Mixing and indirect CPV in charm decays at LHCb

Federico Betti on behalf
of the LHCb collaboration

LHCb

12th International Workshop on the CKM Unitarity Triangle

21 September 2023

THE UNIVERSITY of EDINBURGH

UK Research and Innovation

Outline

- Mixing formalism
- Charm at LHCb
- ΔY_f in $D^0 \to h^+h^-$
- $y_{CP}^{f} - y_{CP}^{K\pi}$
- $D^0 \to K_s^0\pi^+\pi^-$
- γ + charm combination
- Prospects and conclusions

$\mathcal{CP}$ violation in charm

$$A_{CP}(D \to f) = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \bar{f})}$$

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

- Direct $\mathcal{CP}$ violation when $|A_f|^2 \neq |\overline{A}_{\bar{f}}|^2$ (see talk by Jolanta)
- For oscillating neutral mesons, mass eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$
  - $\mathcal{CP}$ violation in mixing when $|q/p| \neq 1$
  - $\mathcal{CP}$ violation in decay-mixing interference when $\phi_f \equiv \arg[(q\overline{A}_f)/(pA_f)] \neq 0$

Phenomenological parametrisation

$$x \equiv \frac{2(m_1 - m_2)}{\Gamma_1 + \Gamma_2}, \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{\Gamma_1 + \Gamma_2}, \quad \left|\frac{q}{p}\right| - 1$$

Theoretical parametrisation

$$x_{12} \equiv \frac{2|M_{12}|}{\Gamma_1 + \Gamma_2}, \quad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma_1 + \Gamma_2}, \quad \phi_{12} \equiv \arg\left(\frac{M_{12}}{\Gamma_{12}}\right)$$

$$x^2 - y^2 = x_{12}^2 - y_{12}^2,$$
$$xy = x_{12}y_{12}\cos\phi_{12},$$
$$\left|\frac{q}{p}\right|^{\pm 2}(x^2 + y^2) = x_{12}^2 + y_{12}^2 \pm 2x_{12}y_{12}\sin\phi_{12}$$

PRL 103 (2009) 071602
PRD 80 (2009) 076008
PRD 103 (2021) 053008

Charm at LHCb

JHEP 05 (2017) 074

$$\sigma(pp \to D^0 X) = 2072 \pm 2 \pm 124\,\mu\text{b}$$
$$\sigma(pp \to D^+ X) = 834 \pm 2 \pm 78\,\mu\text{b}$$
$$\sigma(pp \to D_s^+ X) = 353 \pm 9 \pm 76\,\mu\text{b}$$
$$\sigma(pp \to D^{*+} X) = 784 \pm 4 \pm 87\,\mu\text{b}$$

- Large $c\bar{c}$ production cross section
  $\sigma(pp \to c\bar{c}X)_{\sqrt{s}=13\text{ TeV}} = (2369 \pm 3 \pm 152 \pm 118)\ \mu\text{b}$
- More than 1 billion $D^0 \to K^-\pi^+$ decays reconstructed with the full LHCb data sample
- Two ways to tag the D^0
  - Prompt tag: look at π charge in $D^{*\pm} \to D^0\pi^\pm \Rightarrow$ higher statistics
  - Semileptonic tag: look at μ charge in $\overline{B} \to D^0\mu^-\overline{\nu}_\mu X \Rightarrow$ access lower decay time
- Time-dependent analyses are less affected by experimental (detection, production) asymmetries than time-integrated measurements
- Selection induces correlations between kinematics and decay time, potentially dangerous for time-dependent analyses $\Rightarrow$ corrections or dedicated trigger lines are needed

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

PRD 104 (2021) 072010

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

$$\Delta Y_f \simeq -x_{12} \sin\phi_f^M + y_{12} a_f^d \simeq -x_{12} \sin\phi_{12}$$

Neglecting *CP* violation in the decay

$$\phi_f^M \equiv \arg\left(\frac{M_{12} A_f}{\bar{A}_f}\right) \simeq \phi_{12}$$

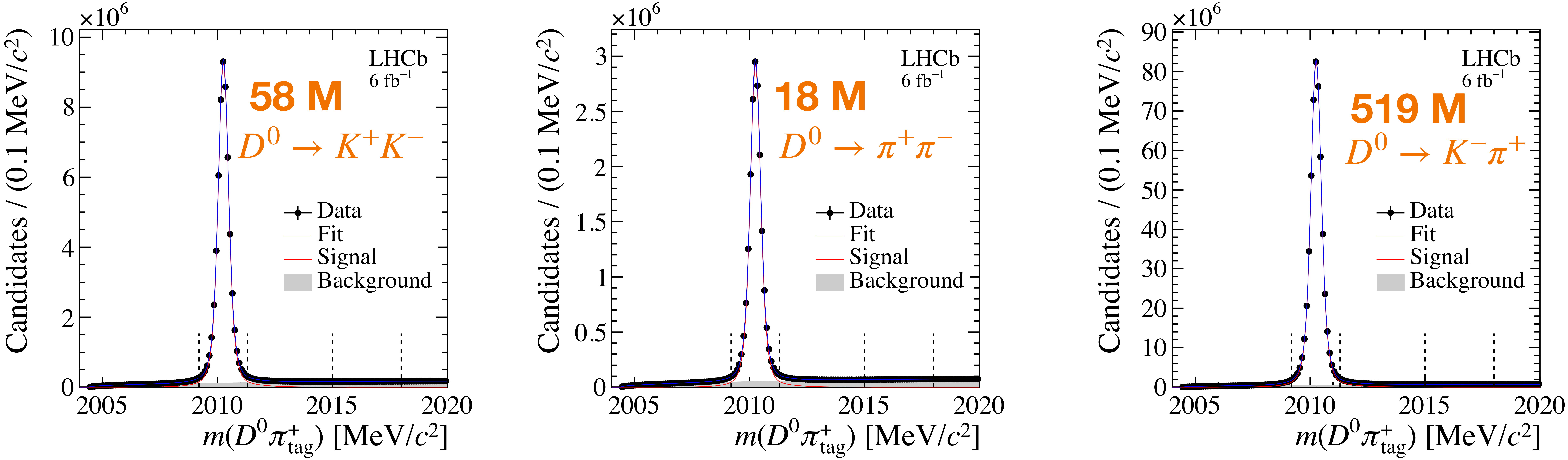
Superweak approximation

- $\Delta Y_{K^+K^-} = \Delta Y_{\pi^+\pi^-} = \Delta Y$ at current level of precision
- SM expectation $\sim 2 \times 10^{-5}$ PRD 103 (2021) 053008, PLB 810 (2020) 135802
- Strategy: measure asymmetry in bins of D^0 decay time and measure the linear slope
- Selection induces correlations between kinematics and decay time ➡ possible time-dependent nuisance asymmetries are removed by equalising D^0 and $\overline{D}^0$ kinematics
- $D^0 \to K^-\pi^+$ is used as a control sample ($\Delta Y_{K^-\pi^+} < 3 \times 10^{-5}$ from experimental results)

