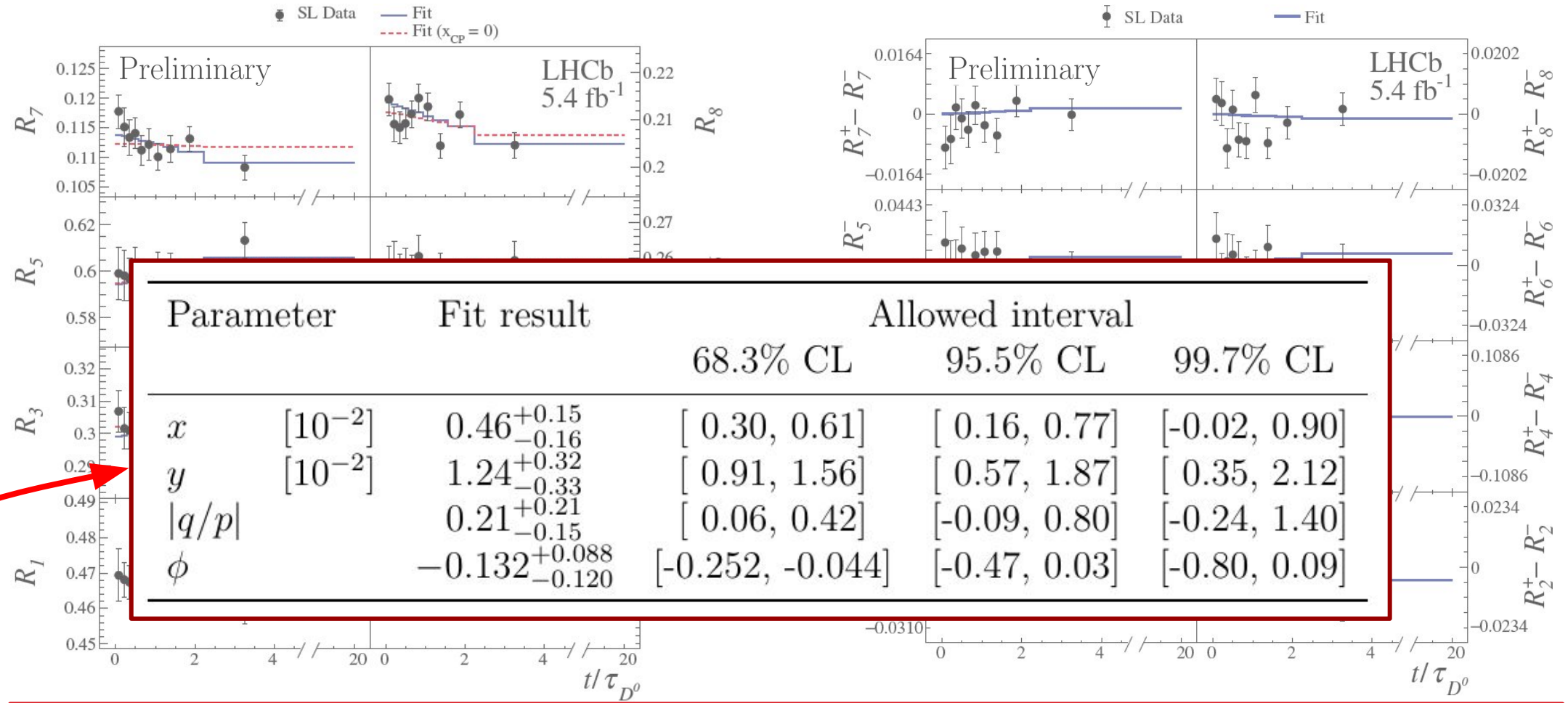

Parameter		Fit result	Allowed interval 68.3% CL	95.5% CL	99.7% CL
x	$[10^{-2}]$	$0.46^{+0.15}_{-0.16}$	[0.30, 0.61]	[0.16, 0.77]	[-0.02, 0.90]
y	$[10^{-2}]$	$1.24^{+0.32}_{-0.33}$	[0.91, 1.56]	[0.57, 1.87]	[0.35, 2.12]
$\lvert q/p\rvert$		$0.21^{+0.21}_{-0.15}$	[0.06, 0.42]	[-0.09, 0.80]	[-0.24, 1.40]
ϕ		$-0.132^{+0.088}_{-0.120}$	[-0.252, -0.044]	[-0.47, 0.03]	[-0.80, 0.09]

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

LHCb-PAPER-2022-020*

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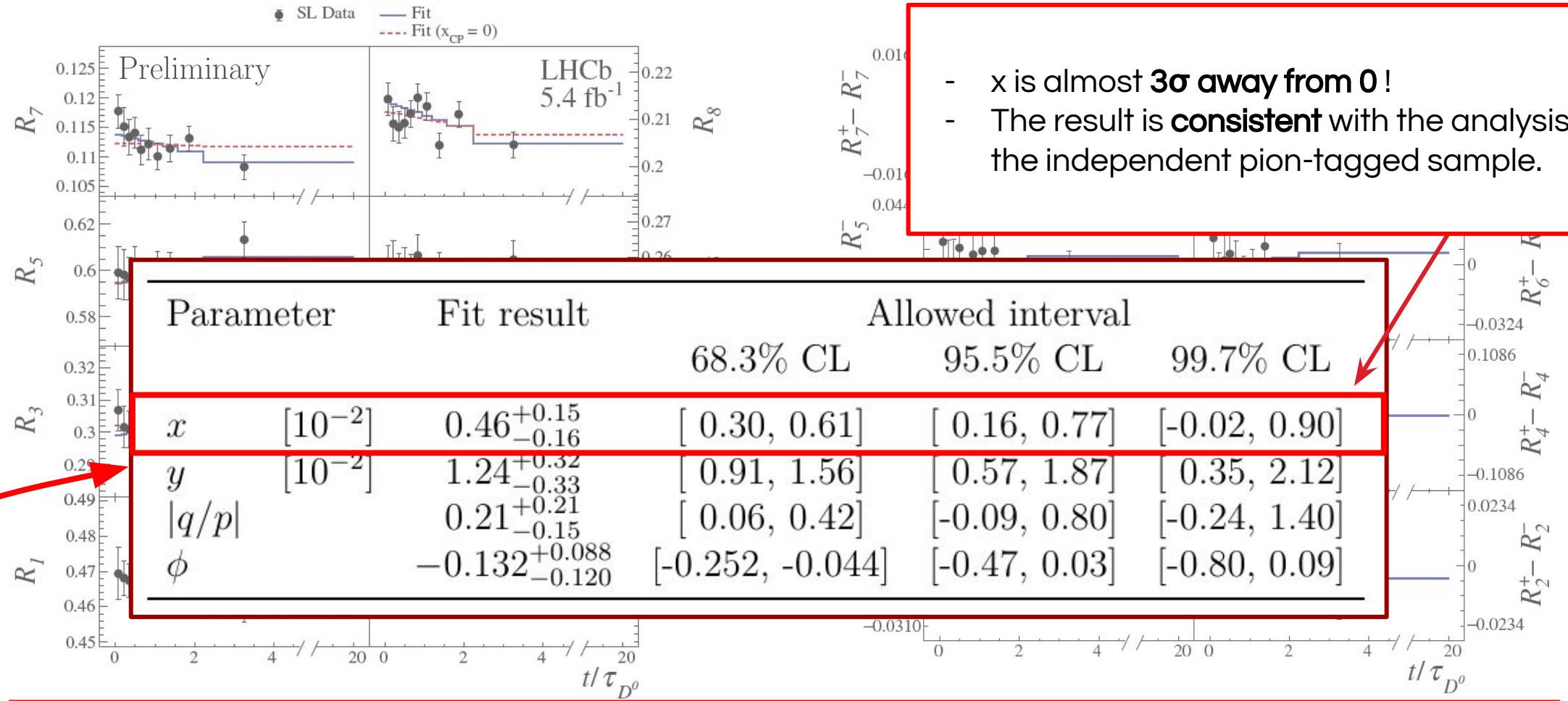

- x is almost **3σ away from 0** !
- The result is **consistent** with the analysis on the independent pion-tagged sample.

