Mixing and CPV in charm decays at LHCb

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of the LHCb collaboration

European Physical Society conference
on high energy physics 2021

28 July 2021

Formalism

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

- Direct CP violation when $|A_f|^2 \neq |\bar{A}_{\bar{f}}|^2$

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

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

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

$\mathcal{CP}$ violation in charm

- $\mathcal{CP}$ violation in charm decays predicted to be small $\sim 10^{-4} - 10^{-3}$
- SM calculations dominated by long distance contributions, need further experimental results to improve predictions
- 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! PRL 122 (2019) 211803
- Still looking for indirect $\mathcal{CP}$ violation (time-dependent $\mathcal{CP}$ asymmetries)
- All results presented today have been obtained with full LHCb Run 2 data

Experimental asymmetries

$$A_{\text{raw}}(D \to f) \simeq A_{CP}(D \to f) + A_{\text{det}}(f) + A_{\text{det}}(\text{tag}) + A_{\text{prod}}(D)$$

Physical CP asymmetry

Final state detection asymmetry

Tagging particle detection asymmetry

Production asymmetry

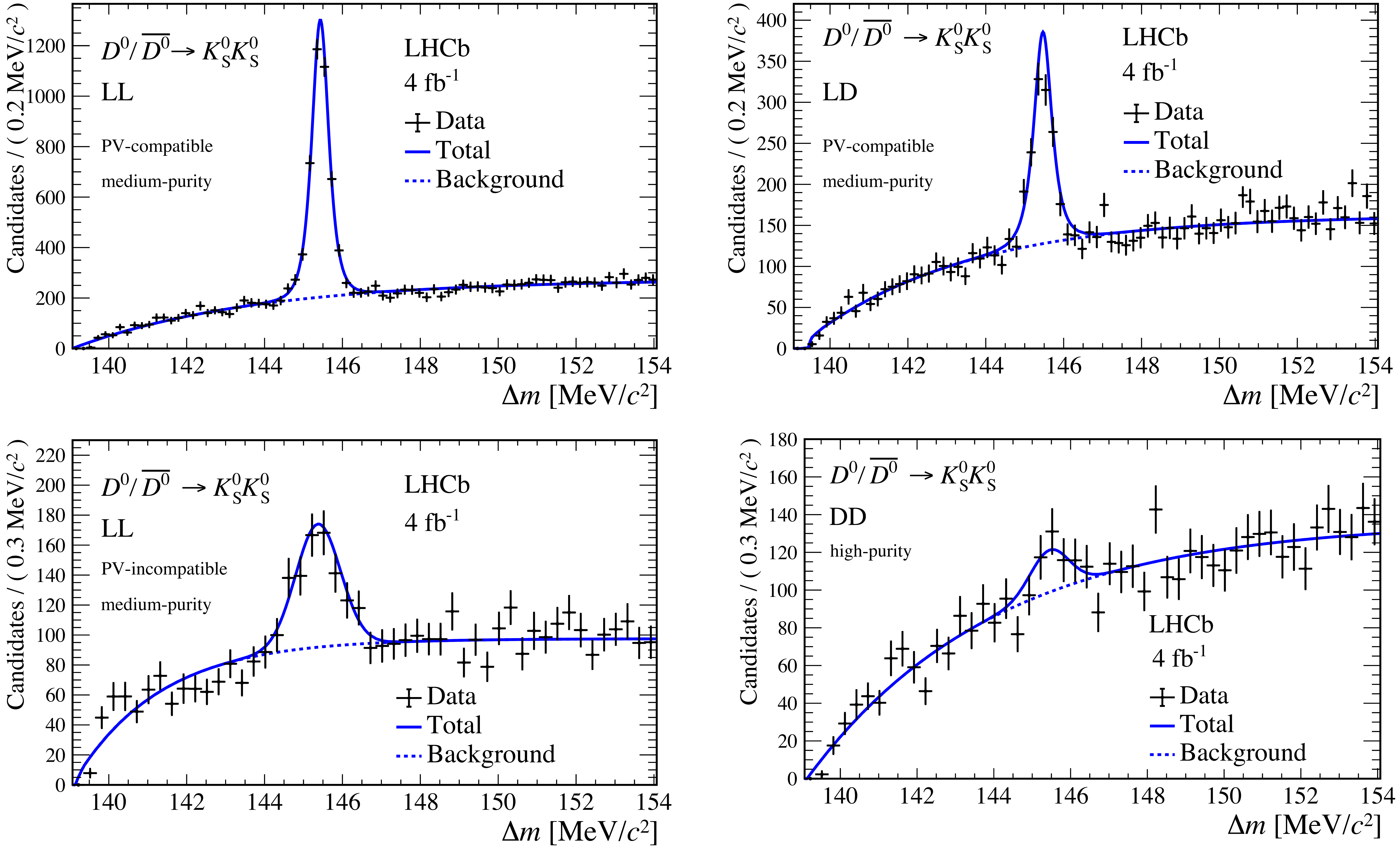
- Measured *raw* asymmetry includes also experimental nuisance asymmetries that must be canceled
- One or more calibration samples are usually used to measure and correct for detection and production asymmetries
- D^0 flavour at production is determined by the charge of the *tagging* pion in the $D^{*\pm} \to D^0\pi^\pm$ decay