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

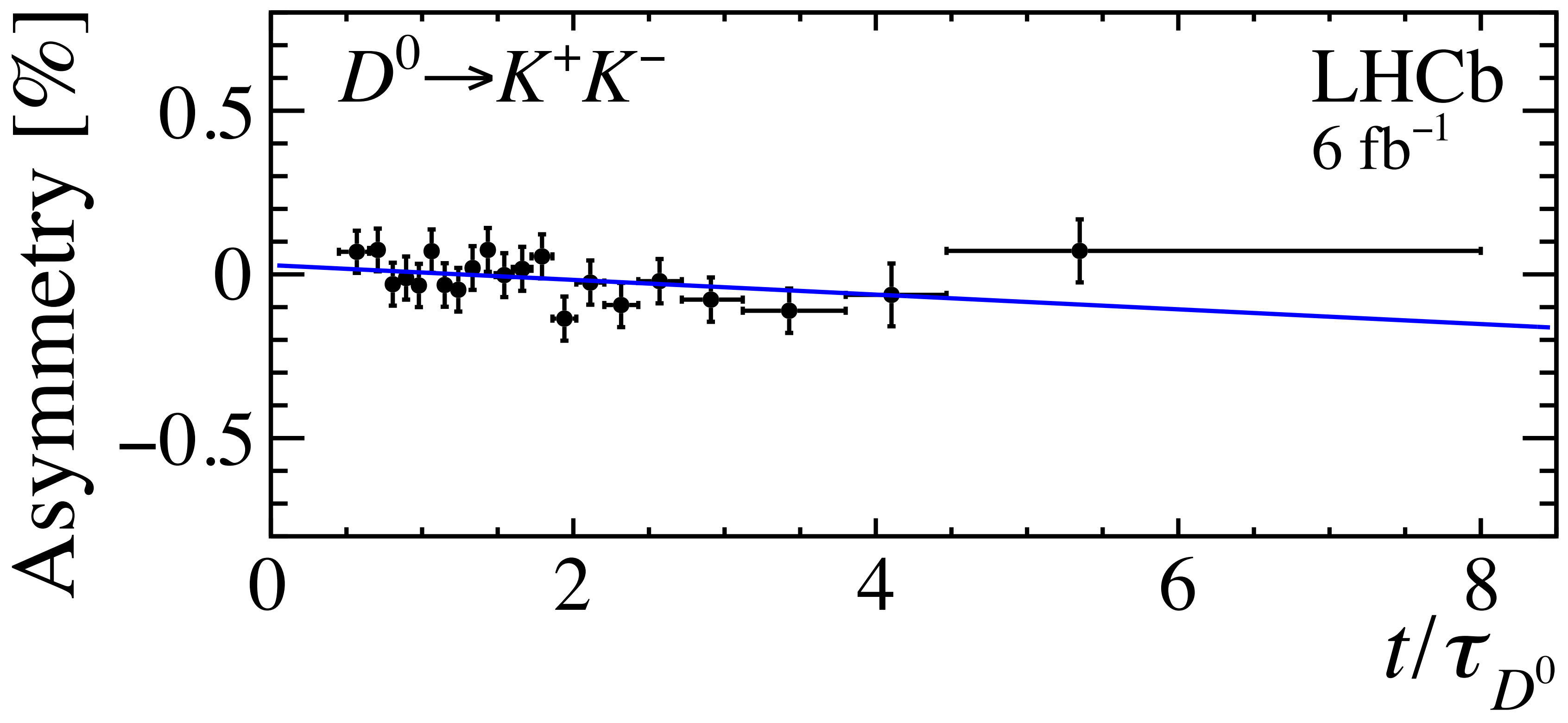
PRD 104 (2021) 072010

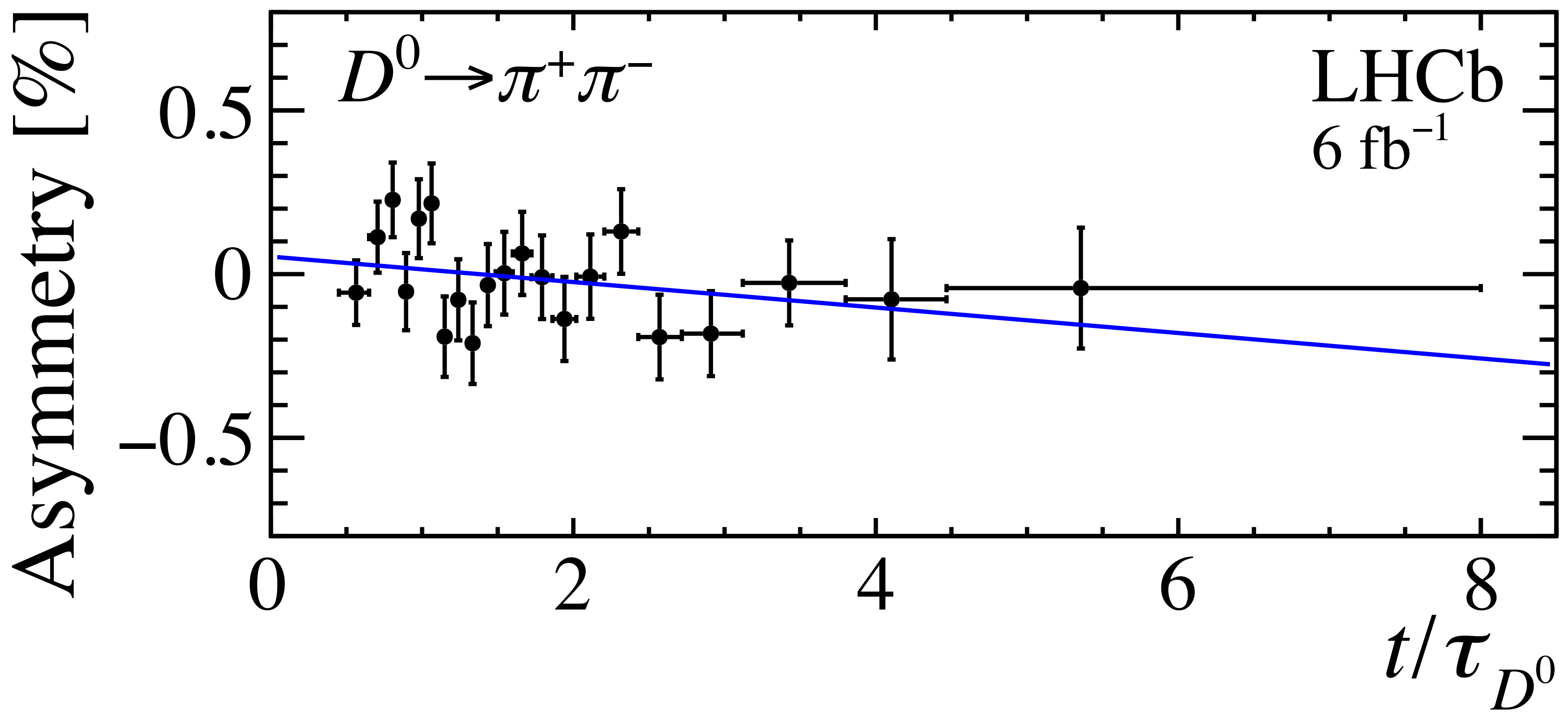
- Combinatorial background removed with sideband subtraction in $m(D^0\pi^+)$ in each decay time
- A correction is applied for contamination of secondary D^0 by measuring their size and asymmetry with a multidimensional fit on (IP, t)



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

PRD 104 (2021) 072010





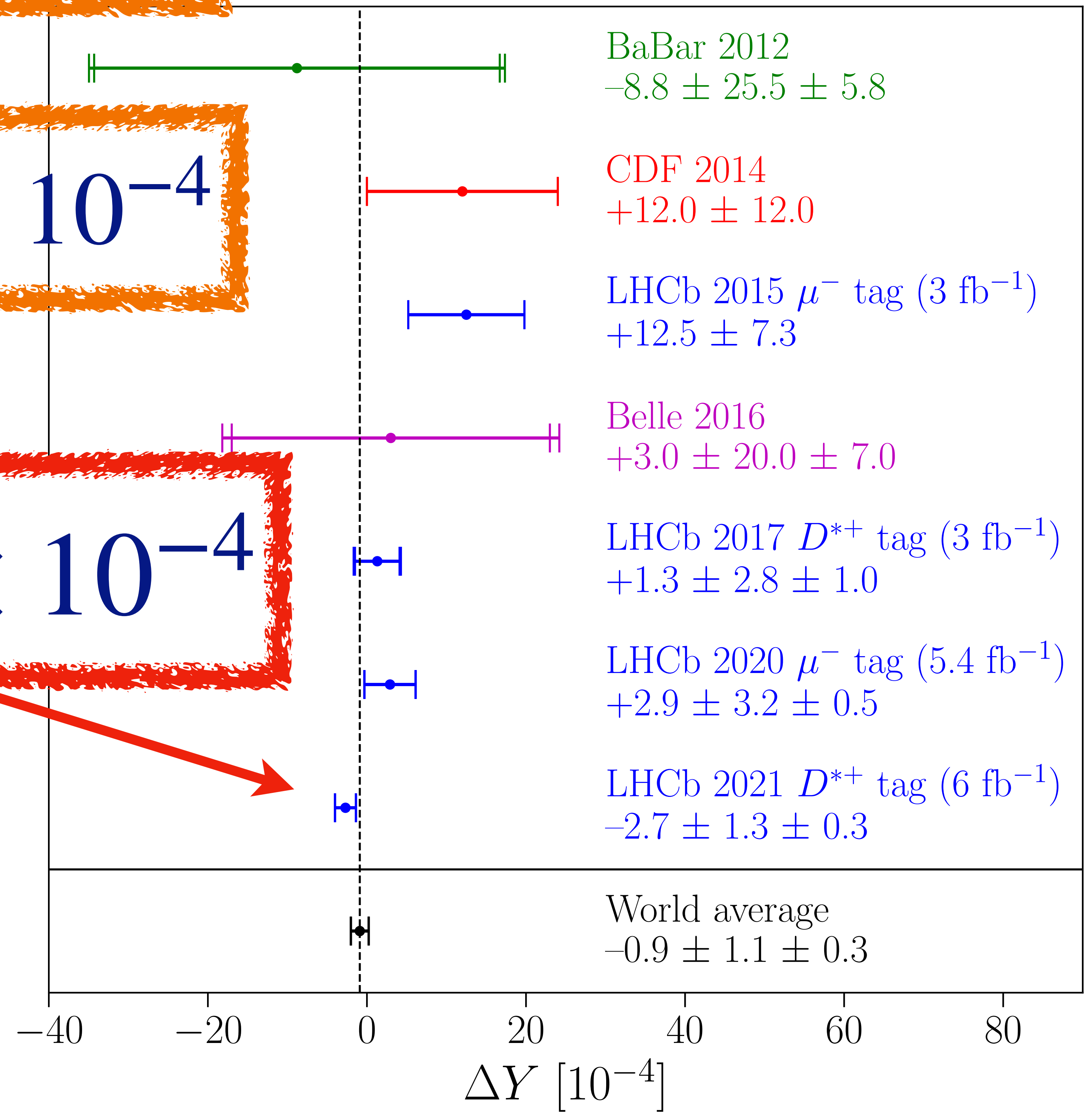
$$\Delta Y_{K^-\pi^+} = (-0.4 \pm 0.5 \pm 0.2) \times 10^{-4}$$

Result on control sample

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

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

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



- Compatible with 0 within 2σ
- This result improves by nearly a factor 2 the precision of the previous world average

$y_{CP}^{f} - y_{CP}^{K\pi}$

PRD 105 (2022) 092013

- y_{CP}^{f} parameterises the difference between the effective decay width of $D^0 \to f \;\; (f = K^-K^+, \pi^-\pi^+)$ and Γ

$$y_{CP}^{f} = \frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\overline{D}^0 \to f)}{2\Gamma} - 1$$

- $D^0 \to K^-\pi^+$ effective width is used as a proxy for Γ, but $y_{CP}^{K\pi}$ must be taken into account

$$\frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\overline{D}^0 \to f)}{\hat{\Gamma}(D^0 \to K^-\pi^+) + \hat{\Gamma}(\overline{D}^0 \to K^-\pi^+)} - 1 \simeq y_{CP}^{f} - y_{CP}^{K\pi}$$

- $y_{CP}^{f} - y_{CP}^{K\pi} \simeq y(1 + \sqrt{R_D})$
  $\Rightarrow$ provides important constraint on y

$$\sqrt{R_D} = \sqrt{\frac{\mathcal{B}(D^0 \to K^+\pi^-)}{\mathcal{B}(D^0 \to K^-\pi^+)}} \simeq 6\,\%$$

$y_{CP}^{f} - y_{CP}^{K\pi}$

PRD 105 (2022) 092013

- Experimentally: measure yield ratio as a function of decay time

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

- Selection efficiency equalised with a novel data-driven kinematic weighting procedure

- Analysis procedure validated on simulation and by checking that $y_{CP}^{CC} = 0$ in the measurement $R^{CC}(t) = \frac{N(D^0 \to \pi^-\pi^+, t)}{N(D^0 \to K^-K^+, t)} \propto e^{-y_{CP}^{CC} t/\tau_{D^0}} \frac{\varepsilon(\pi^-\pi^+, t)}{\varepsilon(K^-K^+, t)}$