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

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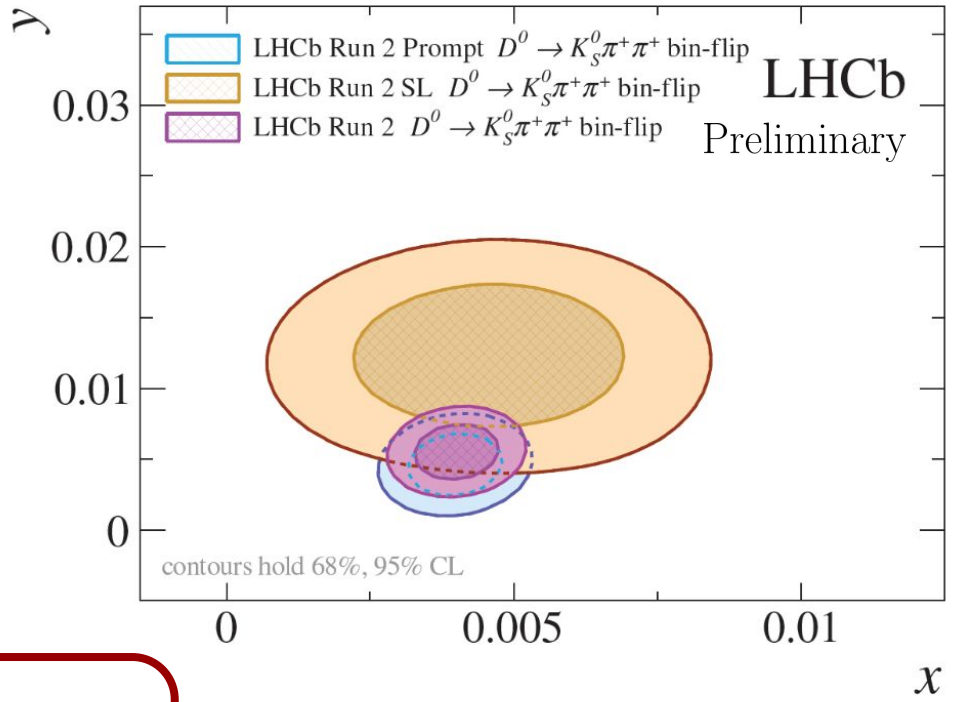
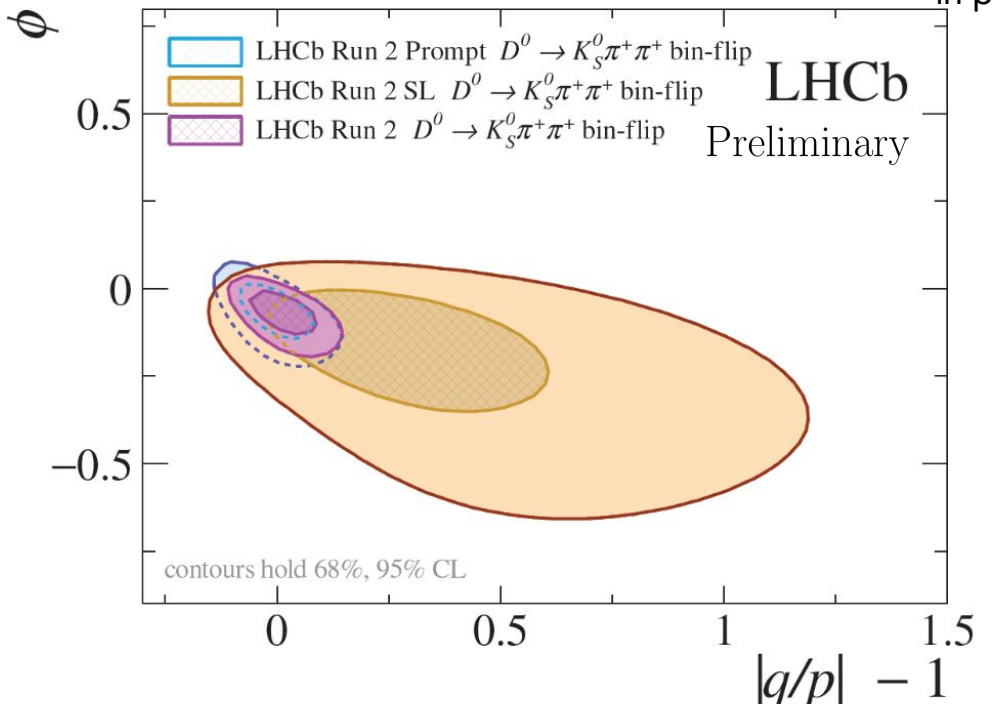




x is different from 0 with significance of 8σ.

$$x = (0.40 \pm 0.05) \times 10^{-2},$$
$$y = (0.55 \pm 0.13) \times 10^{-2},$$

$$|q/p| = 1.012^{+0.050}_{-0.048},$$
$$\phi = -0.061^{+0.037}_{-0.044}\ \text{rad}.$$

This result represents an ***independent measurement and complements*** the knowledge of the charm-mixing parameters.

Measurement of $y_{CP} - y_{CP}^{K\pi}$

PRD 105, 092013 (2022)

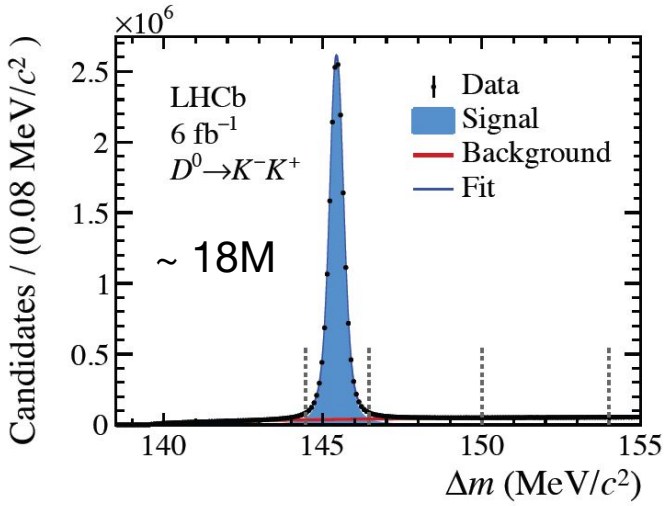
- The parameter is measured from decay-time ratios R^f

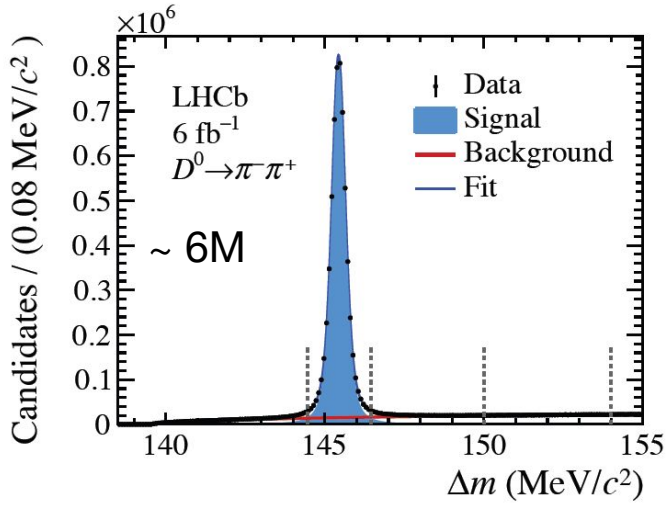
$$R^f(t) = \frac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} \propto e^{-(y_{CP}^f - y_{CP}^{K\pi})\, t/\tau_{D^0}} \frac{\varepsilon(f,t)}{\varepsilon(K^-\pi^+, t)}$$

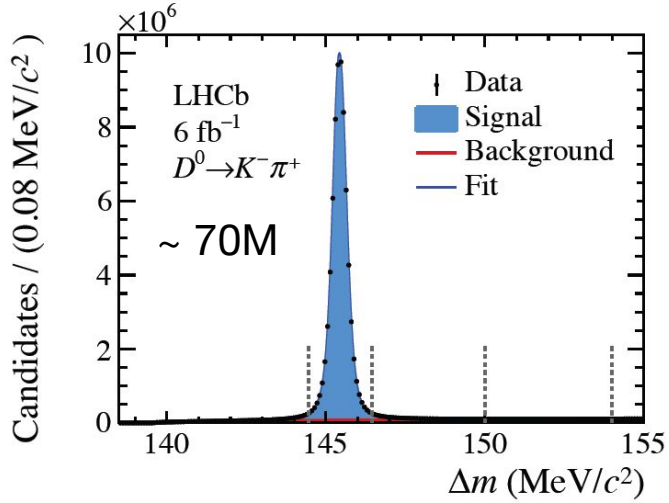
$$\approx -0.4 \times 10^{-3}$$

$$f = KK, \pi\pi$$

- Analysis on Run2 dataset π-tagged sample



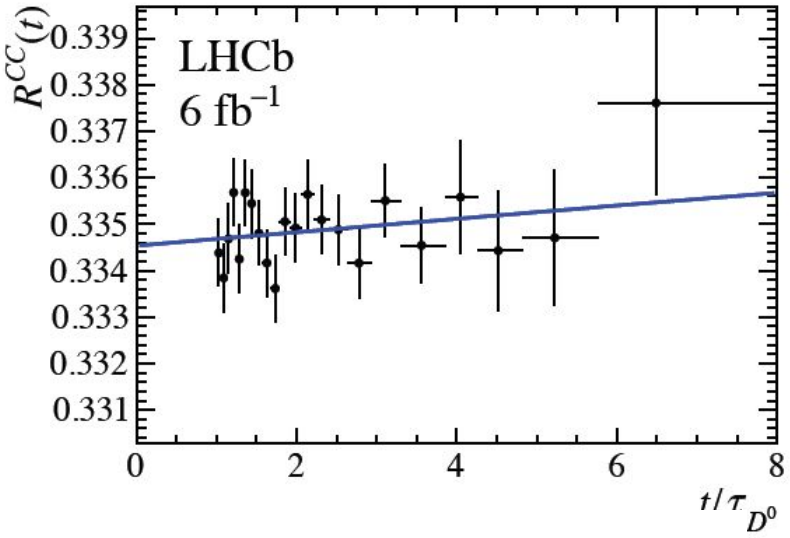


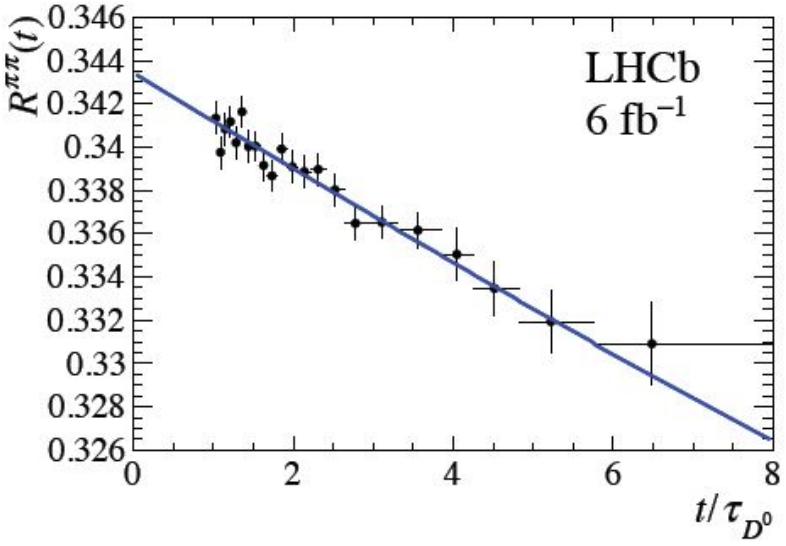


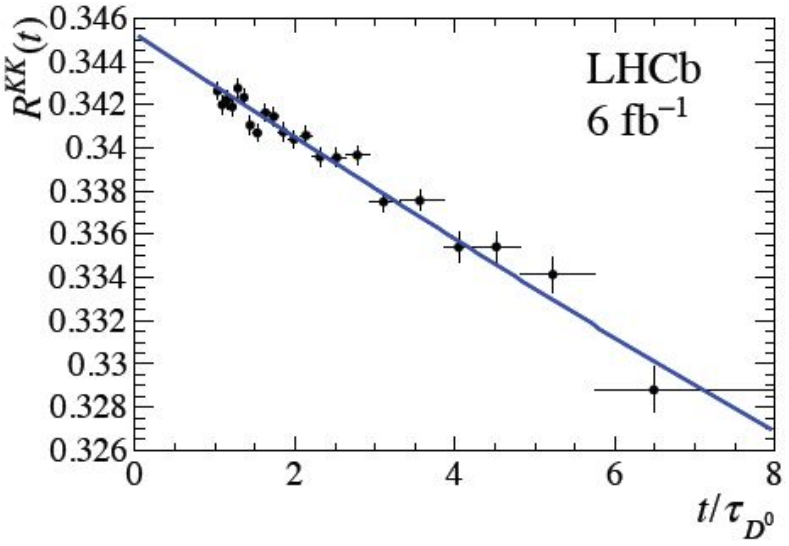
Measurement of $y_{CP} - y_{CP}^{K\pi}$

PRD 105, 092013 (2022)