Direct $\mathcal{CP}$ violation

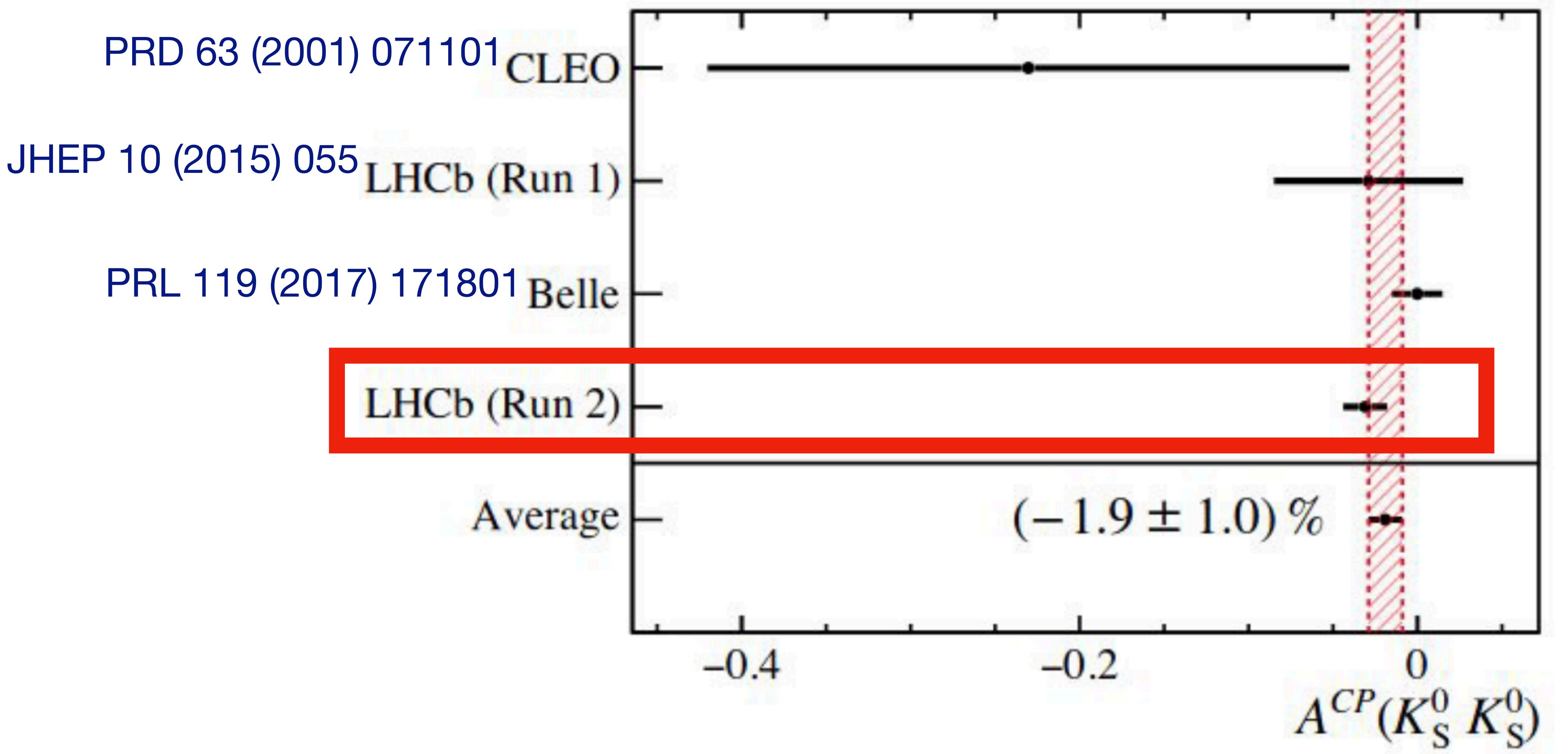
$A_{CP}(D^0 \to K_S^0 K_S^0)$

$$A_{CP} = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\,\%$$

arXiv:2105.01565



- Consistent with no CP violation at 2.4σ
- Most precise measurement of this quantity to date

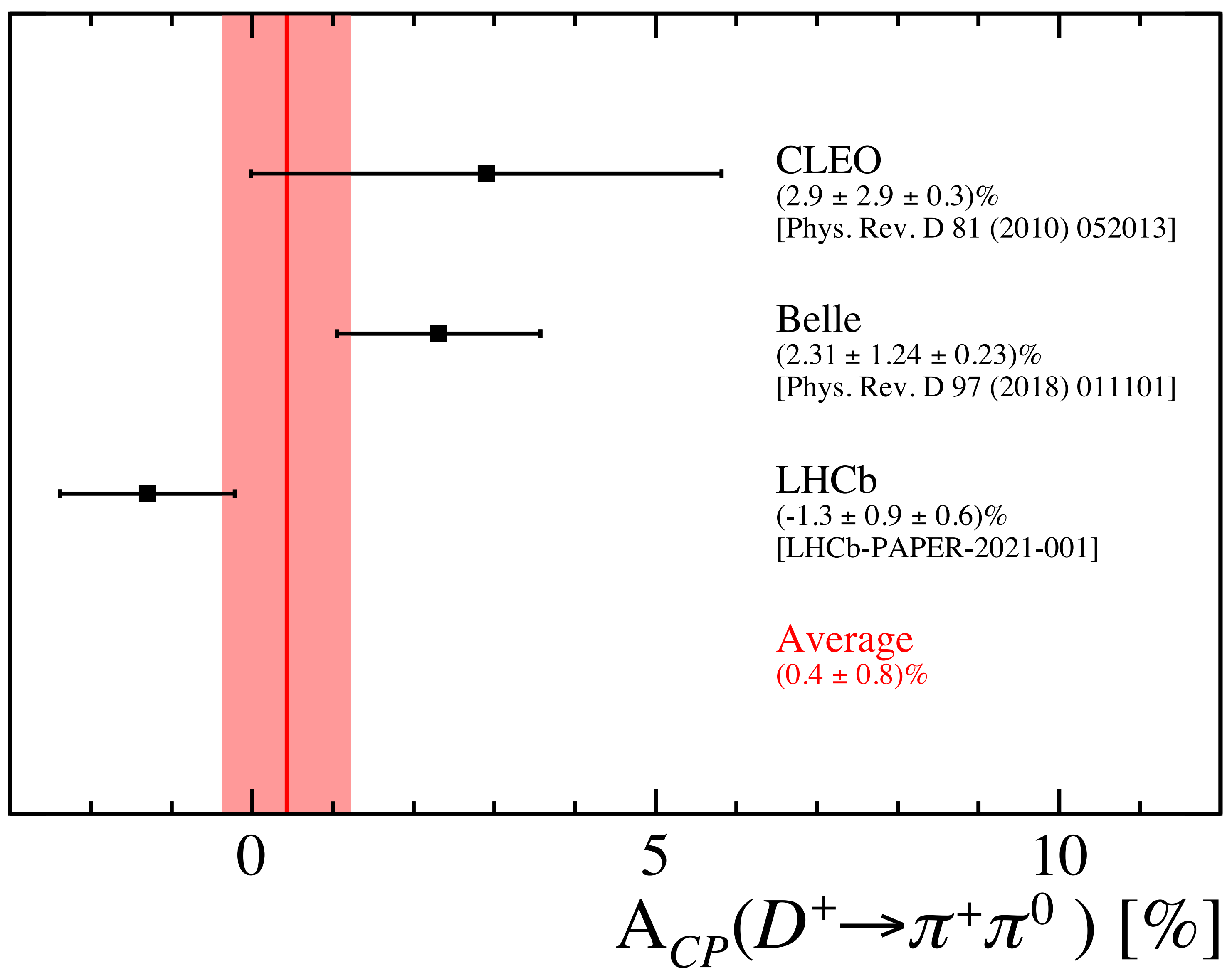


$A_{CP}(D^+_{(s)} \to h^+\pi^0, h^+\eta)$

- All compatible with *CP* symmetry
- First five results are the most precise measurements to date

JHEP 06 (2021) 019

$$\mathcal{A}_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%,$$
$$\mathcal{A}_{CP}(D^+ \to K^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%,$$
$$\mathcal{A}_{CP}(D^+ \to \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\%,$$
$$\mathcal{A}_{CP}(D^+ \to K^+\eta) = (-6 \pm 10 \pm 4)\%,$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%,$$
$$\mathcal{A}_{CP}(D_s^+ \to \pi^+\eta) = (0.8 \pm 0.7 \pm 0.5)\%,$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\eta) = (0.9 \pm 3.7 \pm 1.1)\%,$$



Indirect CP violation

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

arXiv:2105.09889

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

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

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

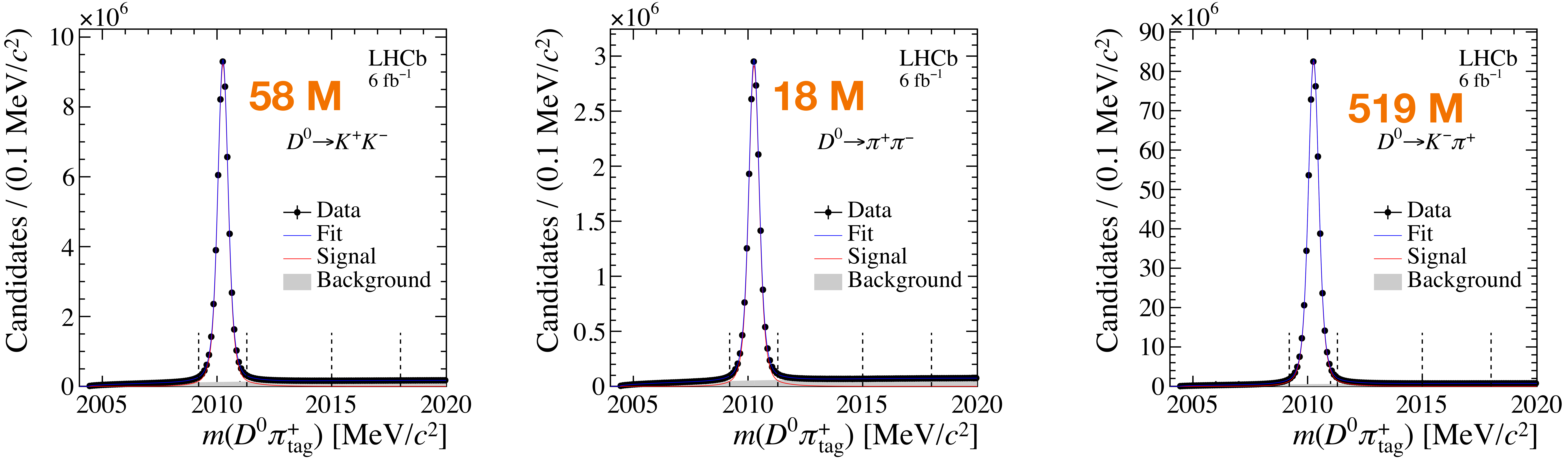
- SM expectation $\sim 2 \times 10^{-5}$ PRD 103 (2021) 053008, PLB 810 (2020) 135802
- Strategy: measure asymmetry in bins of D^0 decay time and measure the linear slope
- Selection induces correlations between kinematics and decay time ➡ possible time-dependent nuisance asymmetries are removed by equalising 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 $D^0 \to \pi^+\pi^-$