- Run 2 data sample, D^0 tagged by prompt decays

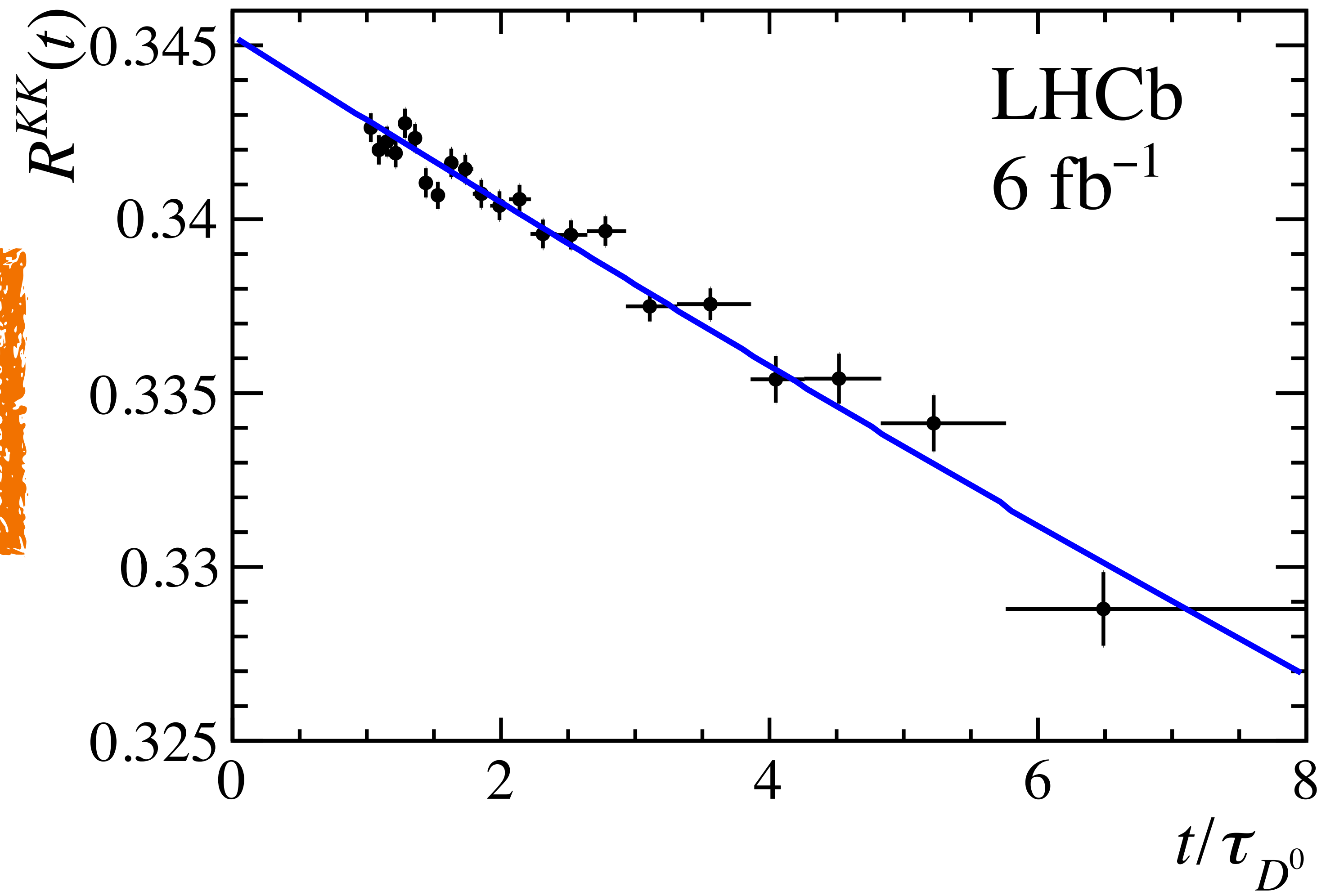
$y_{CP}^{f} - y_{CP}^{K\pi}$

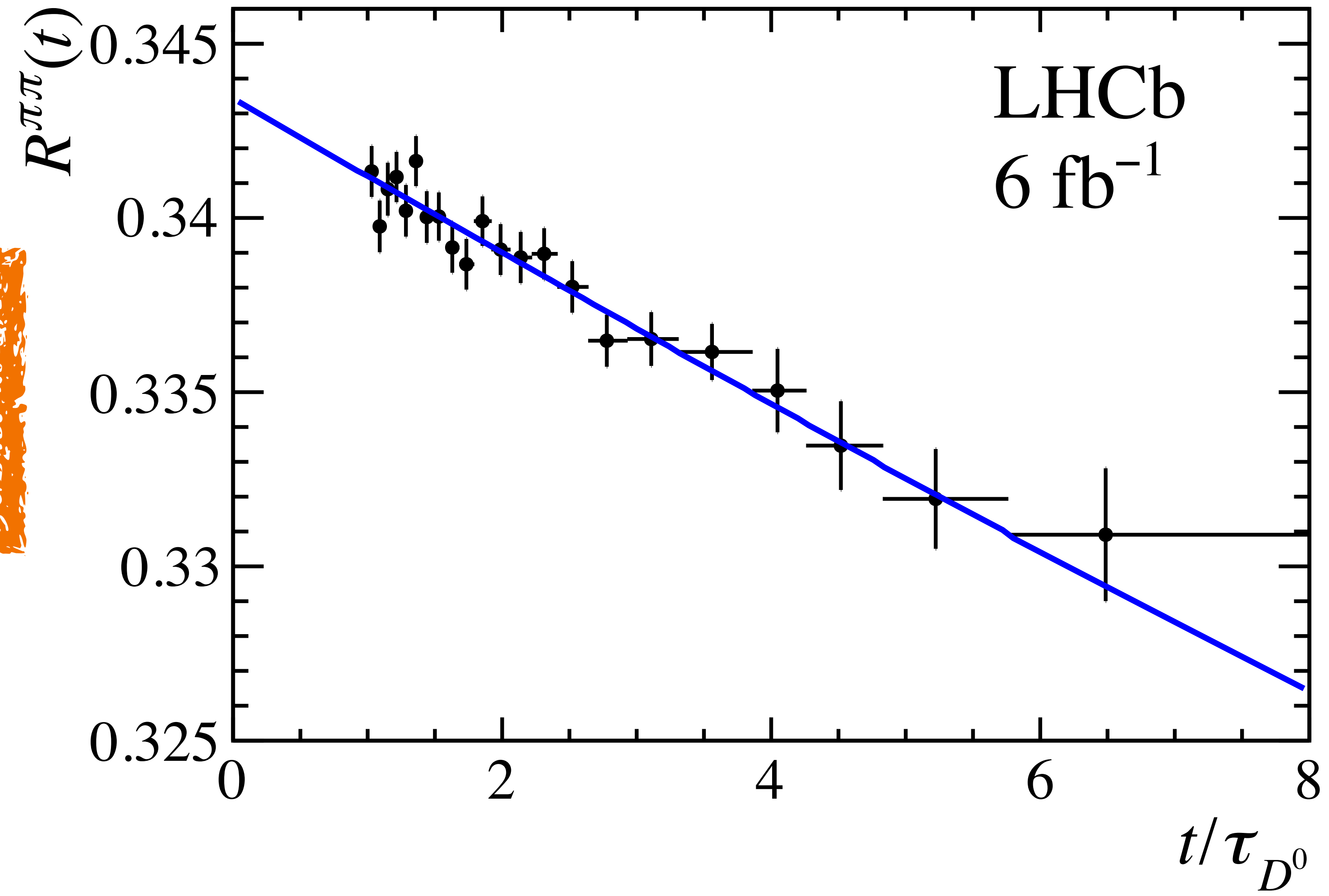
PRD 105 (2022) 092013

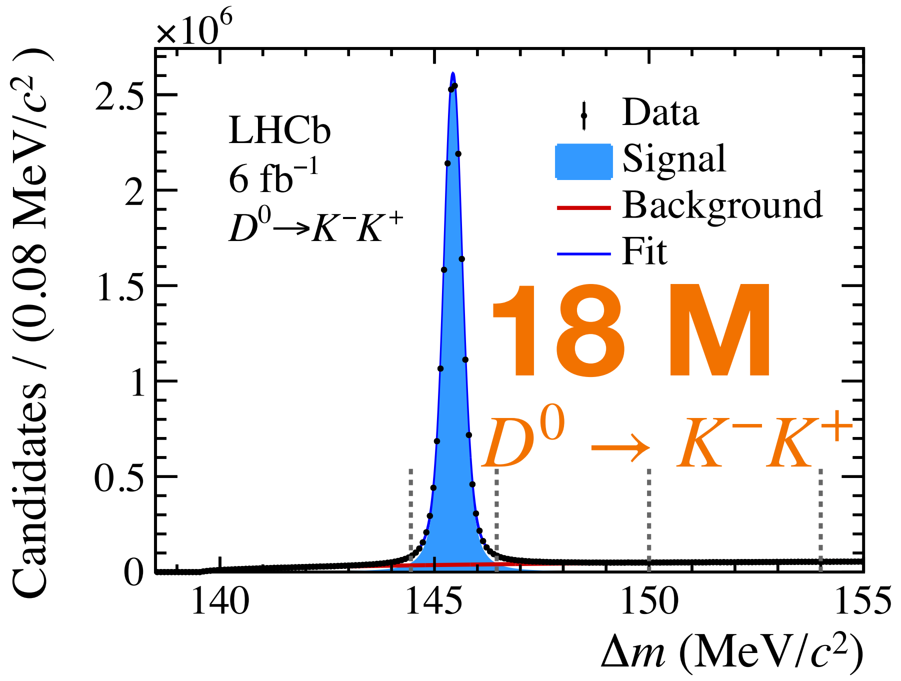
$$y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3}$$

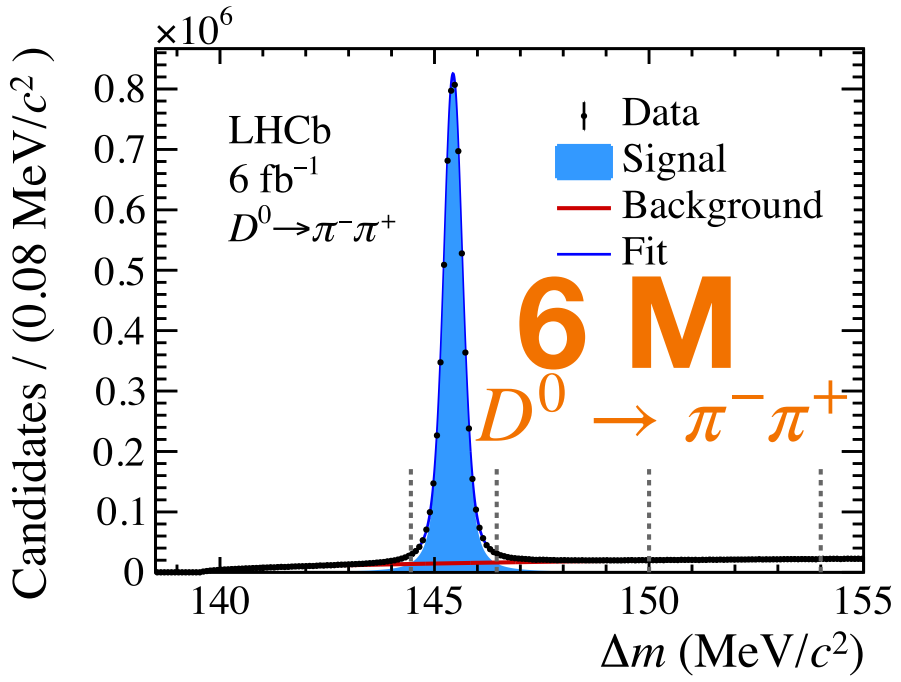
$y_{CP}^{CC} = (0.15 \pm 0.36) \times 10^{-3}$
→ compatible with 0

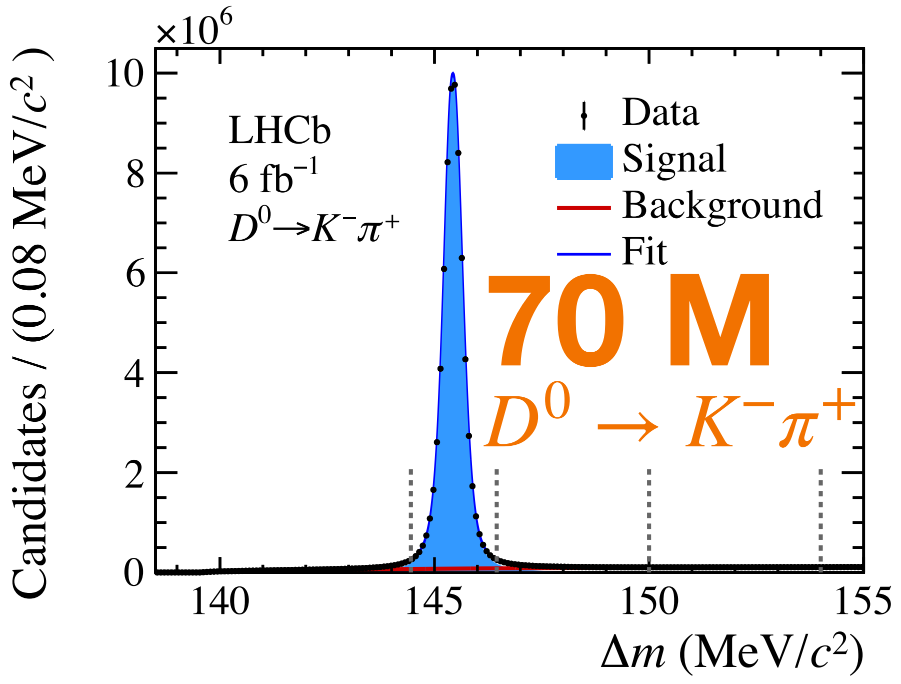
$$y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3}$$