- Validate the analysis procedure with $R^{CC}(t) = \frac{N(D^0 \to \pi^-\pi^+, t)}{N(D^0 \to K^-K^+, t)} \propto e^{y_{CP}^{CC}\, t/\tau_{D^0}} \frac{\varepsilon(\pi^-\pi^+, t)}{\varepsilon(K^-K^+, t)}$







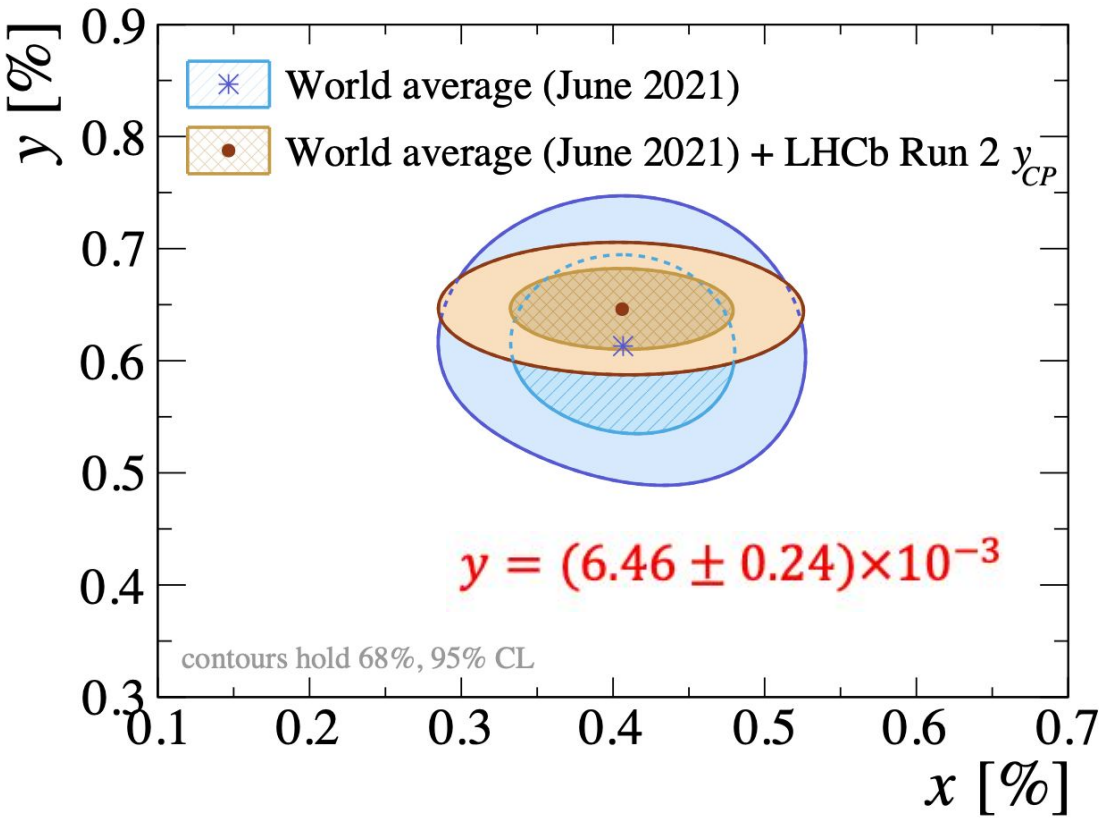
$y_{CP}^{CC} = (-0.44 \pm 0.53) \times 10^{-3}$ $y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3}$ $y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3}$

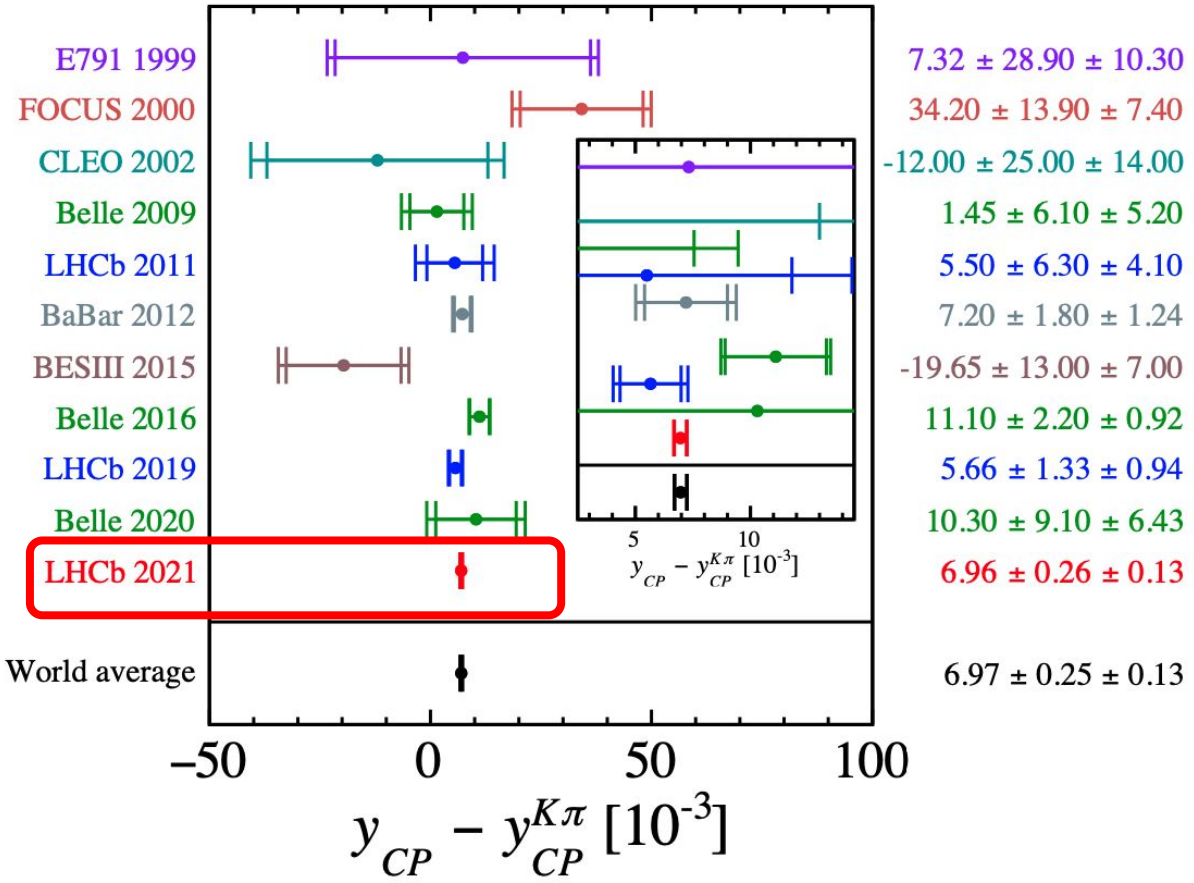
Compatible with zero as expected

$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$$

Measurement of $y_{CP} - y_{CP}^{K\pi}$

PRD 105, 092013 (2022)





This measurement is ***four times*** more precise than the previous world average value.

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

PRD 104 072010 (2021)

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

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

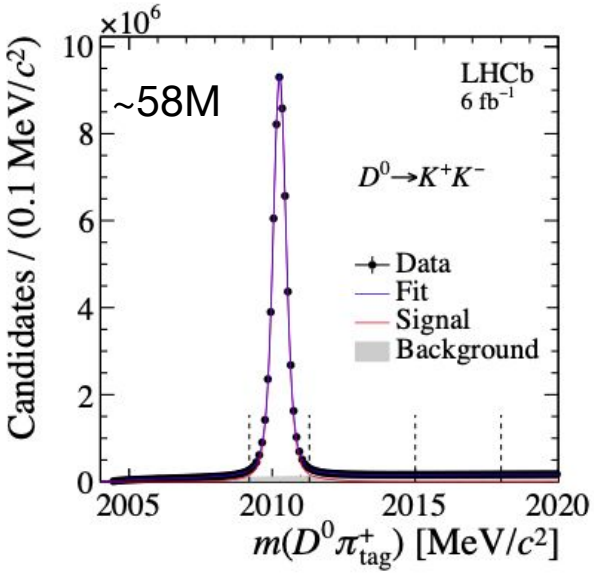
Final state dependent CPV

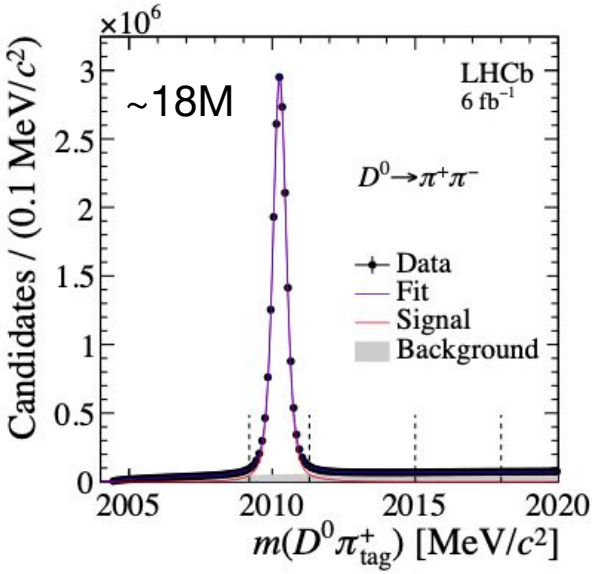
$$\Delta Y_f = -A_{\Gamma,f}$$

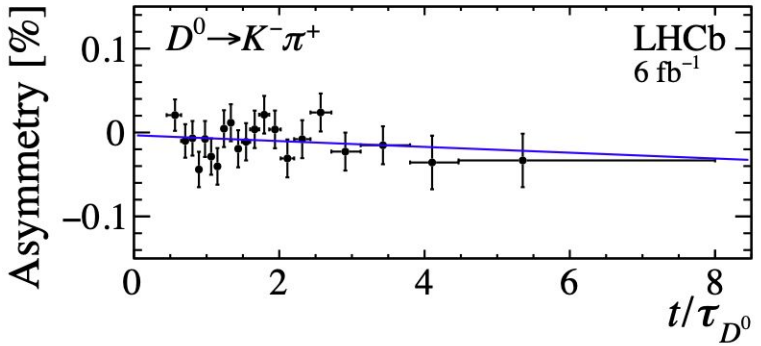
$$\approx x\phi - y\left(\left|\frac{q}{p}\right| - 1\right)$$