arXiv:2105.09889

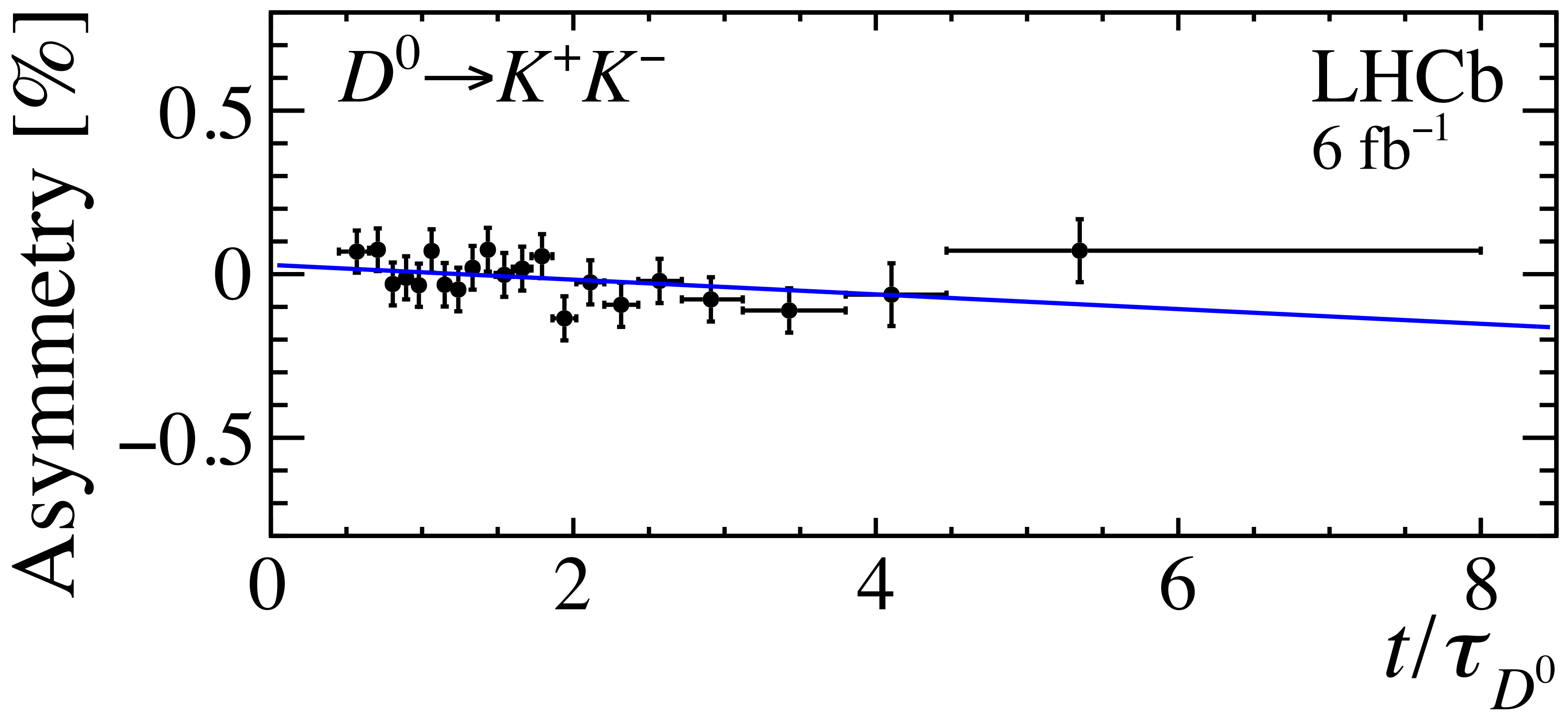
- Combinatorial background removed with sideband subtraction in $m(D^0\pi^+)$ in each decay time

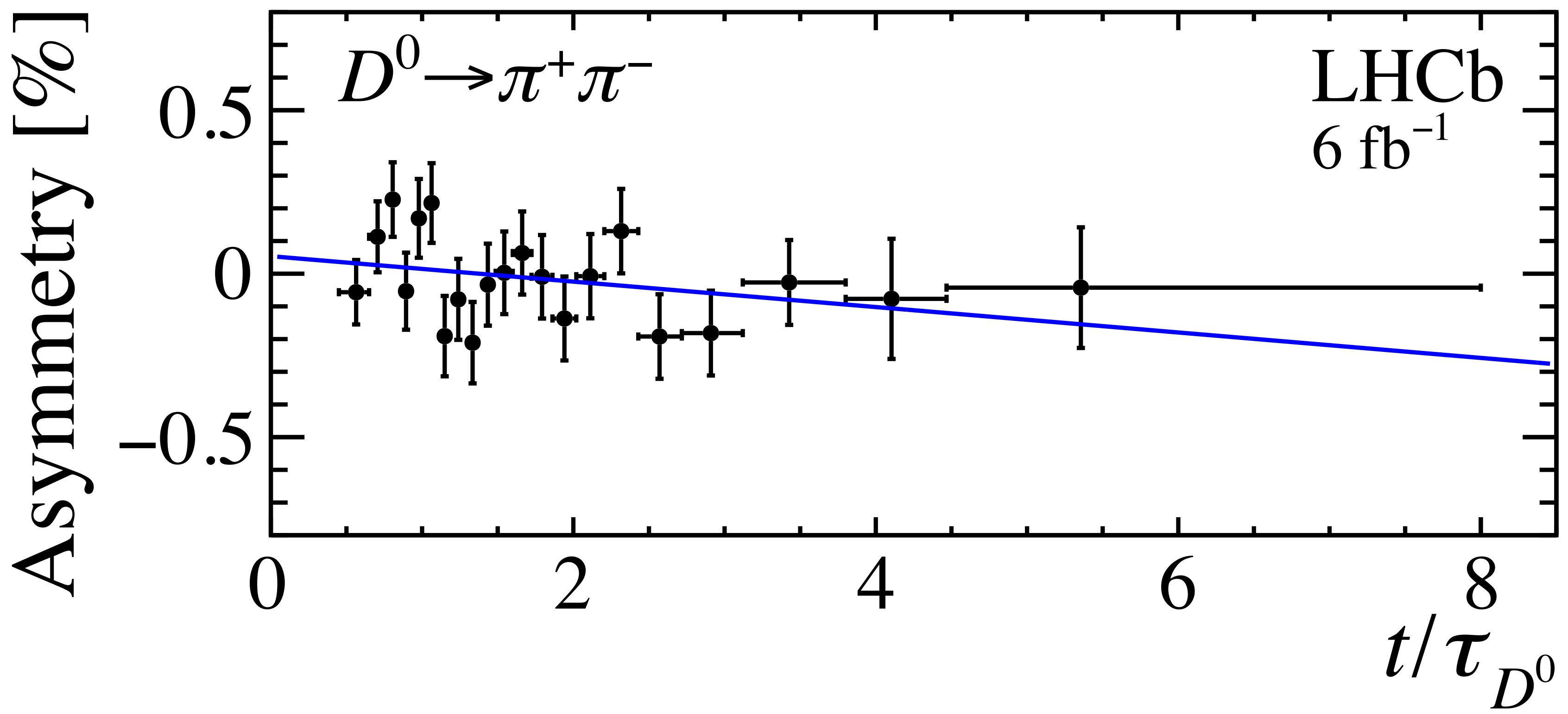
- A correction is applied for contamination of secondary D^0 by measuring their size and asymmetry with a multidimensional fit on (IP, t)