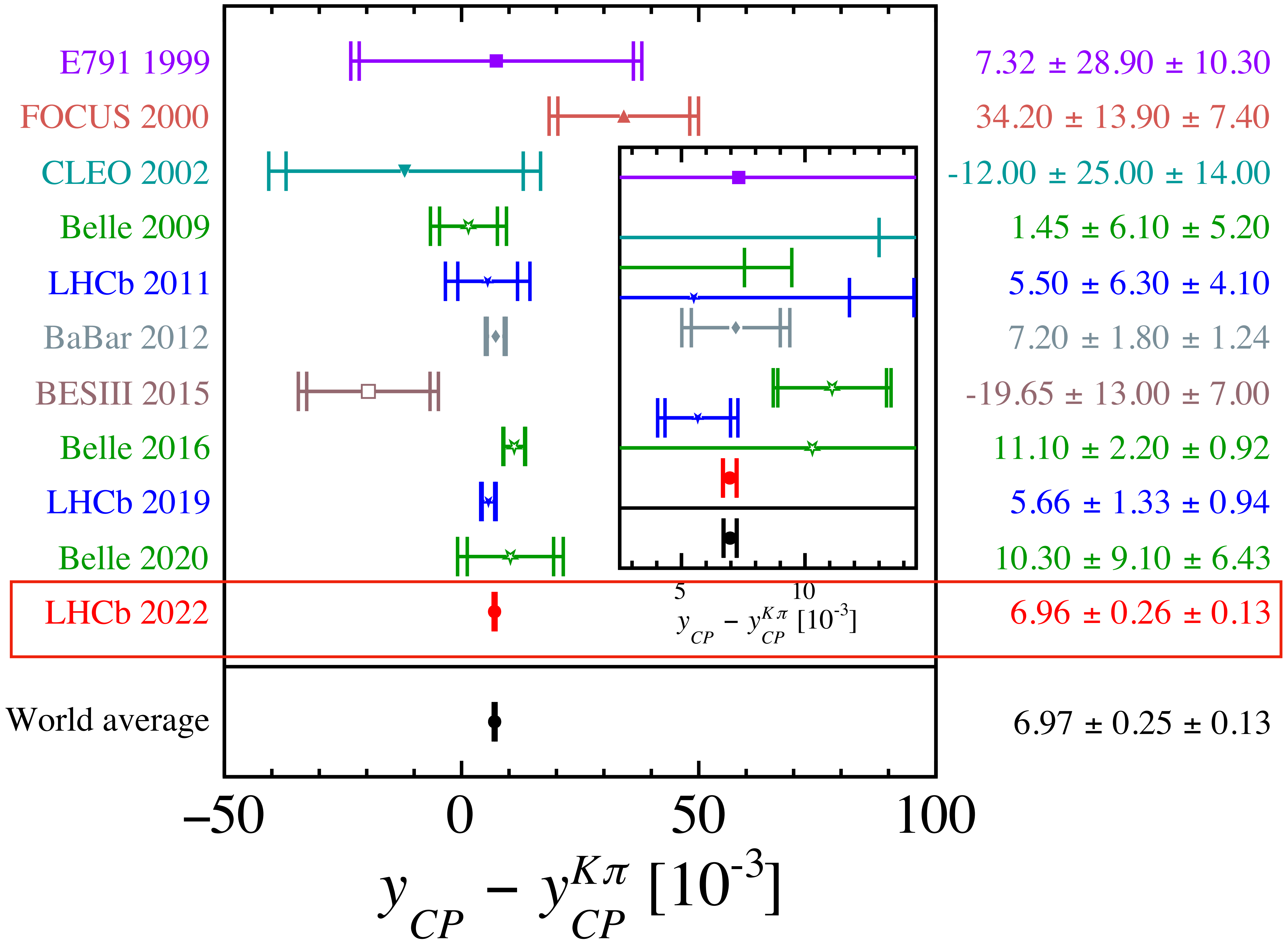




$y_{CP}^{f} - y_{CP}^{K\pi}$

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

Four times more precise than previous world average!



PRD 105 (2022) 092013

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

- $D^0 \to K_s^0\pi^+\pi^-$ is particularly sensitive to x

PRD 99 (2019) 012007

- Analysis performed with model-independent *bin-flip* method, which does not require accurate modelling of the efficiency
- Prompt tag: led to observation of $x \neq 0$ PRL 127 (2021) 111801
- Semileptonic tag: allows to probe the low decay-time region (most recent with Run 2 data reported here)

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

PRD 99 (2019) 012007

- Measure, as a function of the D^0 decay time, the yield ratios between symmetric bins in the Dalitz plot (m_+^2, m_-^2) ➡ they can be written as a function of x_{CP}, y_{CP}, Δx and Δy

- Signal selection induces correlation between decay time and phase-space that could bias the measurement ➡ a data-driven correction is applied to make the decay-time acceptance uniform in the phase space

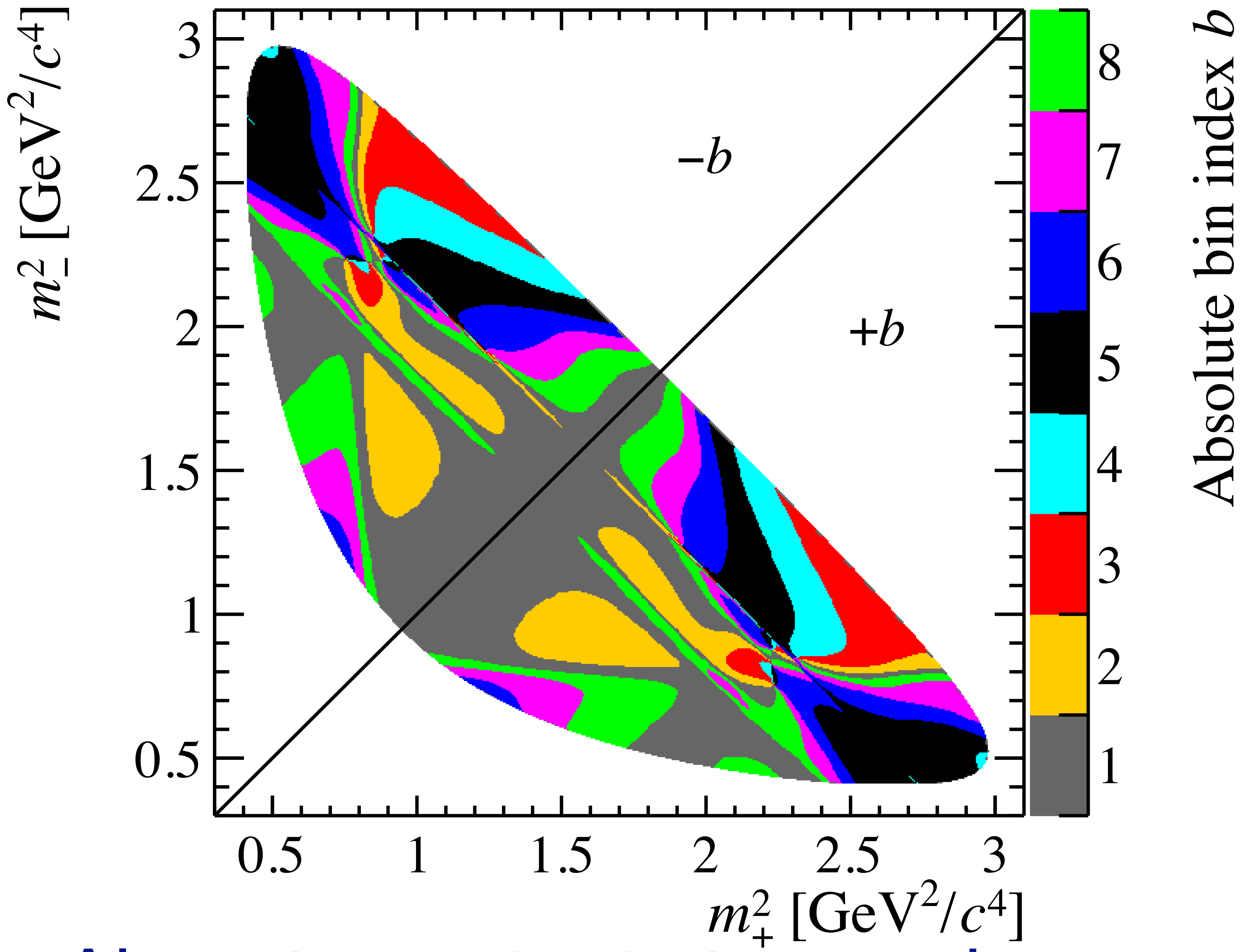
$$x_{CP} = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

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

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

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

$$m_{\pm}^2 \equiv \begin{cases} m^2(K_S^0\pi^{\pm}) & \text{for } D^0 \to K_S^0\pi^+\pi^- \\ m^2(K_S^0\pi^{\mp}) & \text{for } \overline{D}^0 \to K_S^0\pi^+\pi^- \end{cases}$$



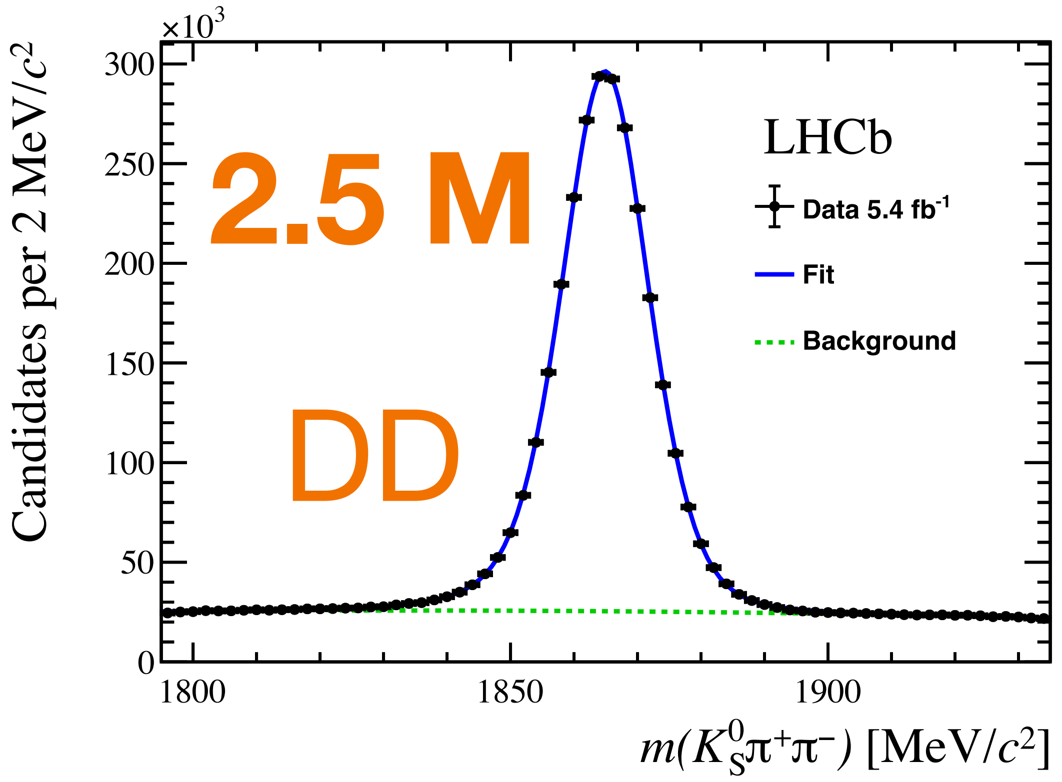
PRD 82 (2010) 112006
PRD 101 (2020) 112002

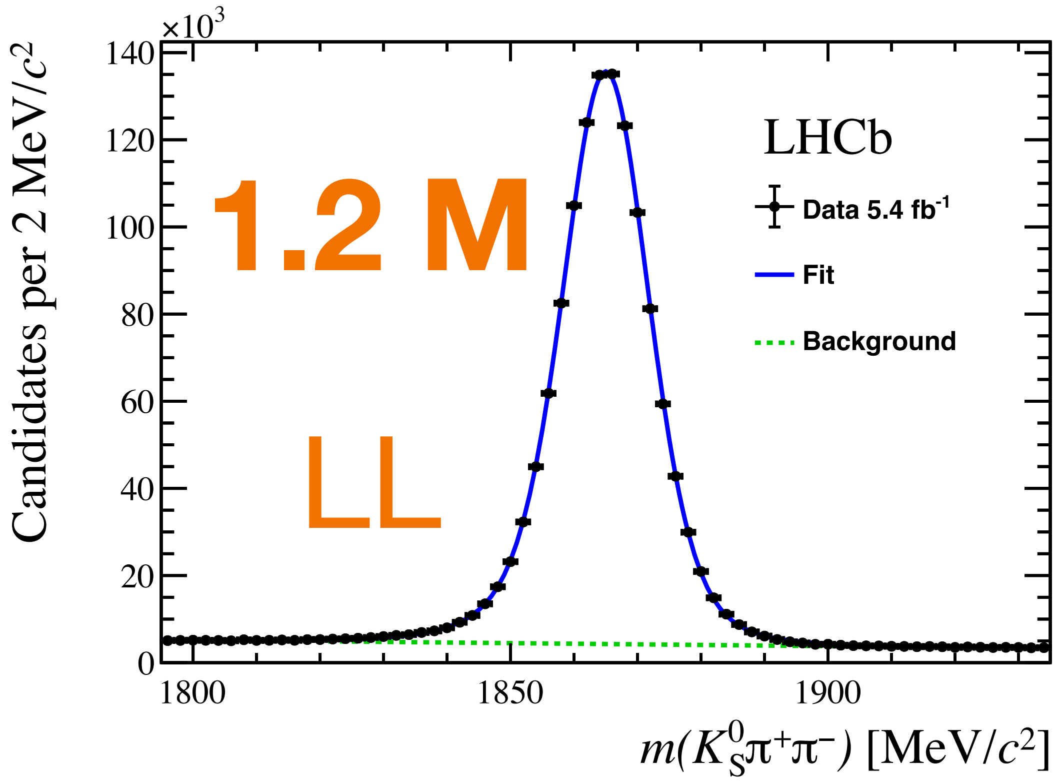
Almost constant strong-phase difference in each Dalitz bin ➡ external inputs from CLEO and BESIII