~ 10^{-5}

- Analysis on Run2 dataset π-tagged sample





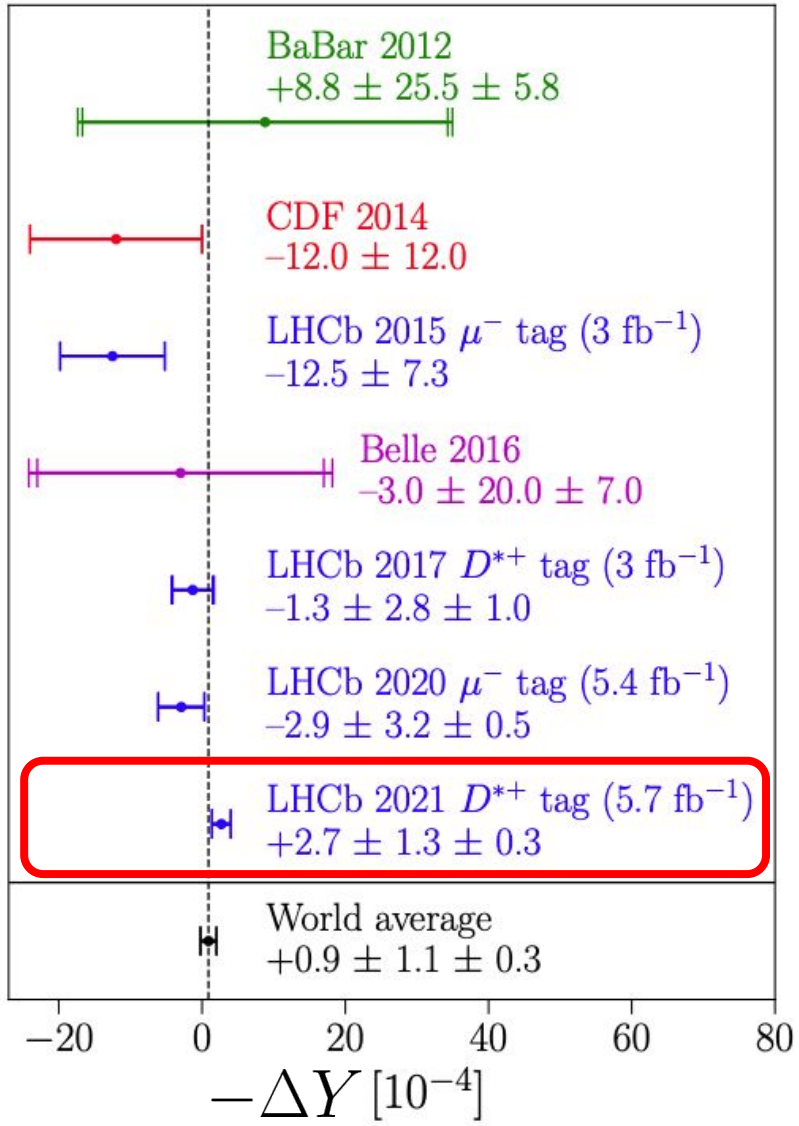


$$\Delta Y_{K^-\pi^+} = (-0.4 \pm 0.5 \pm 0.2) \times 10^{-4}$$

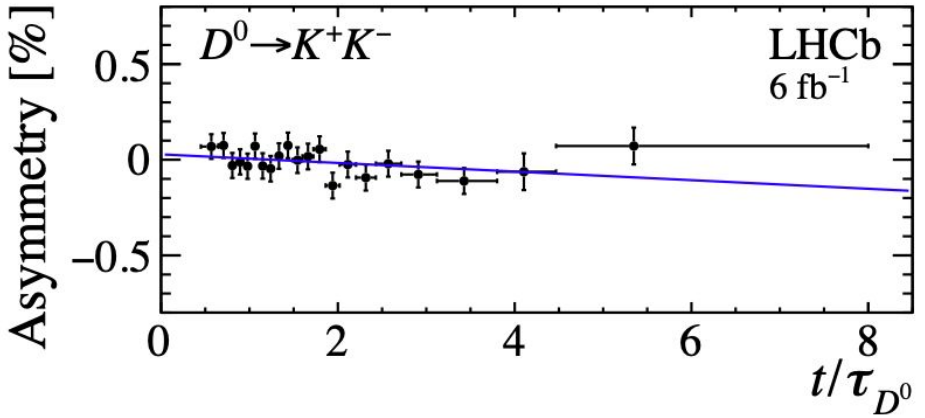
Control sample
No significant CPV

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

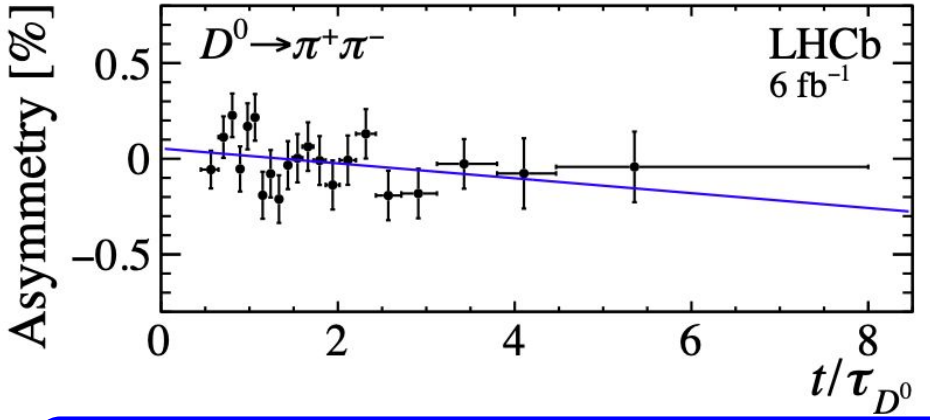
PRD 104 072010 (2021)



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



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



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

Conclusions

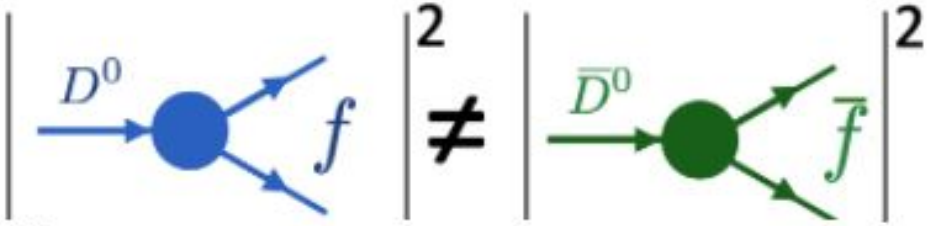
- LHCb has produced the largest dataset of charm hadrons.
  - This leads to new interesting results and provides often world-best measurements.
  - More results are coming soon!
- The measurements are limited by statistics
  - This is expected to be improved in Run 3 which is starting this year with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

Thank you!
Any questions?

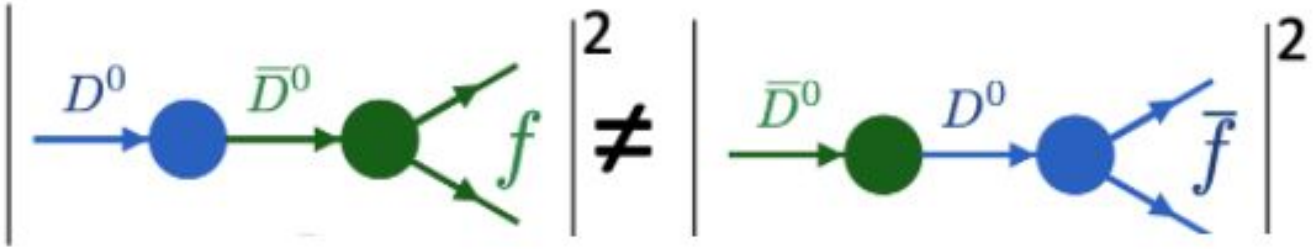
BACKUP

Mixing and CPV

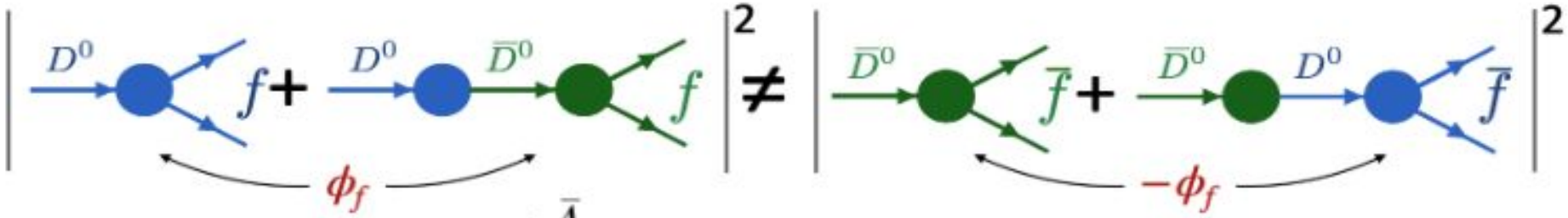
Direct CPV



CPV in mixing [Indirect CPV]