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

arXiv:2105.09889





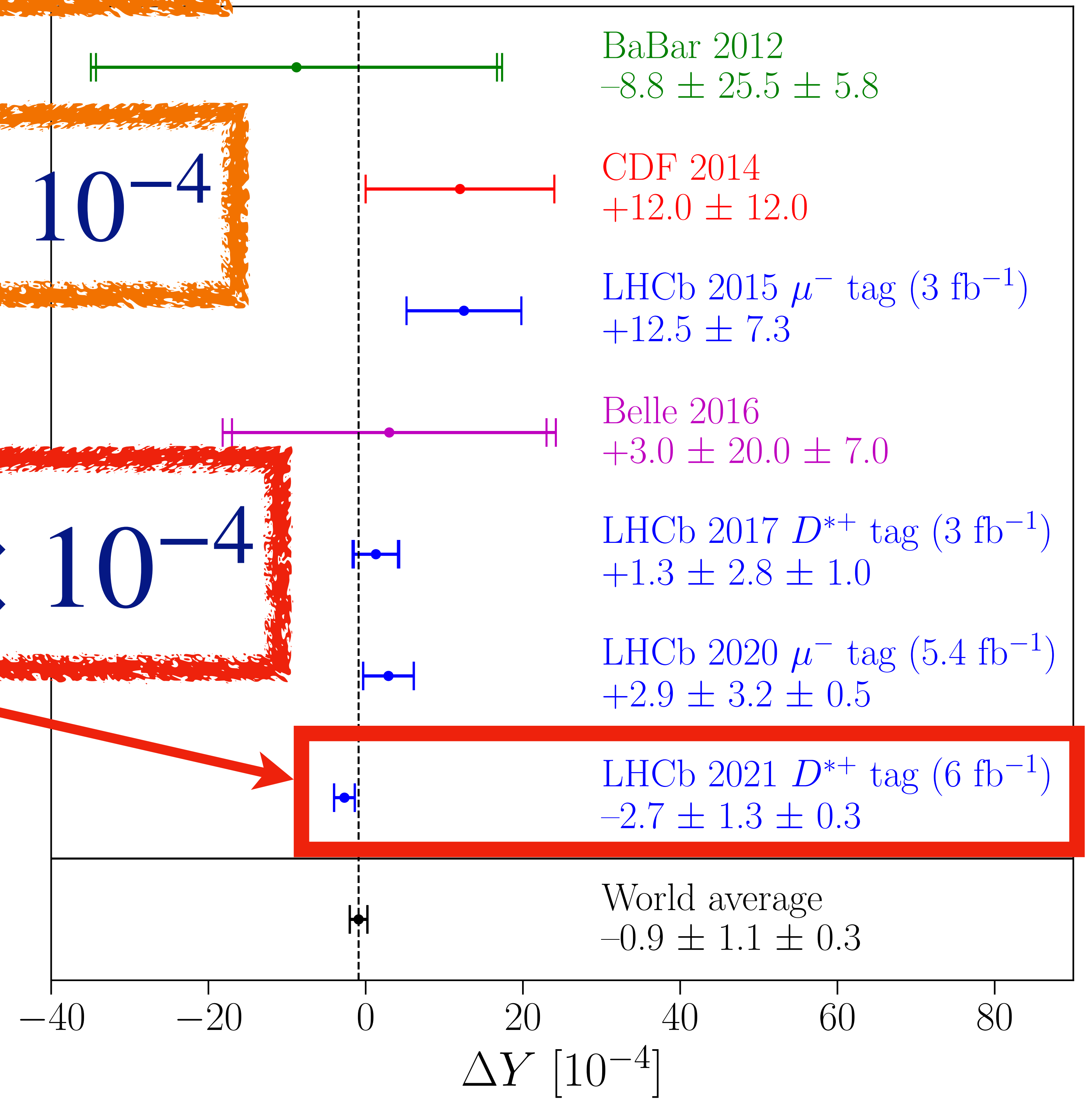
$$\Delta Y_{K^-\pi^+} = (-0.4 \pm 0.5 \pm 0.2) \times 10^{-4}$$

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

D^0 mixing parameters with $D^0 \to K_s^0 \pi^+ \pi^-$

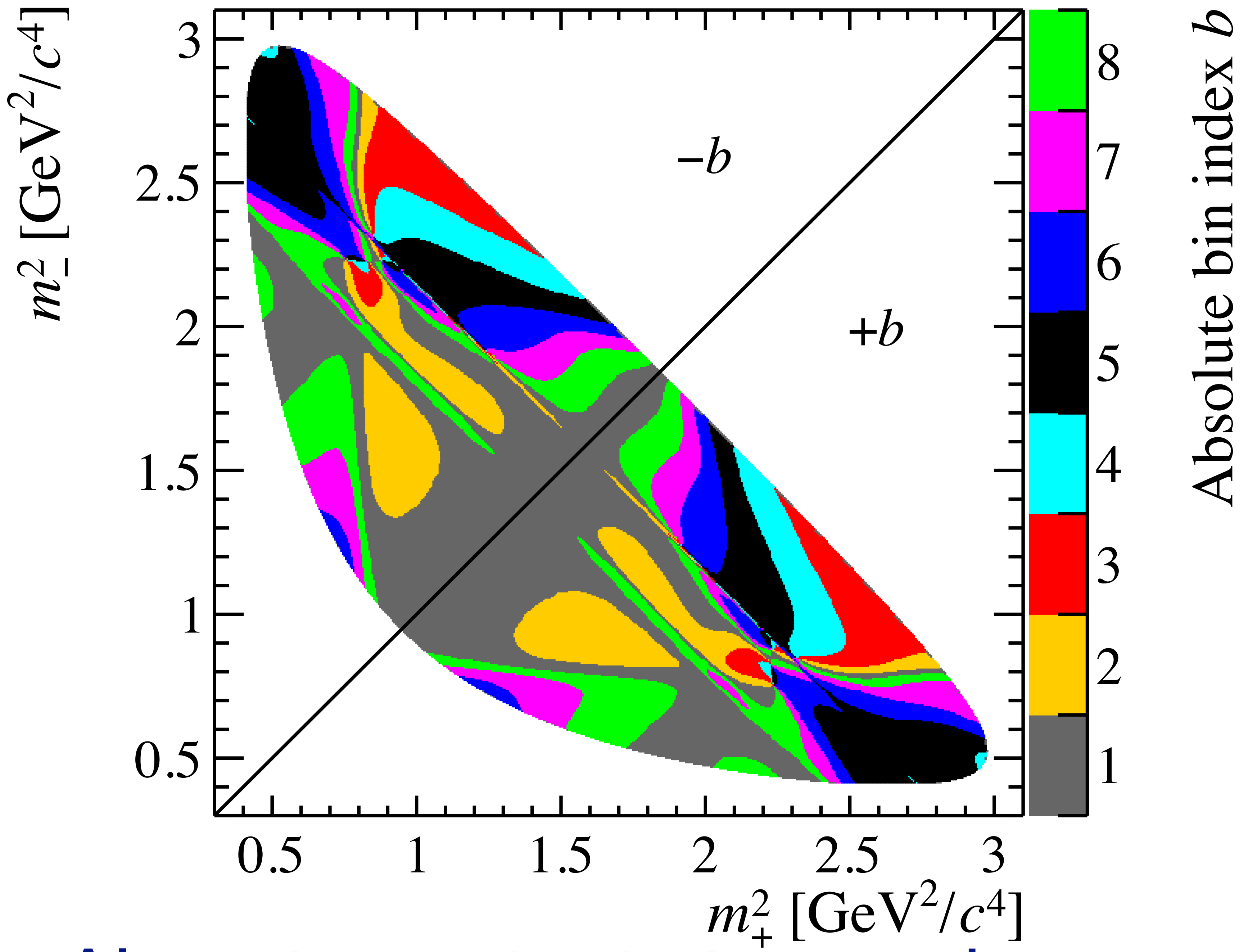
- $D^0 \to K_s^0 \pi^+ \pi^-$ is particularly sensitive to x arXiv:2106.03744