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

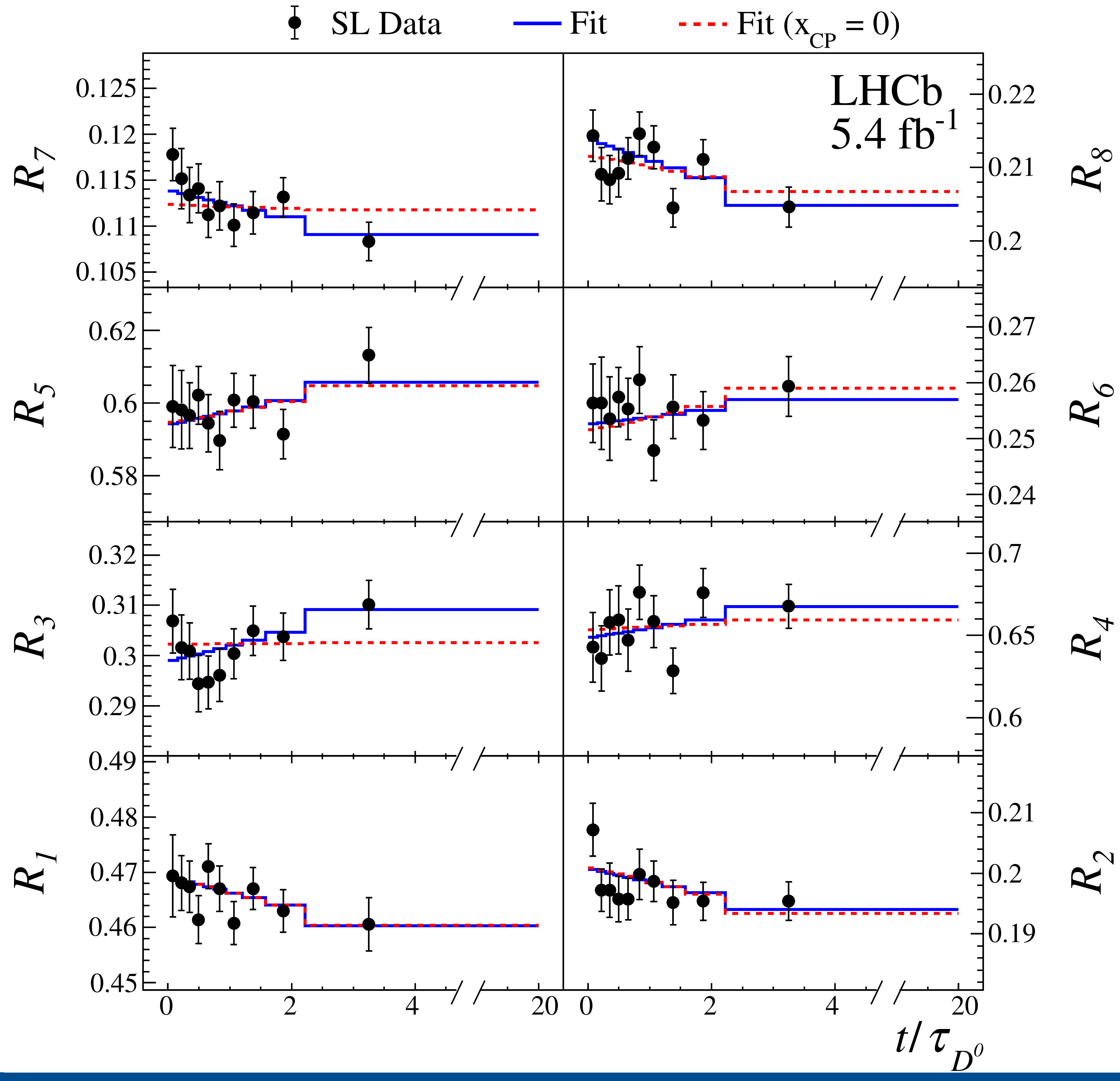
PRD 108 (2023) 052005

Two categories of $K_s^0 \to \pi^+\pi^-$: long-long (LL) and downstream-downstream (DD)

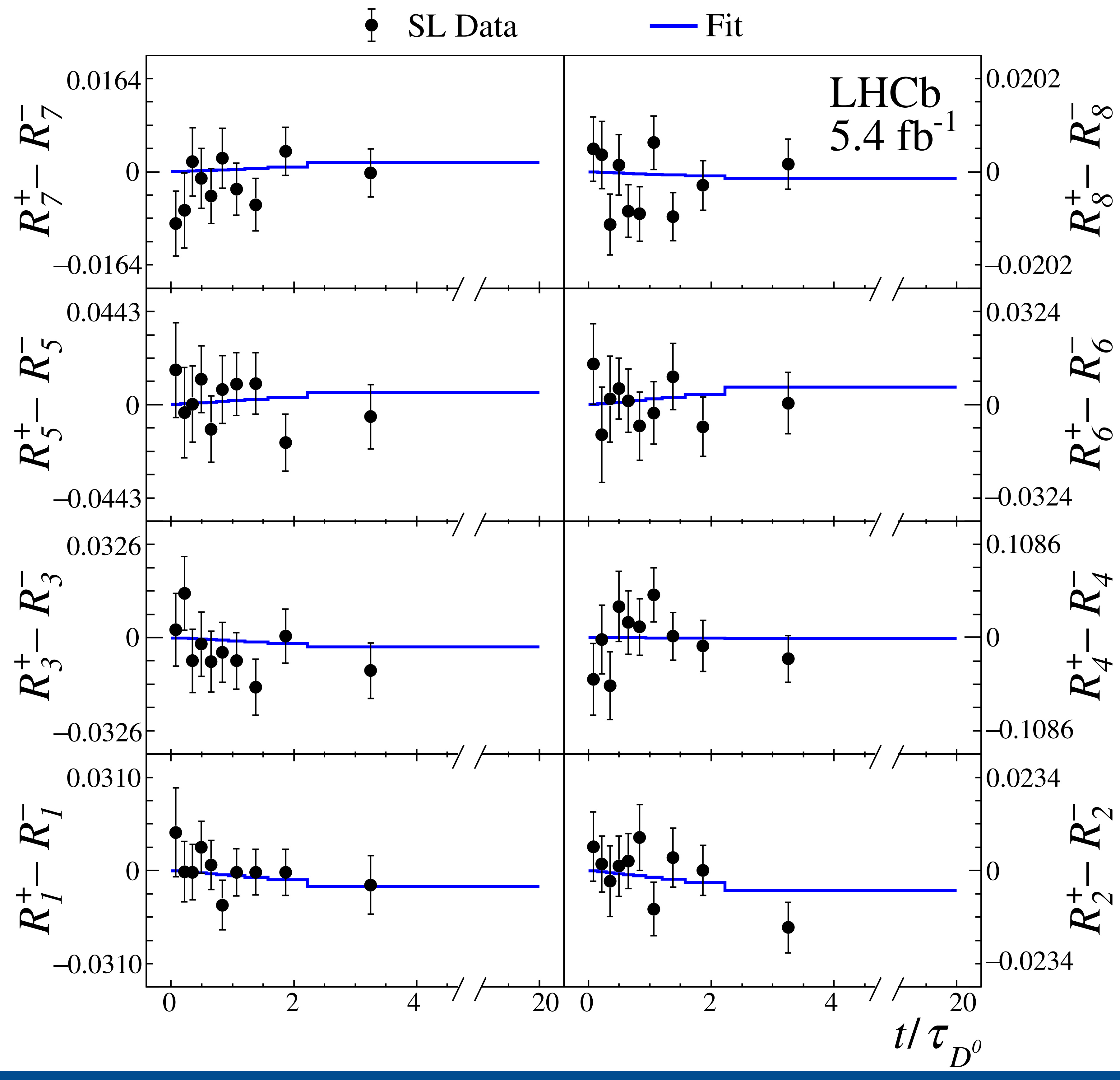




- *CP*-averaged ratios
- Deviations from constant values are due to mixing



- Differences of D^0 and $\overline{D}^0$ yield ratios
- Deviations from constant values are due to *CP* violation



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

PRL 127 (2021) 111801

PRD 108 (2023) 052005

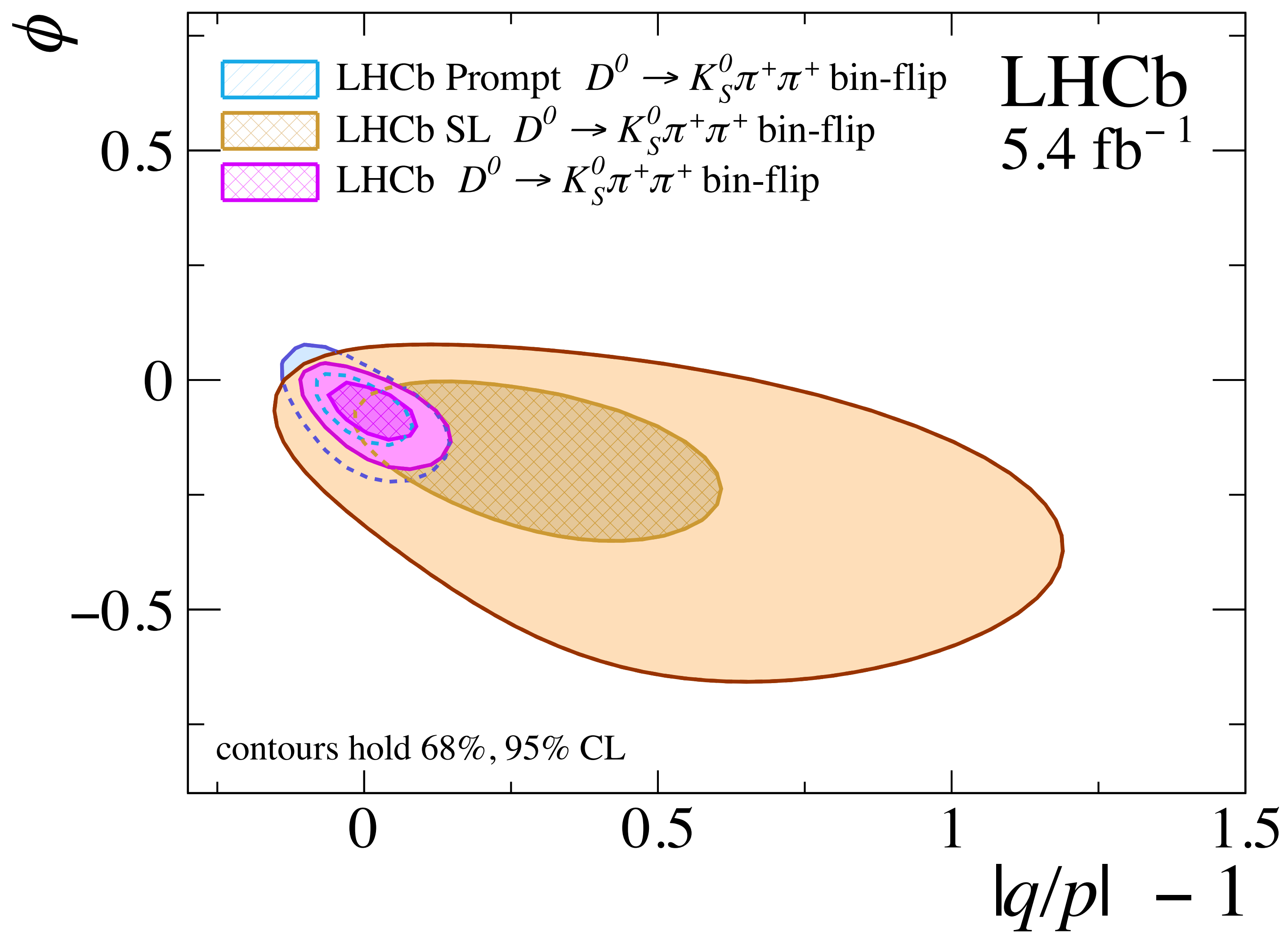
Combination with prompt Run 2 result:

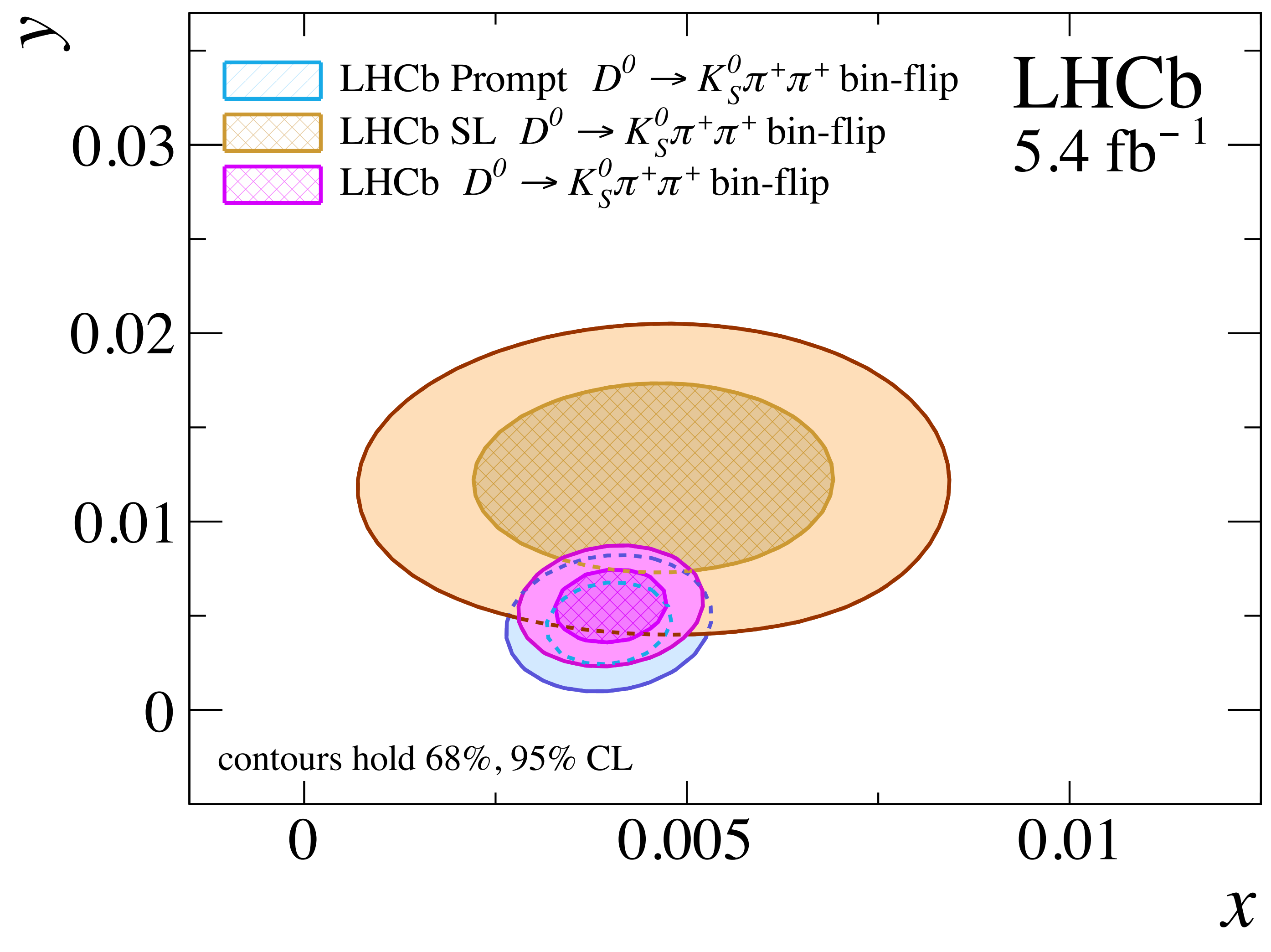
$$x_{CP} = [4.01 \pm 0.45(\text{stat}) \pm 0.20(\text{syst})] \times 10^{-3},$$
$$y_{CP} = [5.51 \pm 1.16(\text{stat}) \pm 0.59(\text{syst})] \times 10^{-3},$$
$$\Delta x = [-0.29 \pm 0.18(\text{stat}) \pm 0.01(\text{syst})] \times 10^{-3},$$
$$\Delta y = [0.31 \pm 0.35(\text{stat}) \pm 0.13(\text{syst})] \times 10^{-3}.$$

→

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

$D^0 \to K_s^0 \pi^+ \pi^-$ mode allowed us to reach a very high precision on mixing and CP violating parameters





γ + charm combination

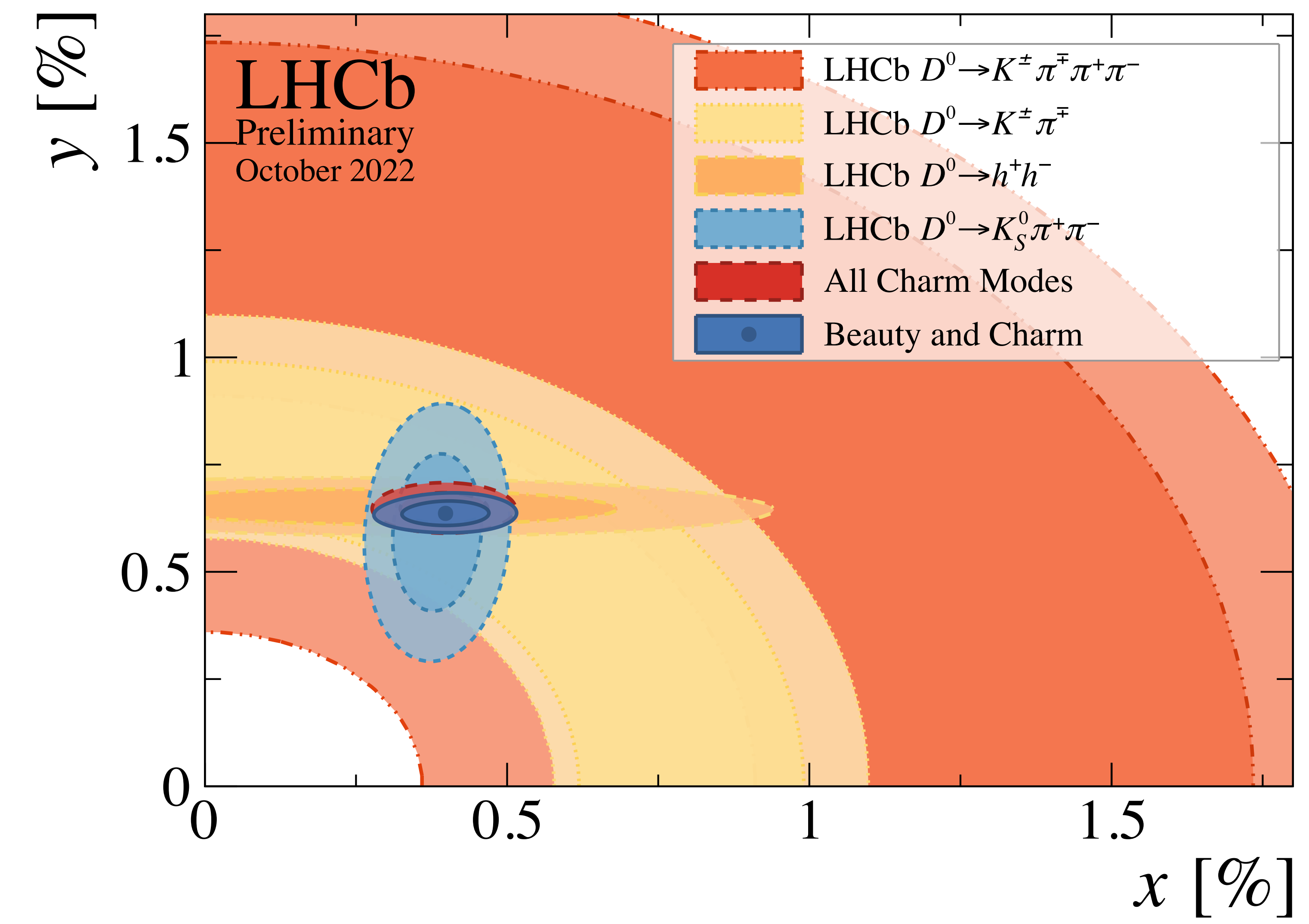
LHCb-CONF-2022-003

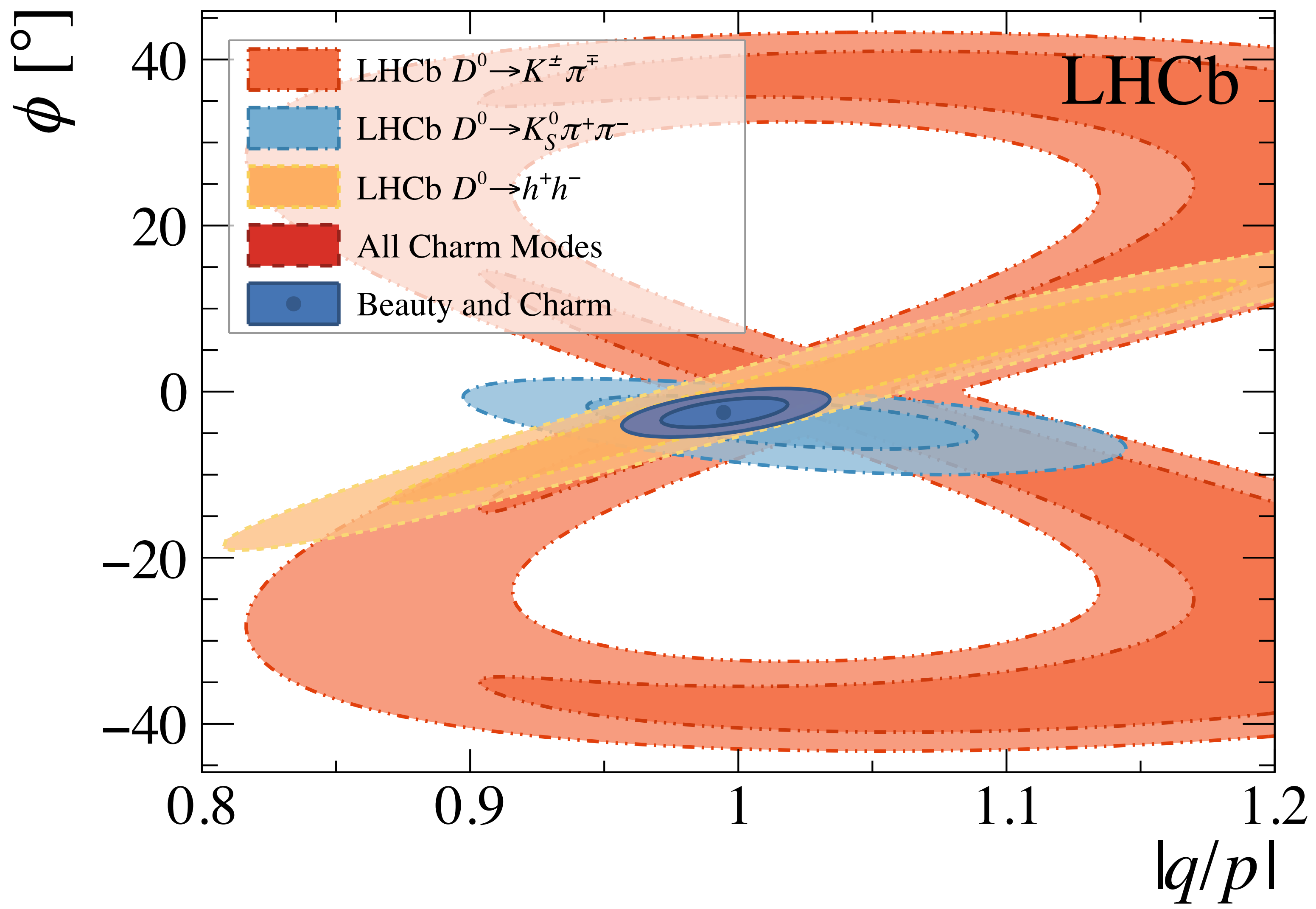
- Measurement in beauty sector help to constraint y and hadronic decay parameters of $D^0 \to K^-\pi^+ \Rightarrow$ common γ + charm mixing/CPV by LHCb since 2021
- All previously mentioned measurements are included in the latest combination