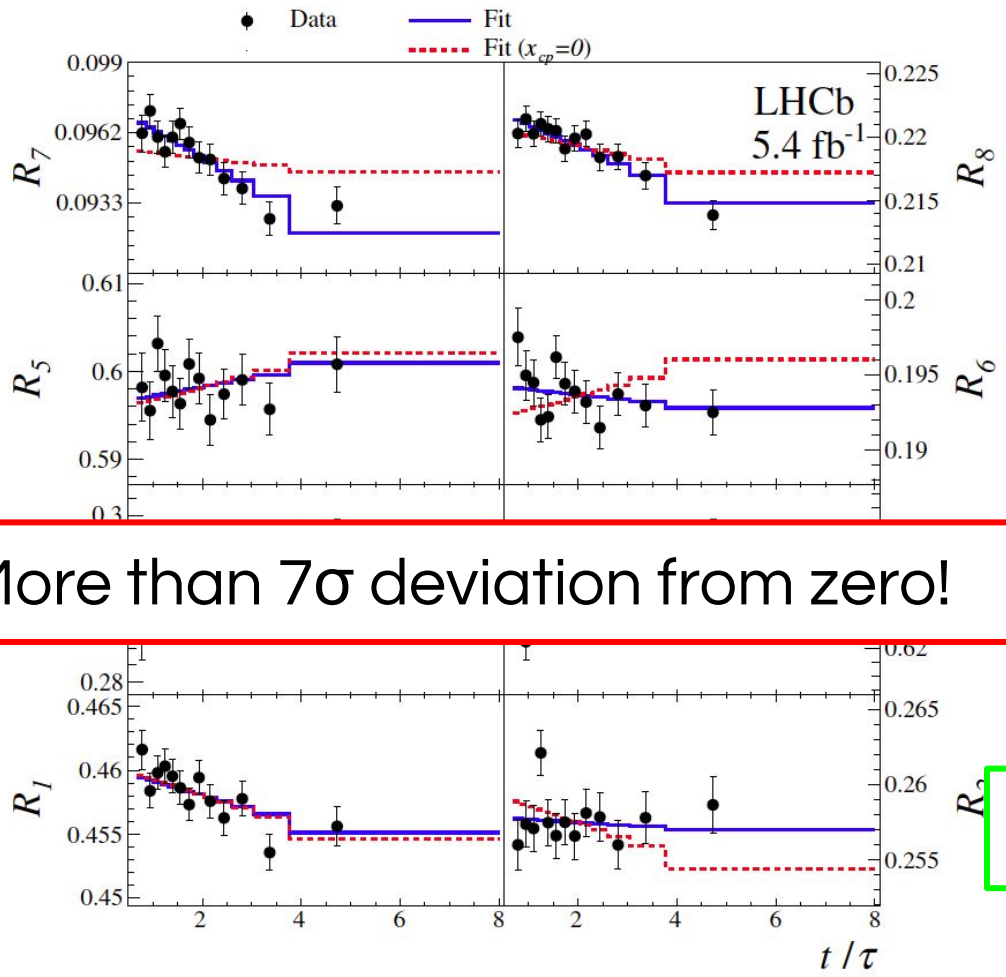


CPV in decay-mixing interference



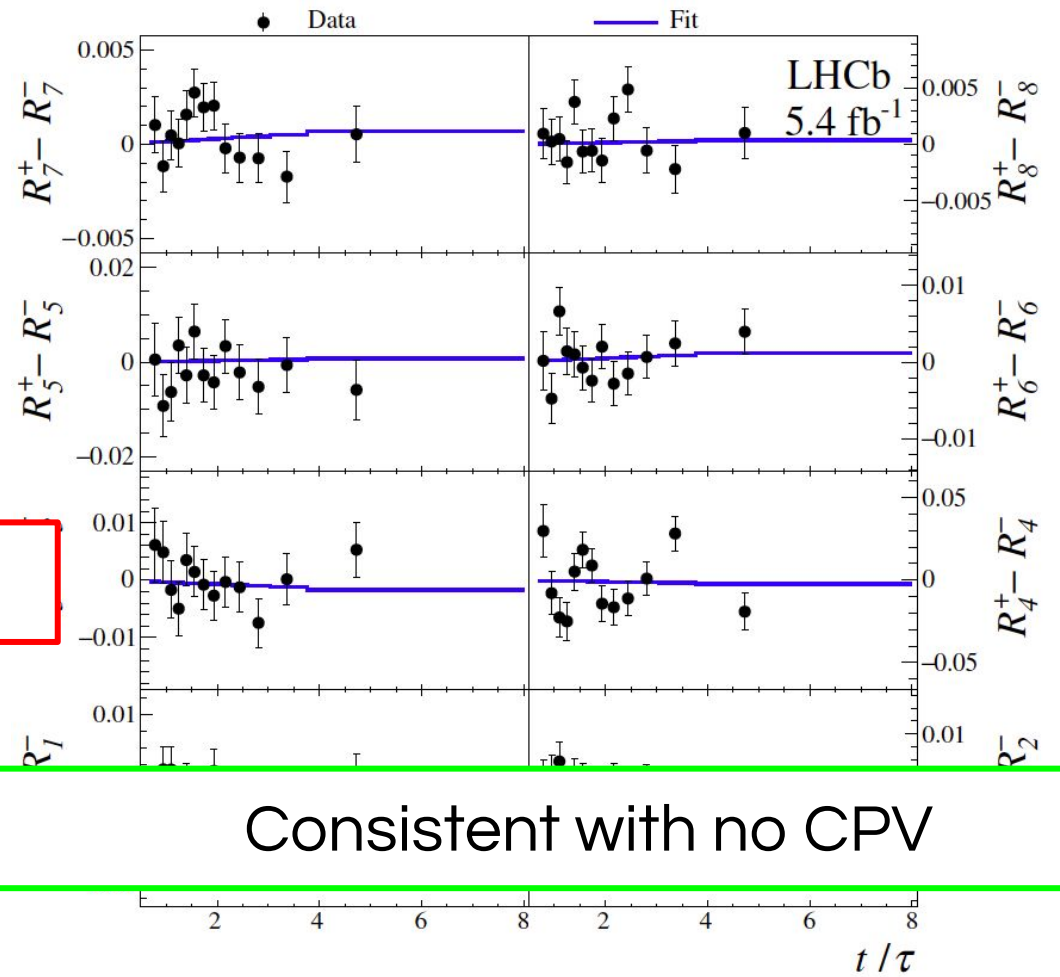
$$\phi_f \equiv \arg\left(\frac{q\bar{A}_f}{pA_f}\right) \qquad \phi_f \neq 0 \rightarrow CPV$$

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



More than 7σ deviation from zero!

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



Consistent with no CPV

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

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

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

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

First observation of a difference between D^0 mass eigenstates with significance of more than 7σ.

However, no significant of CPV is observed.

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

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

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

LHCb-PAPER-2022-020

Resolution, efficiency, and decorrelation procedure

- Efficiency variation within the bins and reconstruction resolution may induce bias.
- Validate analysis procedure.

Source	x_{CP}	y_{CP}	Δx	Δy
Reconstruction and selection	0.06	0.79	0.28	0.24
Detection asymmetry	0.06	0.03	0.01	0.09
Mass-fit model	0.03	0.09	0.01	0.01
Unrelated $D^0\mu$ combinations	0.24	0.22	0.01	0.05
Total systematic	0.26	0.83	0.28	0.26
Strong phase inputs	0.32	0.68	0.16	0.21
Statistical (w/o phase inputs)	1.45	3.04	0.92	1.91
Statistical	1.48	3.12	0.93	1.92

$\pi^+\pi^-$ detection asymmetry

- Reconstruction of pion tracks may induce an artificial asymmetry between D^0 flavours.
- Estimate the detection asymmetry from two Cabibbo-favoured D^+_s decays.

Mass-fit model

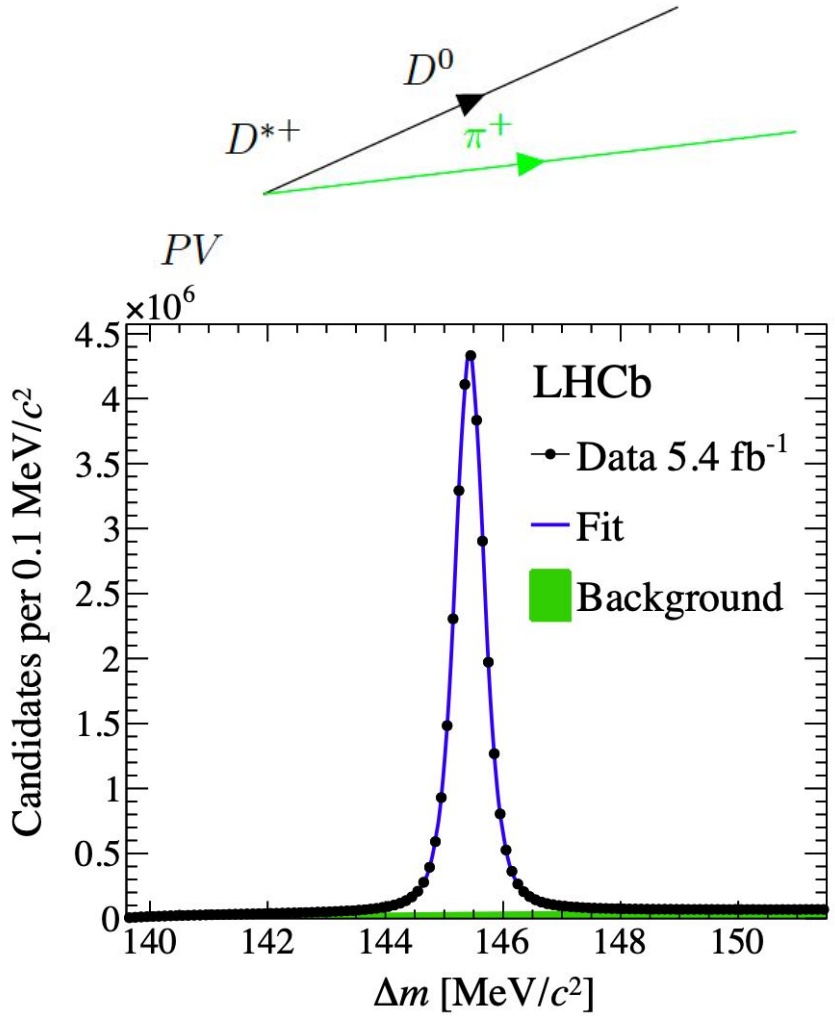
- Yields are extracted with specific choices of PDF.
- Use alternative PDFs to estimate systematics.