PRD 99 (2019) 012007

- Analysis performed with model-independent *bin-flip* method, which does not require accurate modelling of the efficiency

- 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

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



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

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

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

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

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

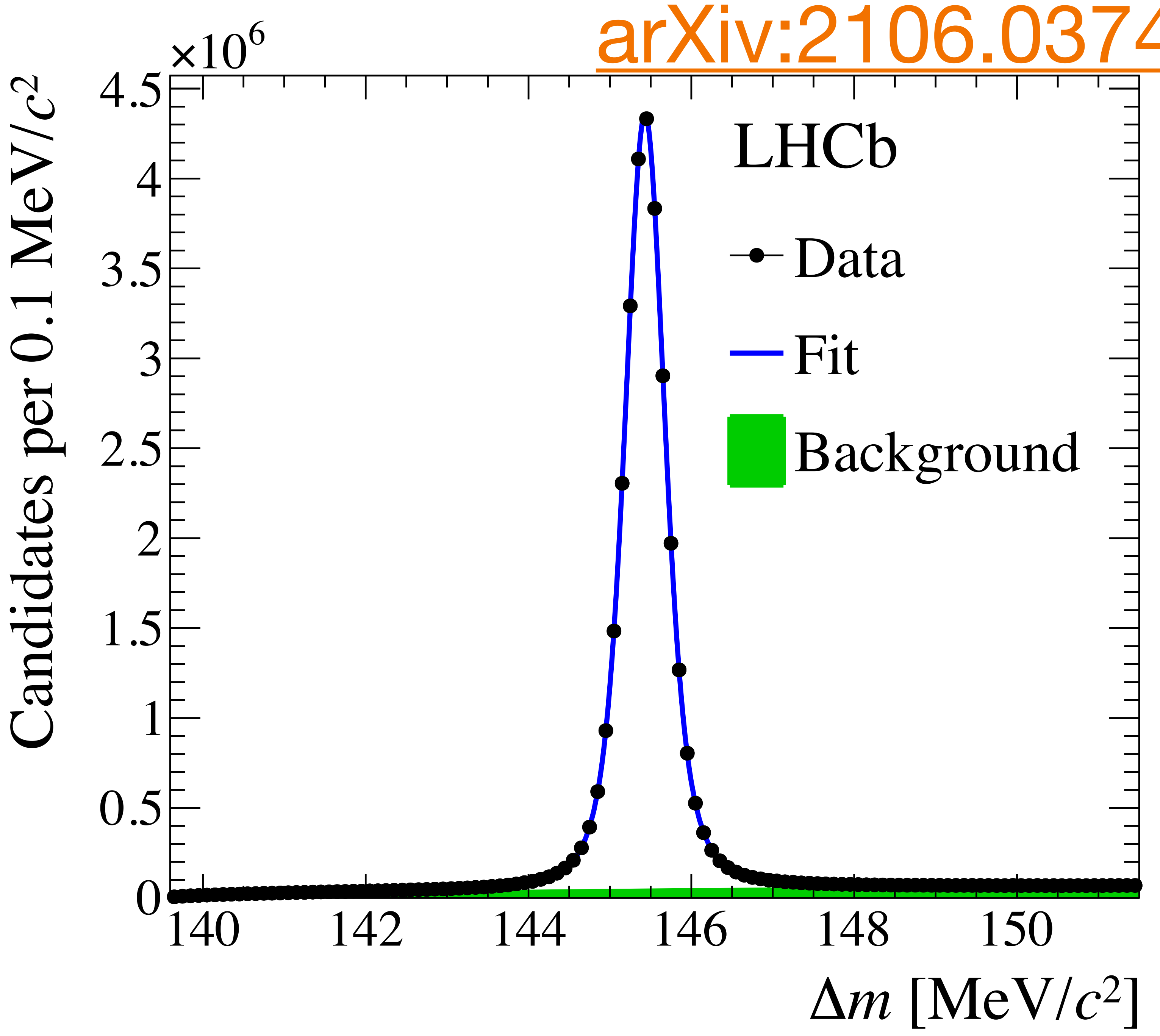
PRD 82 (2010) 112006

PRD 101 (2020) 112002

D^0 mixing parameters with $D^0 \to K_s^0\pi^+\pi^-$

arXiv:2106.03744

- In each of the 2 (flavour) x 16 (Dalitz bin) x 13 (decay time bin) subsamples, a fit is performed to $\Delta m = m(D^{*+}) - m(D^0)$ to obtain the yield ➡ 31 M signal decays in total