See talk by Innes

Frequentist approach
173 observables
52 parameters

Quantity	Value	68.3% CL Uncertainty	68.3% CL Interval	95.4% CL Uncertainty	95.4% CL Interval
$x[\%]$	0.398	$^{+0.050}_{-0.049}$	$[0.349, 0.448]$	$^{+0.099}_{-0.10}$	$[0.30, 0.497]$
$y[\%]$	0.636	$^{+0.020}_{-0.019}$	$[0.617, 0.656]$	$^{+0.041}_{-0.039}$	$[0.597, 0.677]$
$\|q/p\|$	0.995	$^{+0.015}_{-0.016}$	$[0.979, 1.010]$	$^{+0.032}_{-0.032}$	$[0.963, 1.027]$
$\phi[^\circ]$	-2.5	$^{+1.2}_{-1.2}$	$[-3.7, -1.3]$	$^{+2.4}_{-2.5}$	$[-5.0, -0.1]$





Future prospects

- The LHCb Upgrade I will reduce σ_{stat} by a factor 3
  - higher integrated luminosity
  - removal of hardware trigger → higher trigger efficiency, smaller detection asymmetries
- After Run 5 (Upgrade II) precisions expected to increase by an order of magnitude

$D^0 \to K_s^0 \pi^+ \pi^-$

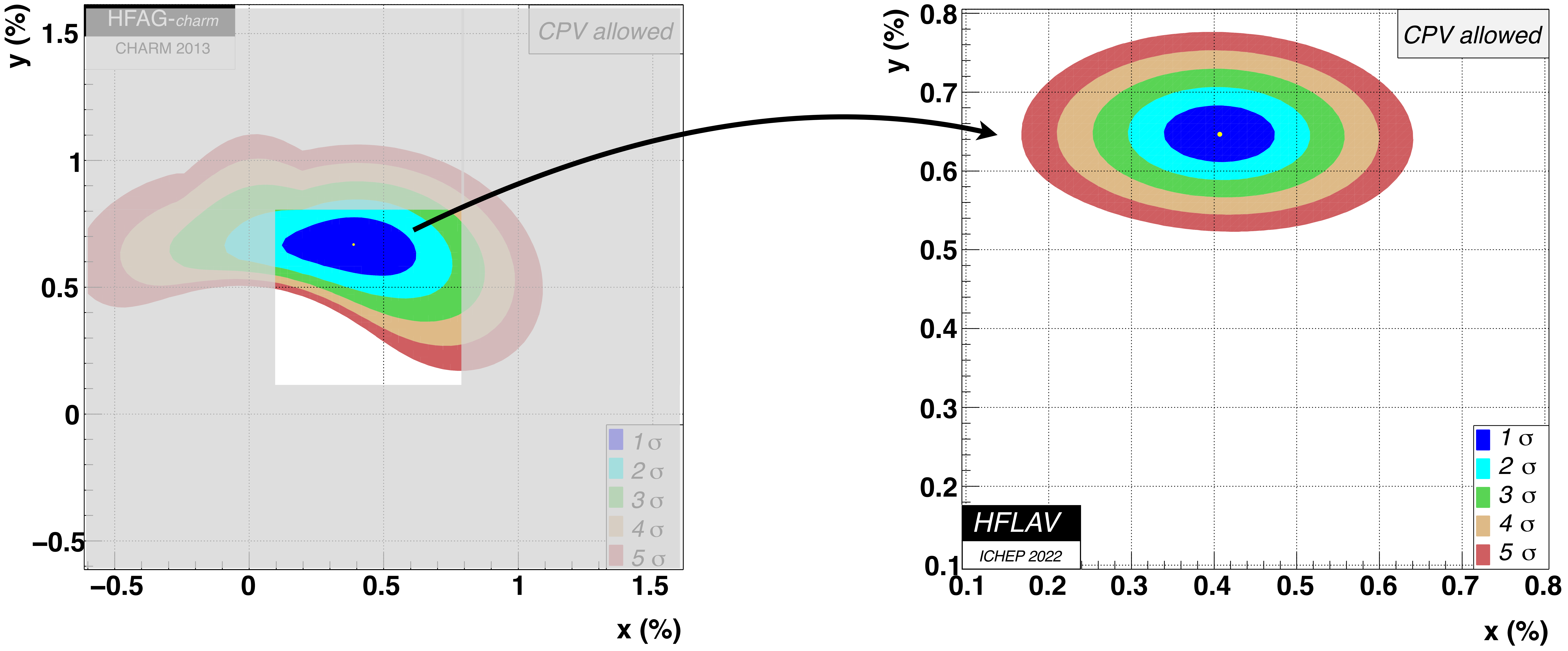
Sample (lumi $\mathcal{L}$)	Tag	Yield	$\sigma(x)$	$\sigma(y)$	$\sigma(\lvert q/p \rvert)$	$\sigma(\phi)$
Run 1–2 (9 fb^{-1})	SL	10M	0.07%	0.05%	0.07	4.6°
	Prompt	36M	0.05%	0.05%	0.04	1.8°
Run 1–3 (23 fb^{-1})	SL	33M	0.036%	0.030%	0.036	2.5°
	Prompt	200M	0.020%	0.020%	0.017	0.77°
Run 1–4 (50 fb^{-1})	SL	78M	0.024%	0.019%	0.024	1.7°
	Prompt	520M	0.012%	0.013%	0.011	0.48°
Run 1–5 (300 fb^{-1})	SL	490M	0.009%	0.008%	0.009	0.69°
	Prompt	3500M	0.005%	0.005%	0.004	0.18°

LHCB-PUB-2018-009

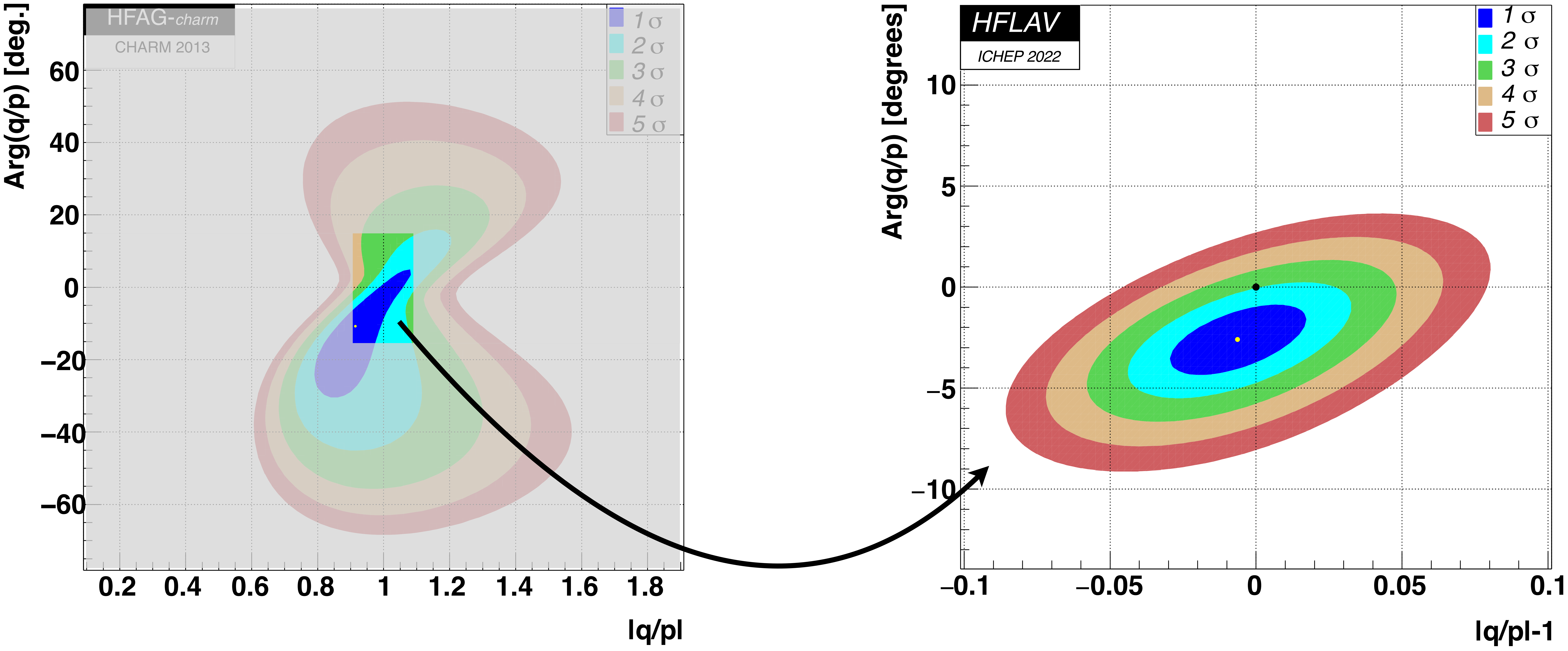
$D^0 \to h^+ h^-$

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

Landscape after 10 years



Landscape after 10 years



Conclusions

- The analysis of the full data sample collected by LHCb allowed D^0 mixing and time-dependent CP violating parameters to be measured with impressive precision $\sim \mathcal{O}(10^{-4})$
- These measurements are statistically dominated $\Rightarrow$ Run 3-5 will allow us to further increase our knowledge in this field
- New improved techniques under study in order to further reduce systematic uncertainties

Backup

$\mathcal{CP}$ violation in charm

- Charm unique laboratory for study of $\mathcal{CP}$ violation in up-type quark decays
- Due to smallness of involved CKM elements and GIM mechanism, $\mathcal{CP}$ violation in charm decays predicted to be small: $A_{\mathcal{CP}} \sim 10^{-4} - 10^{-3}$
- SM calculations dominated by long distance contributions
- LHCb huge charm data sample allowed direct $\mathcal{CP}$ violation to be observed in $D^0 \to h^+h^-$ decays by LHCb in March 2019!
  $\Rightarrow$ observed value challenges first-principles QCD calculations $\Rightarrow$ enhancement of QCD rescattering or NP?
- Further measurements are needed in charm sector

Charm at LHCb

- Large $c\bar{c}$ production cross section
  $\sigma(pp \to c\bar{c}X)_{\sqrt{s}=13\ \text{TeV}} = (2369 \pm 3 \pm 152 \pm 118)\ \mu\text{b}$
- More than 1 billion $D^0 \to K^-\pi^+$ decays reconstructed with the full LHCb data sample
- LHCb detector: JINST 3 (2008) S08005
  - Excellent vertex resolution ($13\ \mu$m in transverse plane for PV)
  - Excellent IP resolution ($\sim 20\ \mu$m)
  - Very good momentum resolution ($\delta p/p \sim 0.5\% - 0.8\,\%$)
  - Excellent PID capabilities
  - Very good trigger efficiency (~90%)