Unrelated $D\mu$ combination

- D^0 flavour may be wrongly tagged with random muons.
- Estimate the mistag probability on $D^0 \to K^-\pi^+$ sample.
- **Provide more precise and better systematics on *x*** than the analysis on Run 1 data. PRL 122 (2019) 231802

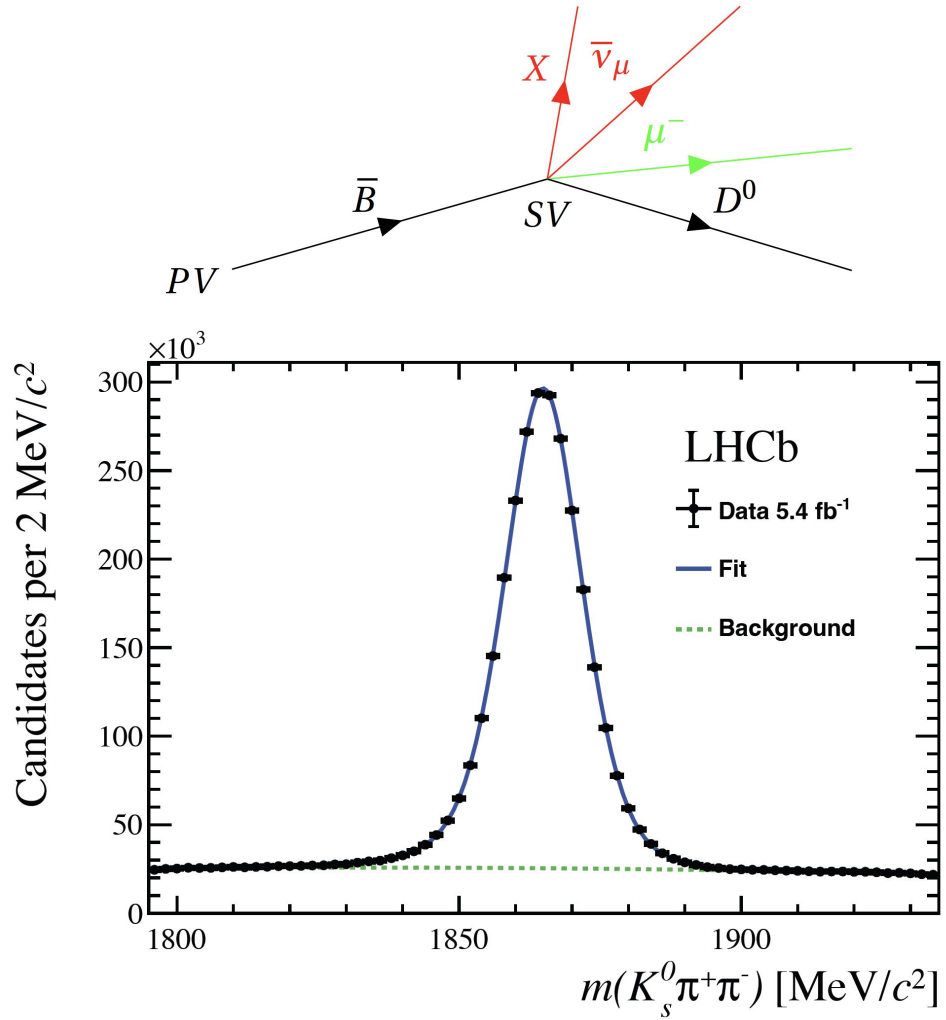
$D^0 \to K^0_S \pi^+ \pi^-$ Binflip Results

PromptTag [PRL 127, 111801 (2021)]



~ 33 M signals

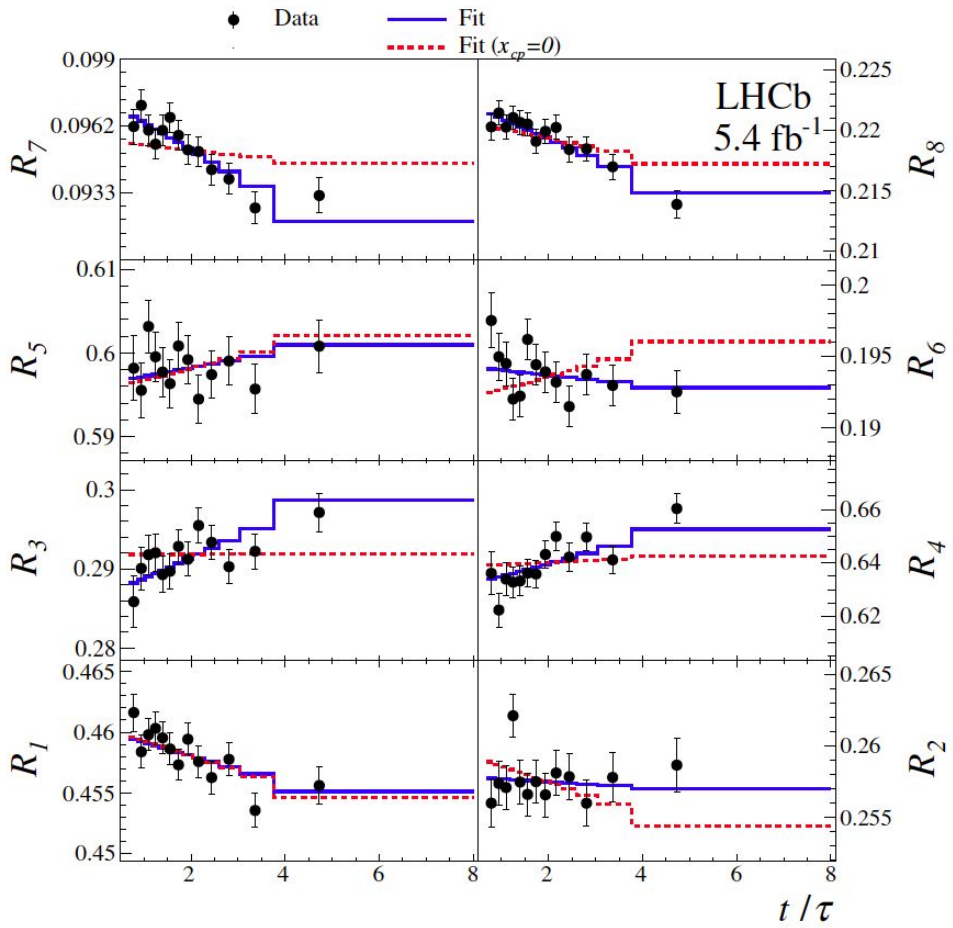
SemileptonicTag [LHCb-PAPER-2022-020]



~ 3.6 M signals

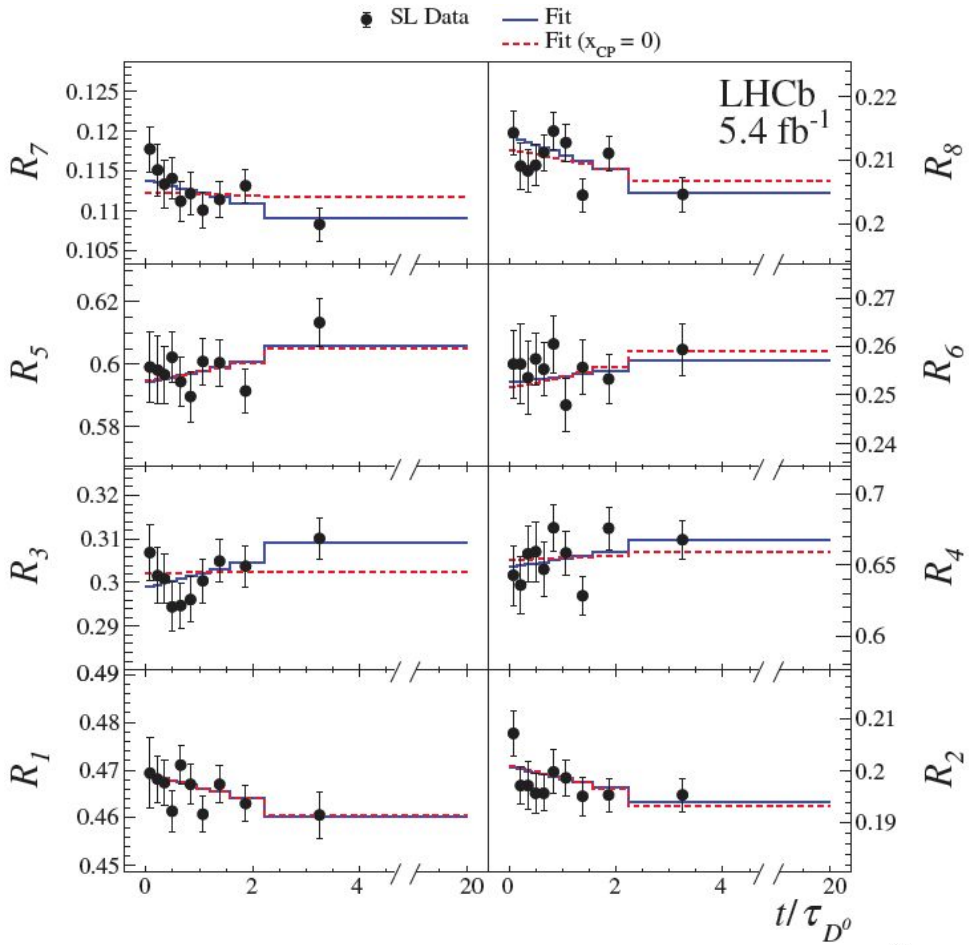
$D^0 \to K^0_S \pi^+ \pi^-$ Binflip Results

PromptTag [PRL 127, 111801 (2021)]