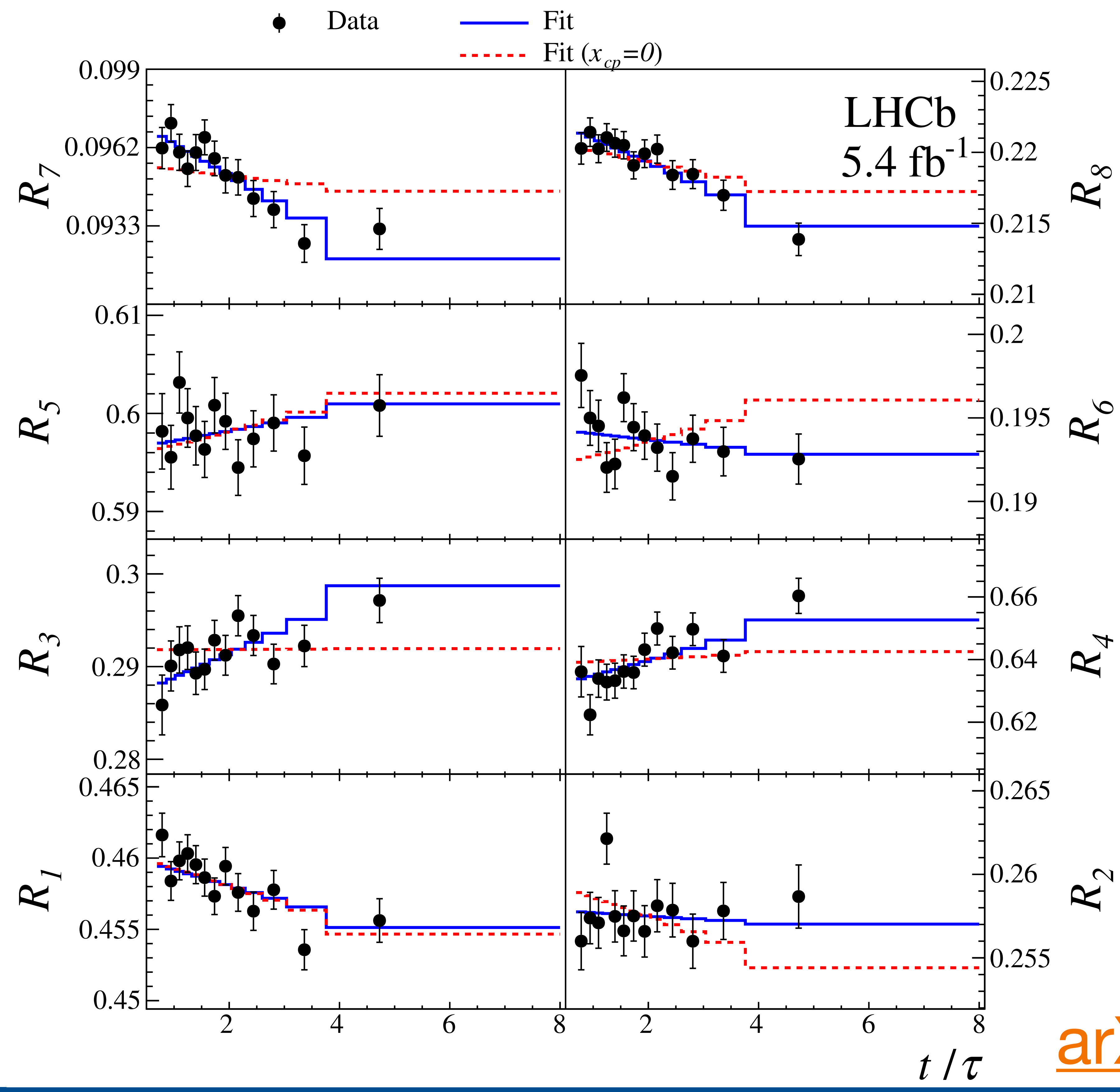
- Signal selection induces correlation between decay time and phase-space that could bias the measurement ➡ a data-driven correction is applied to make the decay-time acceptance uniform in the phase space

- Correction is applied for residual detection asymmetry of pions, calculated from the difference of raw asymmetries of calibration samples $D_s^+ \to \pi^+\pi^+\pi^-$ and $D_s^+ \to \phi\pi^+$

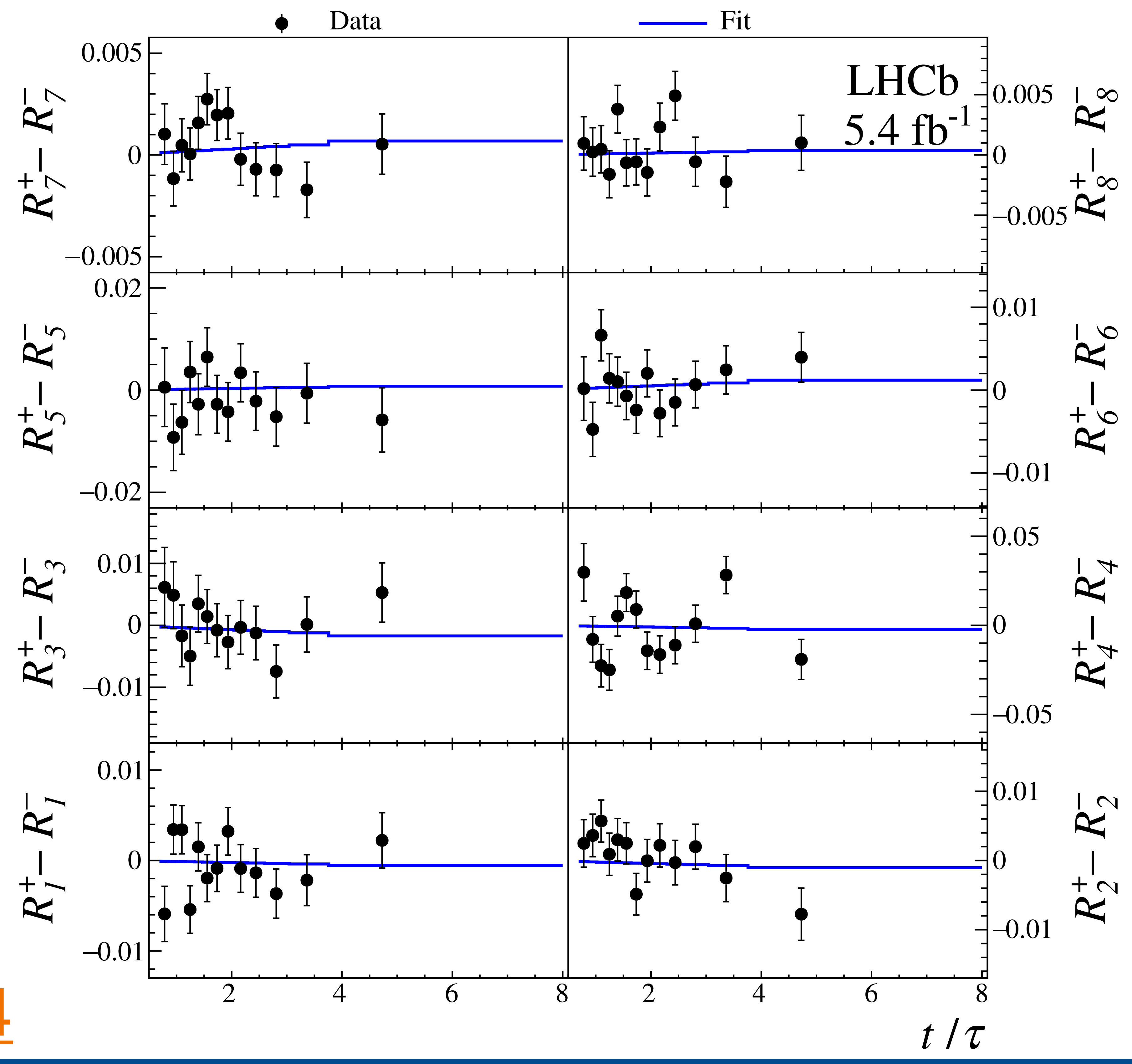
$$A_{\text{meas}}(D_s^+ \to \pi^+\pi^+\pi^-) = A_{\text{det}}(\pi^+\pi^-) + A_{\text{det}}(\pi^+) + A_{\text{prod}}(D_s^+) + A_{\text{trigger}}(D_s^+)$$
$$A_{\text{meas}}(D_s^+ \to \phi\pi^+) = A_{\text{det}}(\pi^+) + A_{\text{prod}}(D_s^+) + A_{\text{trigger}}(D_s^+)$$