JHEP 05 (2017) 074

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$$\sigma(pp \to D^+ X) = 834 \pm 2 \pm 78\,\mu\text{b}$$
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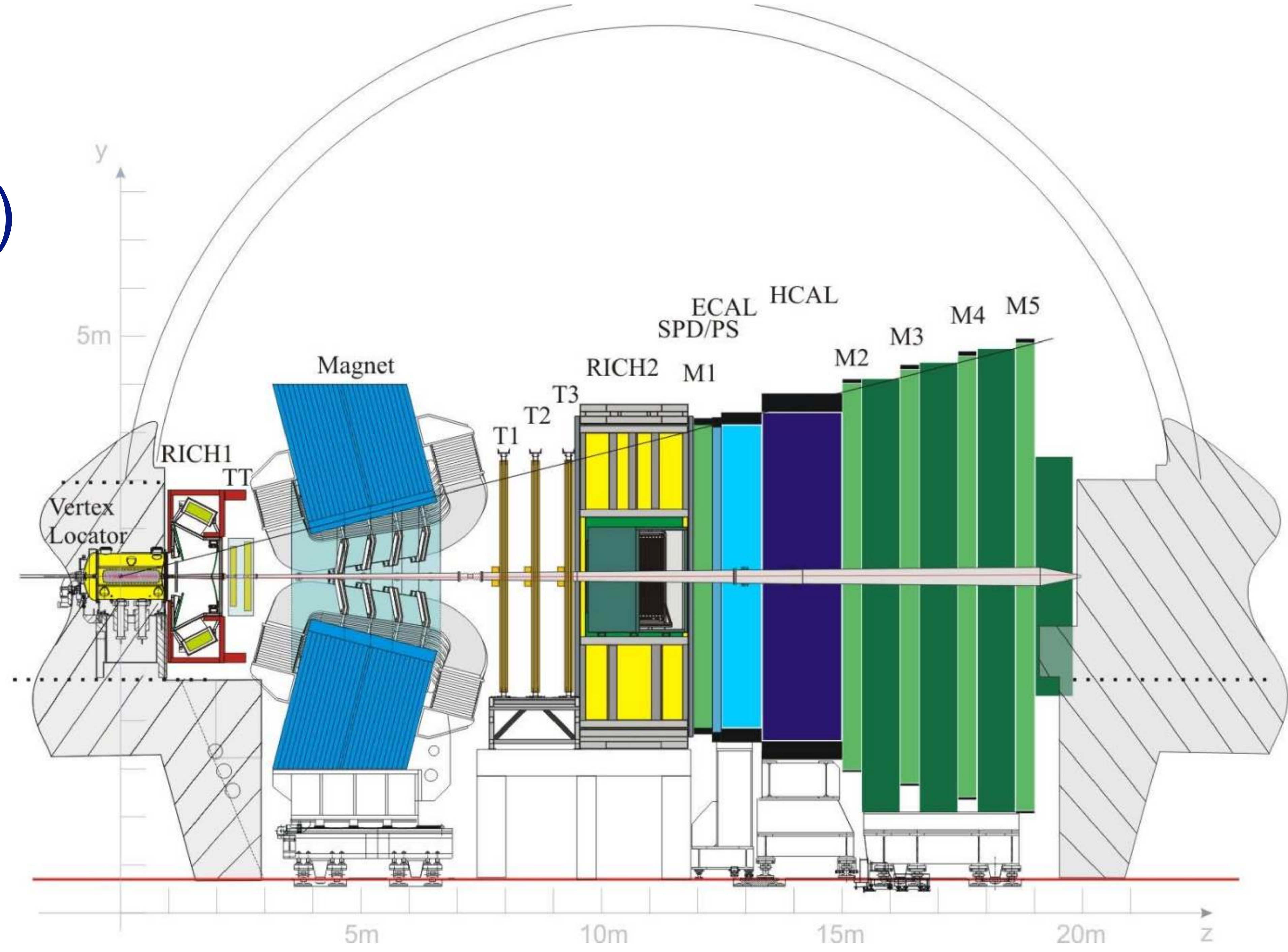

ΔY_f in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

- Signal yield obtained with a sideband subtraction in $m(D^0\pi^+)$ after fitting the distribution in each decay time
- A correction is applied for contamination of secondary D^0 by measuring their size and asymmetry with a multidimensional fit on (IP, t)

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

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

- Systematic uncertainties

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

γ + charm combination

LHCb-CONF-2022-003

B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]	Run 1&2	**New**
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[31]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[32]	Run 1&2	As before
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[38]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[39]	Run 1&2	As before
D decay	**Observable(s)**	**Ref.**	**Dataset**	**Status since Ref. [14]**
$D^0 \to h^+h^-$	ΔA_{CP}	[24, 40, 41]	Run 1&2	As before
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[16, 24, 25]	Run 2	**New**
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[42]	Run 1	As before
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[15]	Run 2	**New**
$D^0 \to h^+h^-$	ΔY	[43–46]	Run 1&2	As before
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[47]	Run 1	As before
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[48]	Run 1&2(*)	As before
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[49]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[50]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[51]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[52]	Run 2	As before
$D^0 \to K^0_S\pi^+\pi^-$ (μ^- tag)	x_{CP}, y_{CP}, Δx, Δy	[17]	Run 2	**New**

Quantity	Value	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
$\gamma[^\circ]$	63.8	$^{+3.5}_{-3.7}$	[60.1, 67.3]	$^{+6.9}_{-7.5}$	[56.3, 70.7]
$r_{B^\pm}^{DK^\pm}$	0.0972	$^{+0.0022}_{-0.0021}$	[0.0951, 0.0994]	$^{+0.0045}_{-0.0042}$	[0.0930, 0.1017]
$\delta_{B^\pm}^{DK^\pm}[^\circ]$	127.3	$^{+3.4}_{-3.5}$	[123.8, 130.7]	$^{+6.5}_{-7.3}$	[120.0, 133.8]
$r_{B^\pm}^{D\pi^\pm}$	0.00490	$^{+0.00059}_{-0.00053}$	[0.00437, 0.00549]	$^{+0.0013}_{-0.0010}$	[0.0039, 0.0062]
$\delta_{B^\pm}^{D\pi^\pm}[^\circ]$	294.0	$^{+9.7}_{-11}$	[283, 303.7]	$^{+19}_{-22}$	[272, 313]
$r_{B^\pm}^{D^*K^\pm}$	0.098	$^{+0.017}_{-0.019}$	[0.079, 0.115]	$^{+0.031}_{-0.037}$	[0.061, 0.129]
$\delta_{B^\pm}^{D^*K^\pm}[^\circ]$	308	$^{+12}_{-25}$	[283, 320]	$^{+21}_{-69}$	[239, 329]
$r_{B^\pm}^{D^*\pi^\pm}$	0.0091	$^{+0.0081}_{-0.0056}$	[0.0035, 0.0172]	$^{+0.016}_{-0.0085}$	[0.0006, 0.025]
$\delta_{B^\pm}^{D^*\pi^\pm}[^\circ]$	137	$^{+22}_{-83}$	[54, 159]	$^{+32}_{-130}$	[7, 169]
$r_{B^\pm}^{DK^{*\pm}}$	0.108	$^{+0.016}_{-0.019}$	[0.089, 0.124]	$^{+0.030}_{-0.039}$	[0.069, 0.138]
$\delta_{B^\pm}^{DK^{*\pm}}[^\circ]$	34	$^{+20}_{-15}$	[19, 54]	$^{+54}_{-28}$	[6, 88]
$r_{B^0}^{DK^{*0}}$	0.249	$^{+0.022}_{-0.025}$	[0.224, 0.271]	$^{+0.044}_{-0.051}$	[0.198, 0.293]
$\delta_{B^0}^{DK^{*0}}[^\circ]$	198	$^{+10}_{-9.6}$	[188.4, 208]	$^{+24}_{-19}$	[179, 222]
$r_{B_s^0}^{D_s^\mp K^\pm}$	0.310	$^{+0.096}_{-0.094}$	[0.216, 0.406]	$^{+0.20}_{-0.22}$	[0.09, 0.51]
$\delta_{B_s^0}^{D_s^\mp K^\pm}[^\circ]$	356	$^{+19}_{-18}$	[338, 375]	$^{+39}_{-38}$	[318, 395]
$r_{B_s^0}^{D_s^\mp K^\pm\pi^+\pi^-}$	0.460	$^{+0.081}_{-0.085}$	[0.375, 0.541]	$^{+0.16}_{-0.17}$	[0.29, 0.62]
$\delta_{B_s^0}^{D_s^\mp K^\pm\pi^+\pi^-}[^\circ]$	346	$^{+12}_{-12}$	[334, 358]	$^{+26}_{-25}$	[321, 372]
$r_{B^0}^{D^\mp\pi^\pm}$	0.030	$^{+0.016}_{-0.012}$	[0.018, 0.046]	$^{+0.041}_{-0.027}$	[0.003, 0.071]
$\delta_{B^0}^{D^\mp\pi^\pm}[^\circ]$	32	$^{+26}_{-40}$	[−8, 58]	$^{+45}_{-86}$	[−54, 77]
$r_{B^\pm}^{DK^\pm\pi^+\pi^-}$	0.079	$^{+0.028}_{-0.034}$	[0.045, 0.107]	$^{+0.049}_{-0.079}$	[0.000, 0.128]*
$r_{B^\pm}^{D\pi^\pm\pi^+\pi^-}$	0.068	$^{+0.026}_{-0.030}$	[0.038, 0.094]	$^{+0.039}_{-0.068}$	[0.000, 0.107]*
$x[\%]$	0.398	$^{+0.050}_{-0.049}$	[0.349, 0.448]	$^{+0.099}_{-0.10}$	[0.30, 0.497]
$y[\%]$	0.636	$^{+0.020}_{-0.019}$	[0.617, 0.656]	$^{+0.041}_{-0.039}$	[0.597, 0.677]
$r_D^{K\pi}[\%]$	5.865	$^{+0.014}_{-0.015}$	[5.850, 5.879]	$^{+0.029}_{-0.030}$	[5.835, 5.894]
$\delta_D^{K\pi}[^\circ]$	190.2	$^{+2.8}_{-2.8}$	[187.4, 193.0]	$^{+5.6}_{-6.1}$	[184.1, 195.8]
$\lvert q/p \rvert$	0.995	$^{+0.015}_{-0.016}$	[0.979, 1.010]	$^{+0.032}_{-0.032}$	[0.963, 1.027]
$\phi[^\circ]$	−2.5	$^{+1.2}_{-1.2}$	[−3.7, −1.3]	$^{+2.4}_{-2.5}$	[−5.0, −0.1]
$a^{\rm d}_{K^+K^-}[\%]$	0.090	$^{+0.057}_{-0.057}$	[0.033, 0.147]	$^{+0.11}_{-0.12}$	[−0.03, 0.20]
$a^{\rm d}_{\pi^+\pi^-}[\%]$	0.240	$^{+0.061}_{-0.062}$	[0.178, 0.301]	$^{+0.12}_{-0.12}$	[0.12, 0.36]

γ + charm combination

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Decay	Parameters	Source	Ref.	Status since Ref. [14]
$B^\pm \to DK^{*\pm}$	$\kappa_{B^\pm}^{DK^{*\pm}}$	LHCb	[33]	As before
$B^0 \to DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb	[53]	As before
$B^0 \to D^\mp\pi^\pm$	β	HFLAV	[13]	As before
$B_s^0 \to D_s^\mp K^\pm(\pi\pi)$	ϕ_s	HFLAV	[13]	As before
$D \to K^+\pi^-$	$\cos\delta_D^{K\pi}$, $\sin\delta_D^{K\pi}$, $(r_D^{K\pi})^2$, x^2, y	CLEO-c	[27]	**New**
$D \to K^+\pi^-$	$A_{K\pi}$, $A_{K\pi}^{\pi\pi\pi^0}$, $r_D^{K\pi}\cos\delta_D^{K\pi}$, $r_D^{K\pi}\sin\delta_D^{K\pi}$	BESIII	[28]	**New**
$D \to h^+h^-\pi^0$	$F_{\pi\pi\pi^0}^+$, $F_{KK\pi^0}^+$	CLEO-c	[54]	As before
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{4\pi}^+$	CLEO-c+BESIII	[26, 54]	**Updated**
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII	[55–57]	As before
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII	[49, 55–57]	As before
$D \to K_S^0K^\pm\pi^\mp$	$r_D^{K_S^0K\pi}$, $\delta_D^{K_S^0K\pi}$, $\kappa_D^{K_S^0K\pi}$	CLEO	[58]	As before
$D \to K_S^0K^\pm\pi^\mp$	$r_D^{K_S^0K\pi}$	LHCb	[59]	As before