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

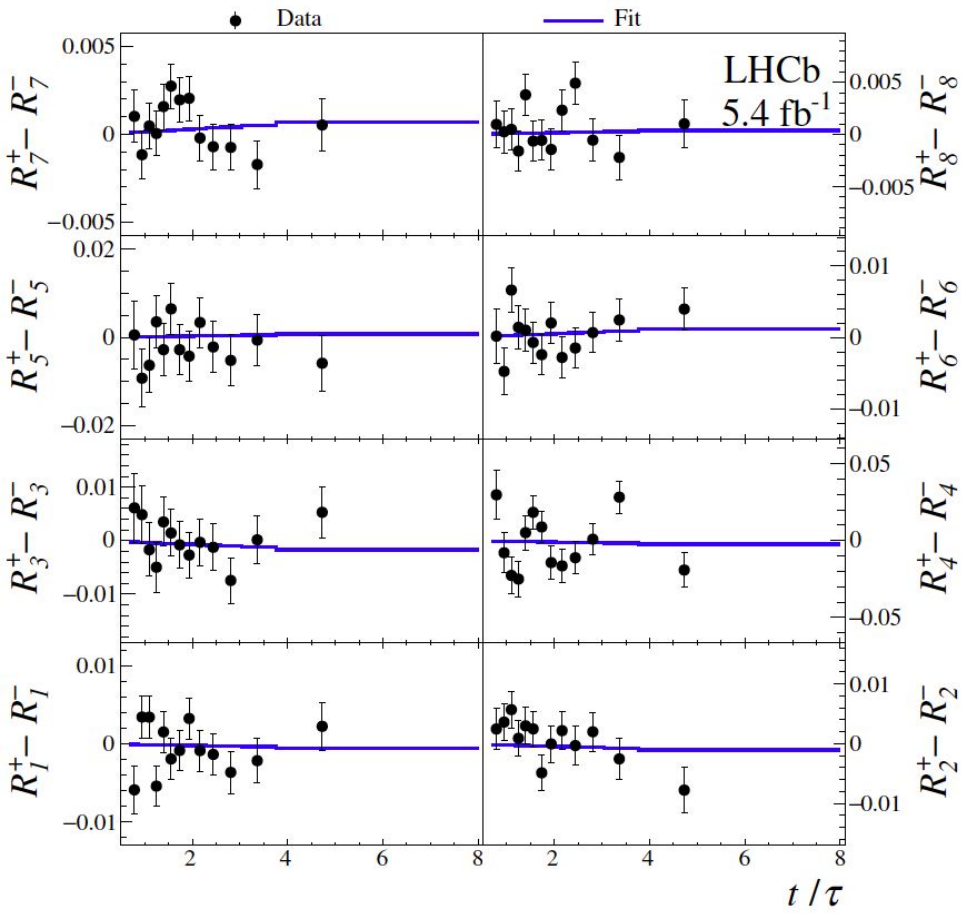
SemileptonicTag [LHCb-PAPER-2022-020]



$$x_{CP} = [\ +4.29 \pm 1.48 \pm 0.26] \times 10^{-3}$$
$$y_{CP} = [+12.61 \pm 3.12 \pm 0.83] \times 10^{-3}$$

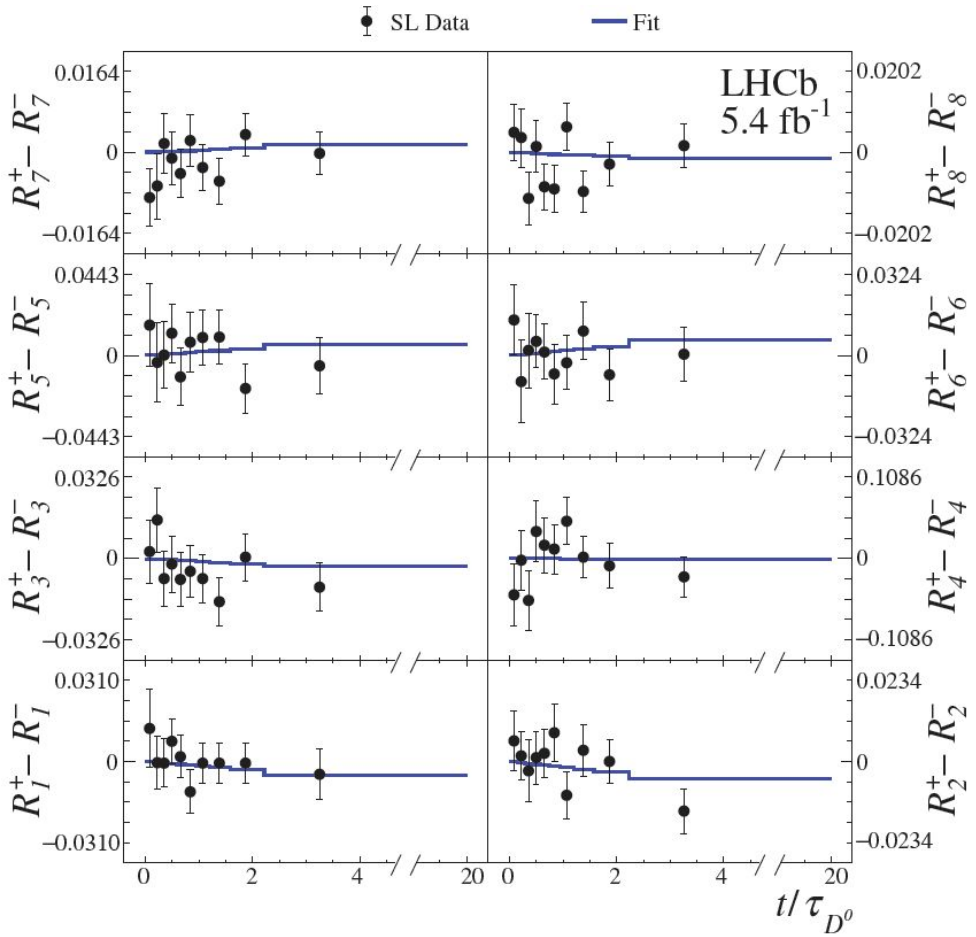
$D^0 \to K^0_S\pi^+\pi^-$ Binflip Results

PromptTag [PRL 127, 111801 (2021)]



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

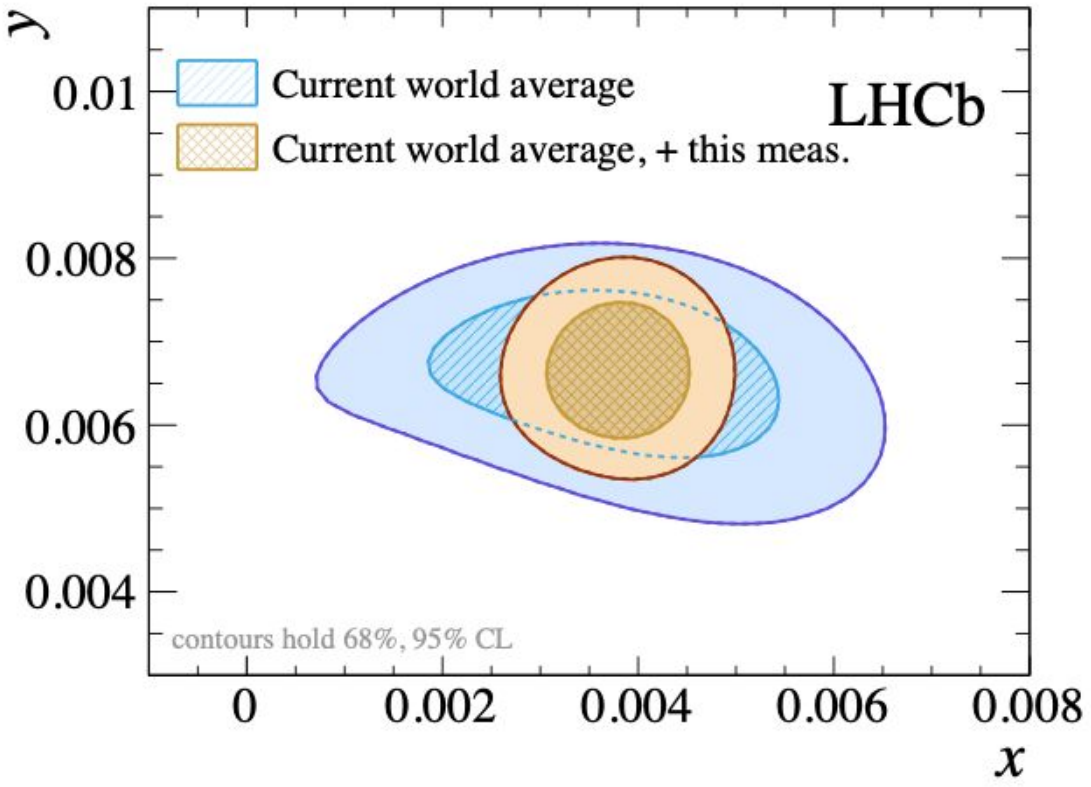
SemileptonicTag [LHCb-PAPER-2022-020]

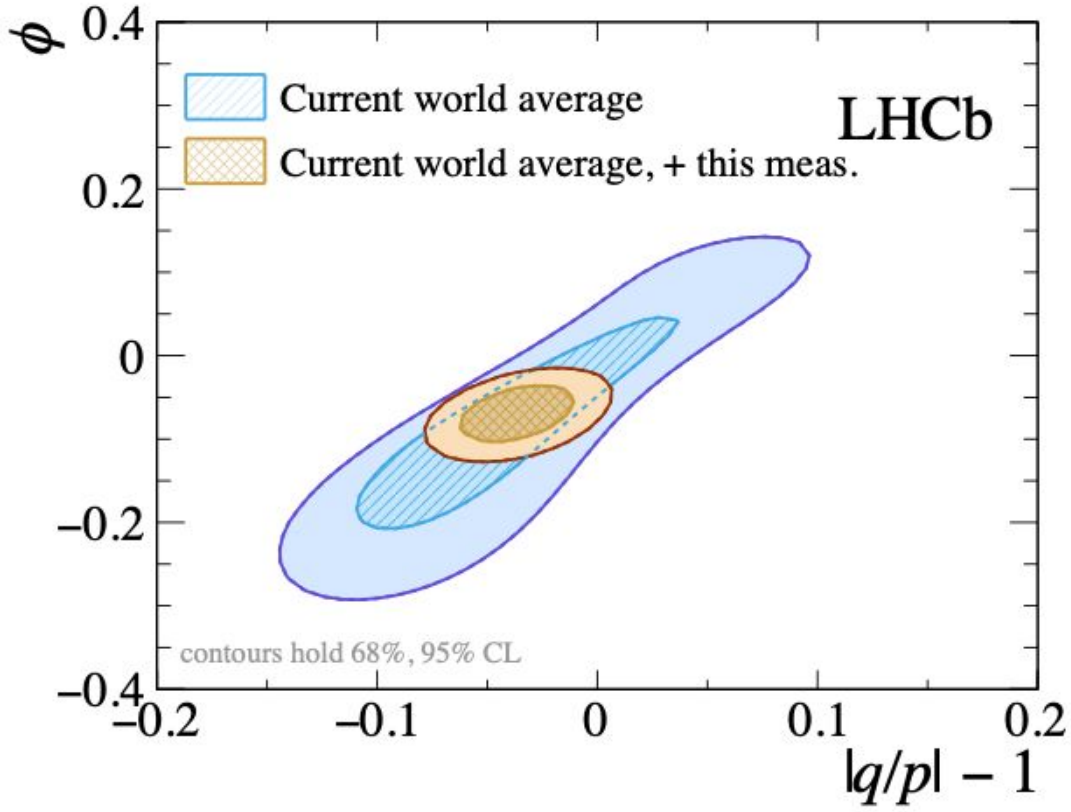


$$\Delta x = [\ -0.77 \pm 0.93 \pm 0.28] \times 10^{-3}$$
$$\Delta y = [\ +3.01 \pm 1.92 \pm 0.26] \times 10^{-3}$$