D^0 mixing parameters with $D^0 \to K_s^0\pi^+\pi^-$

- 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



arXiv:2106.03744

D^0 mixing parameters with $D^0 \to K_s^0\pi^+\pi^-$

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

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

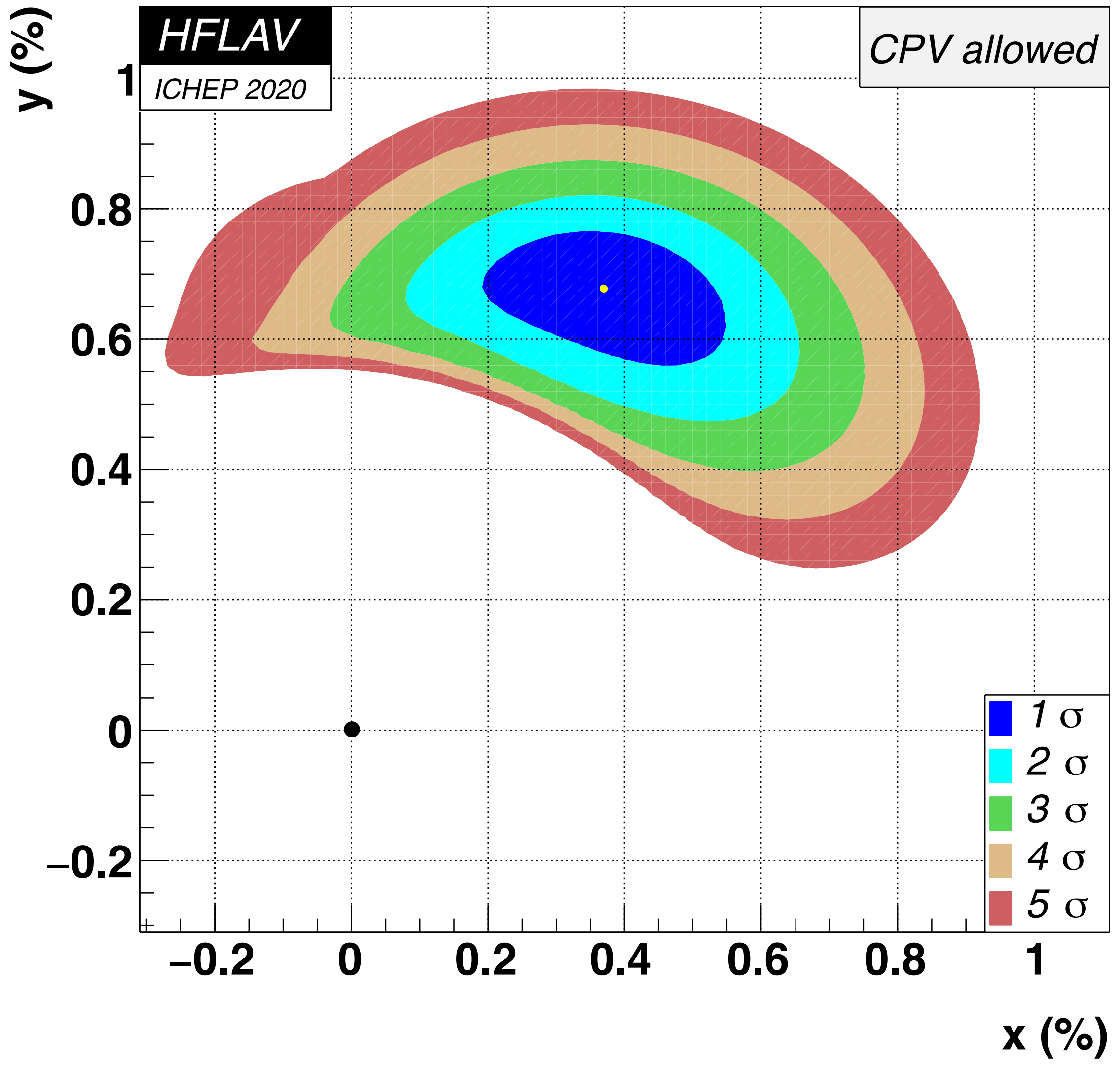
First observation with a significance of more than 7 standard deviations of the mass difference between D^0 mass eigenstates