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

arXiv:2106.03744





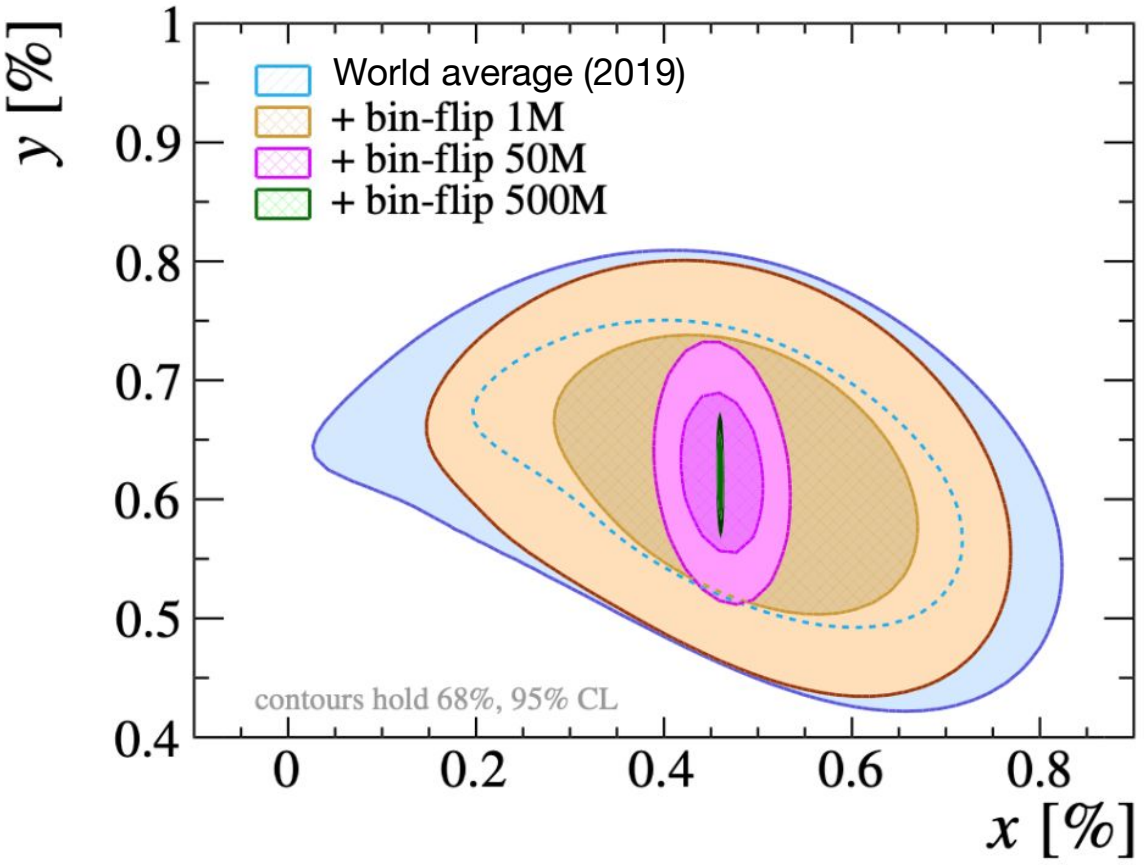
First observation of a difference between

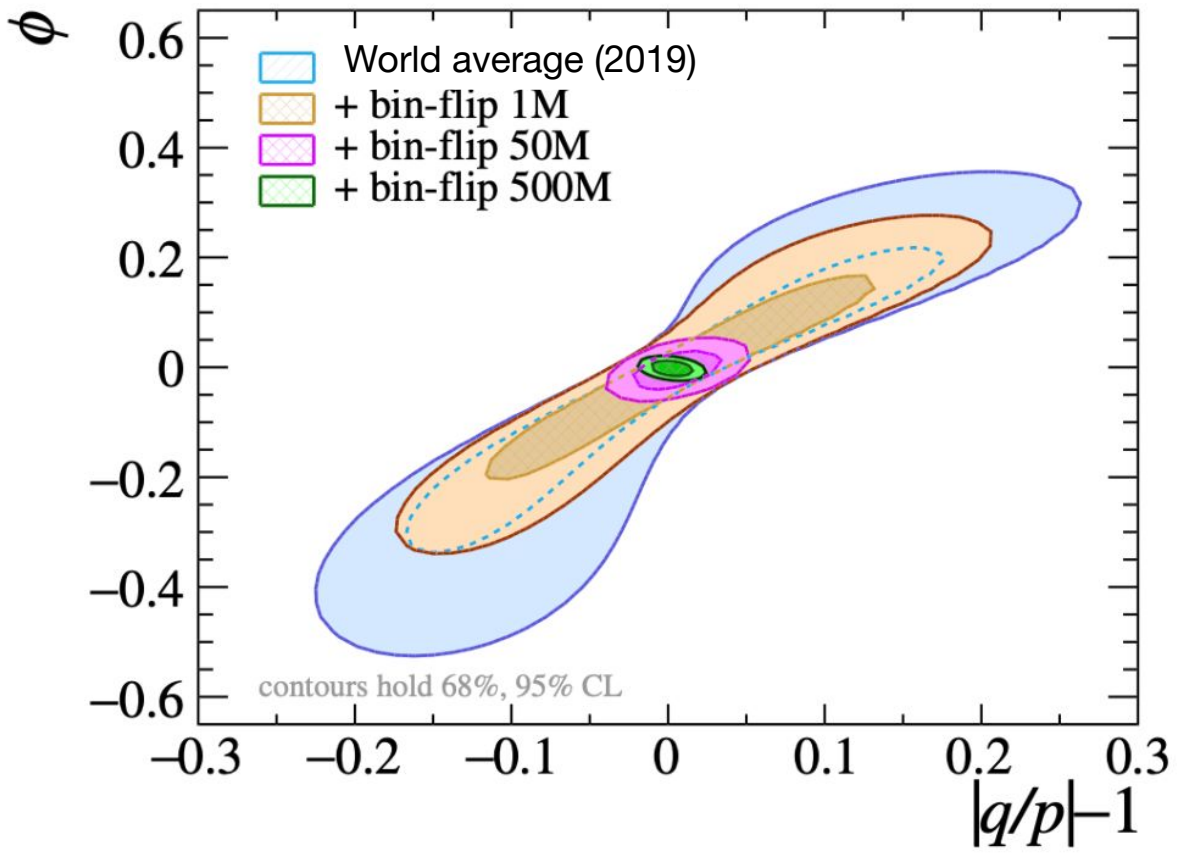
“ D^0 mass eigenstates (> 7σ significance) ”

However, no significant CPV is observed.

Binflip sensitivity

PRD 99, 012007 (2019)





Measurement of $y_{CP} - y_{CP}^{K\pi}$

PRD 105, 092013 (2022)

Table 1: Systematic uncertainties for the $y_{CP}^{\pi\pi} - y_{CP}^{K\pi}$ and $y_{CP}^{KK} - y_{CP}^{K\pi}$ measurements.

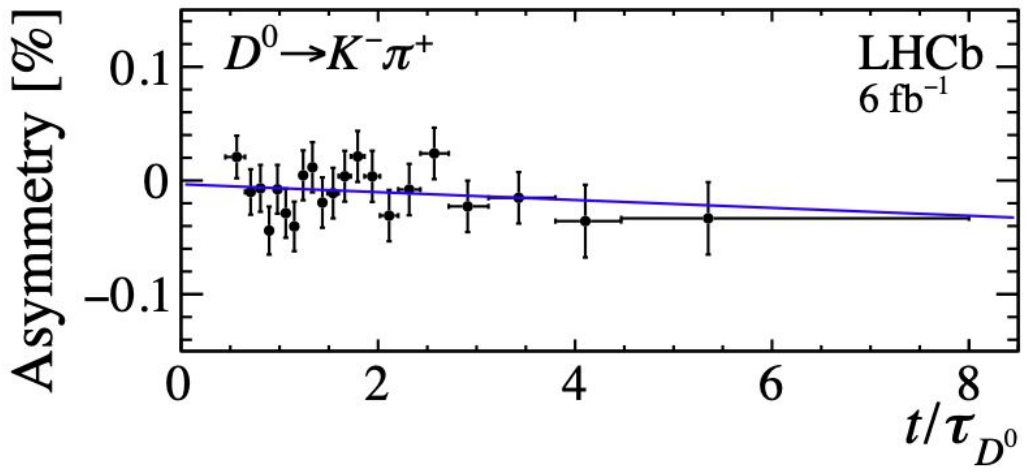
	$\sigma(y_{CP}^{\pi\pi} - y_{CP}^{K\pi})$ $[10^{-3}]$	$\sigma(y_{CP}^{KK} - y_{CP}^{K\pi})$ $[10^{-3}]$
Combinatorial background	0.12	0.07
Treatment of secondary decays	0.03	0.03
Kinematic weighting procedure	0.08	0.02
Input D^0 lifetime	0.03	0.03
Residual nuisance asymmetries	0.03	< 0.01
Peaking background	0.02	0.11
Fit bias	0.03	0.03
Total	0.16	0.14

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

PRD 104 072010 (2021)

- 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 $m(D^0\pi^+_{\rm tag})$ 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