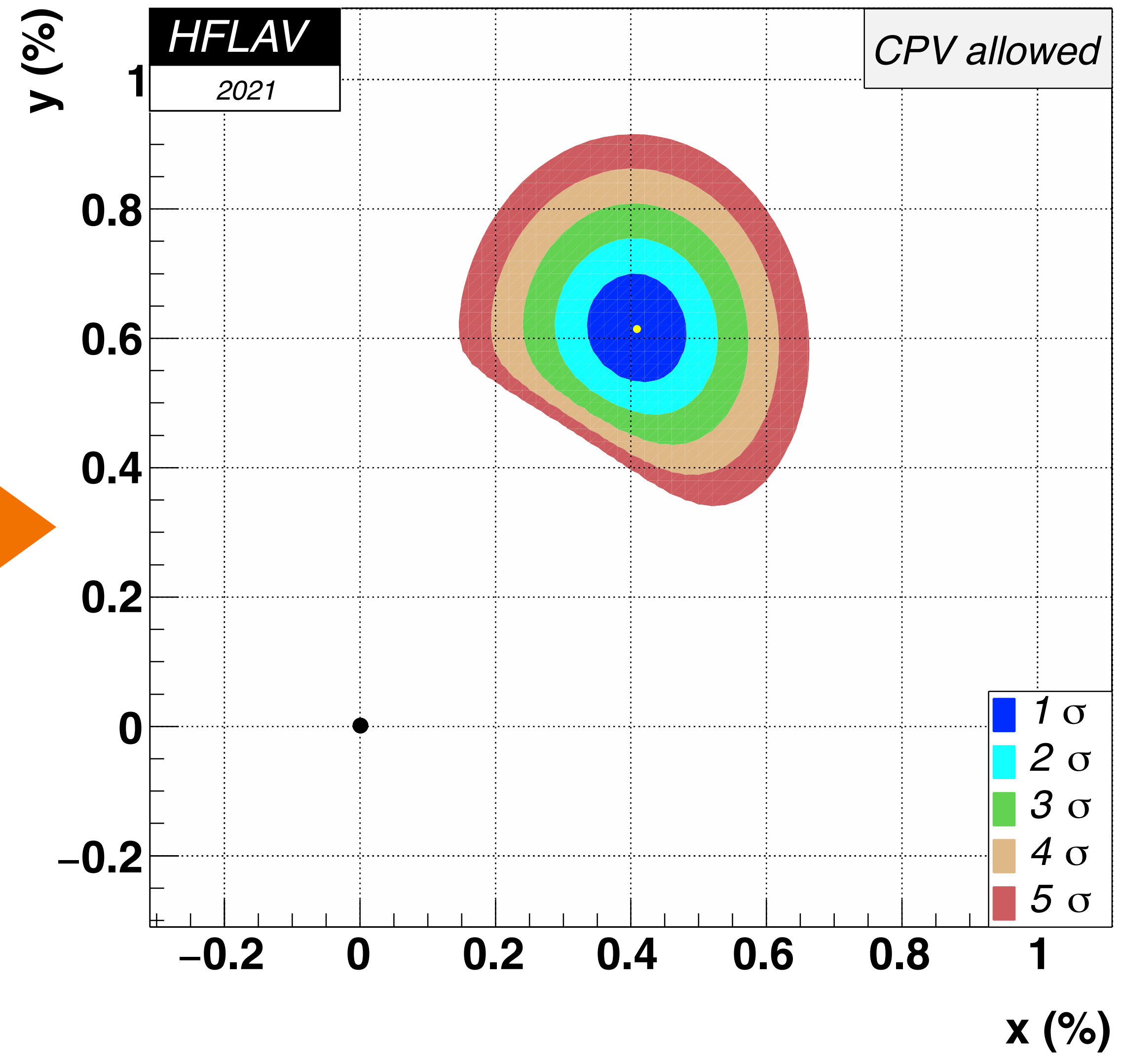
arXiv:2106.03744

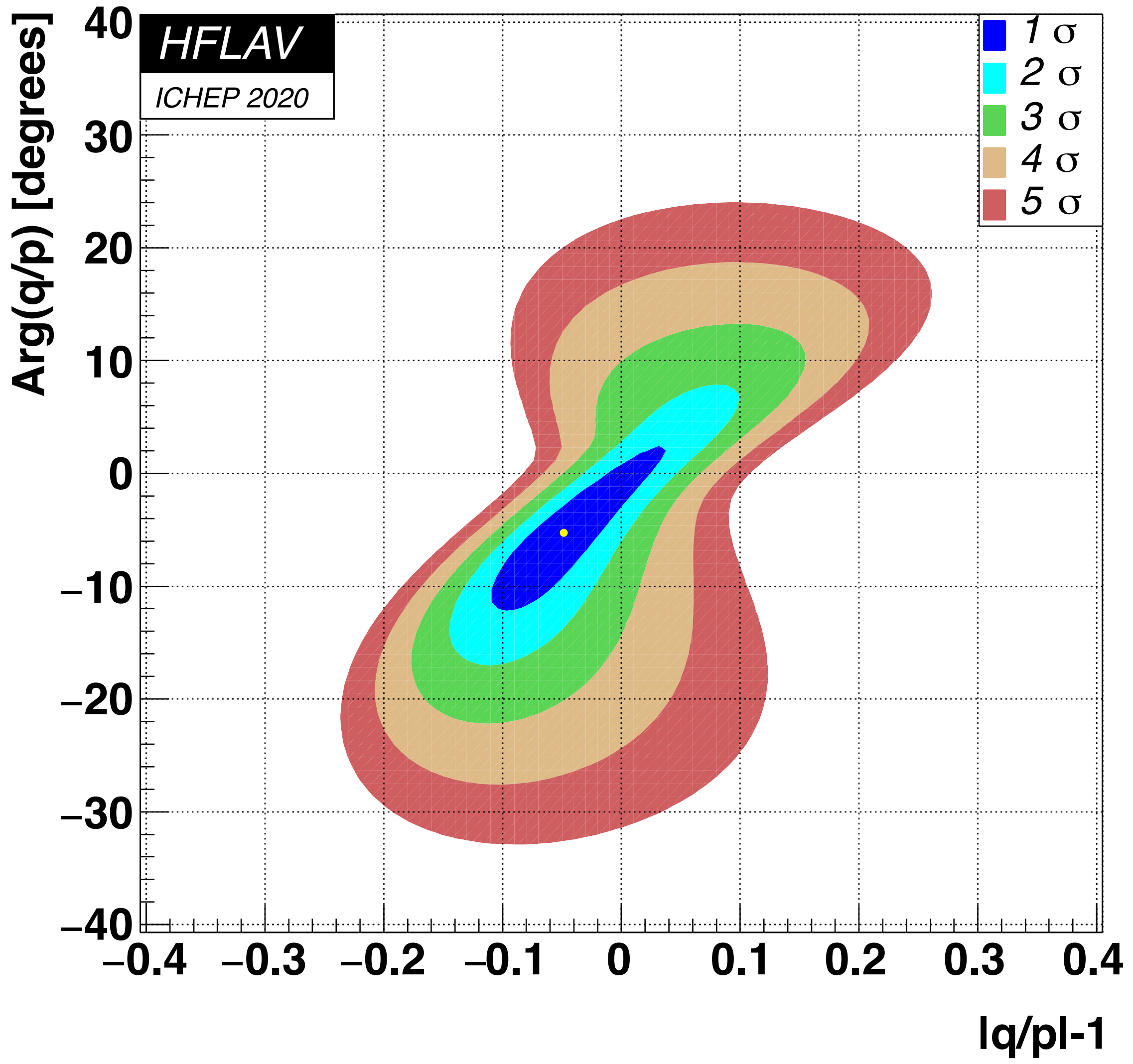
New world averages

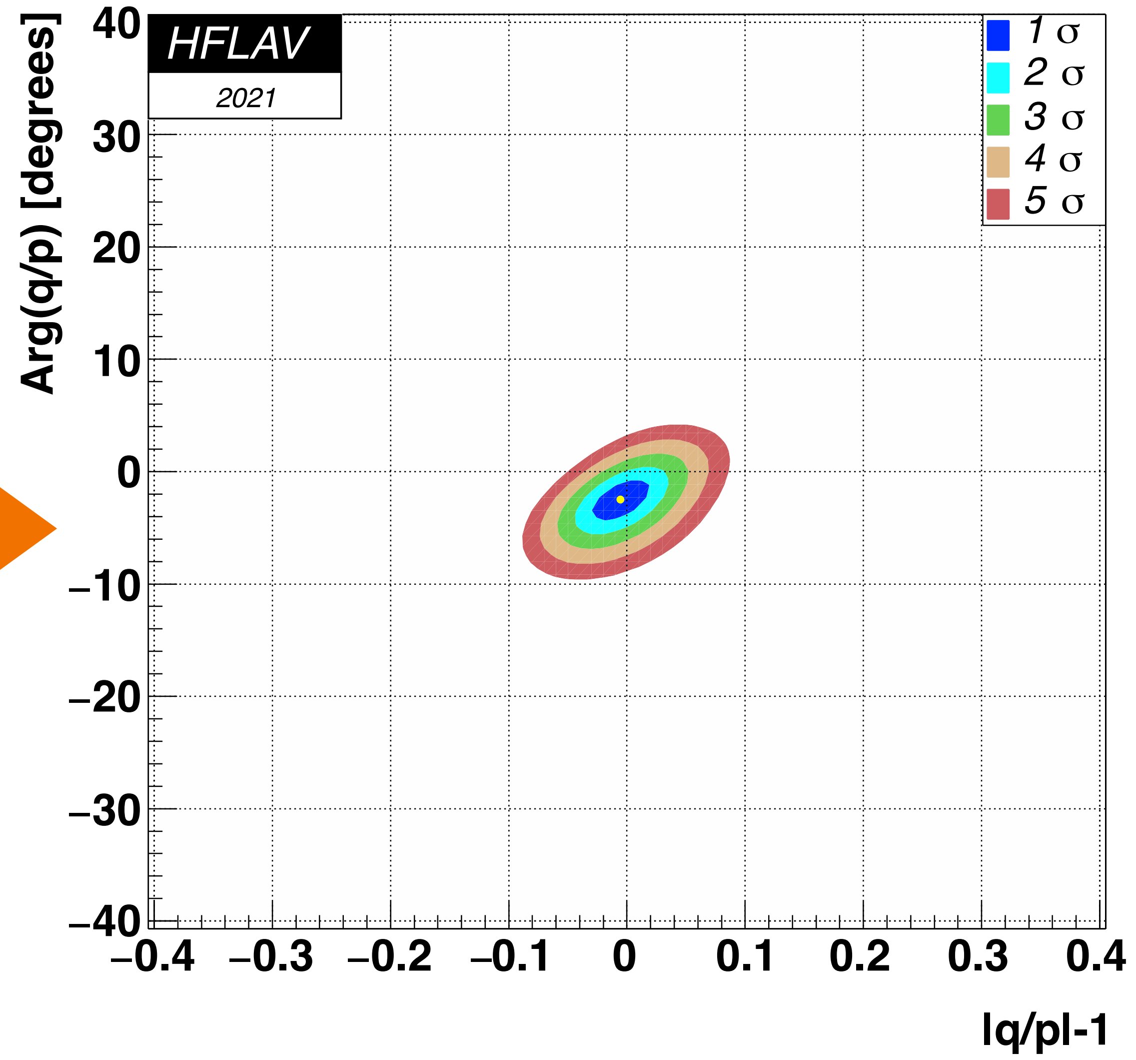
Phenomenological parametrisation

Great improvement on the knowledge of x and q/p









HFLAV Eur. Phys. J. C (2021) 81 226
Recently updated

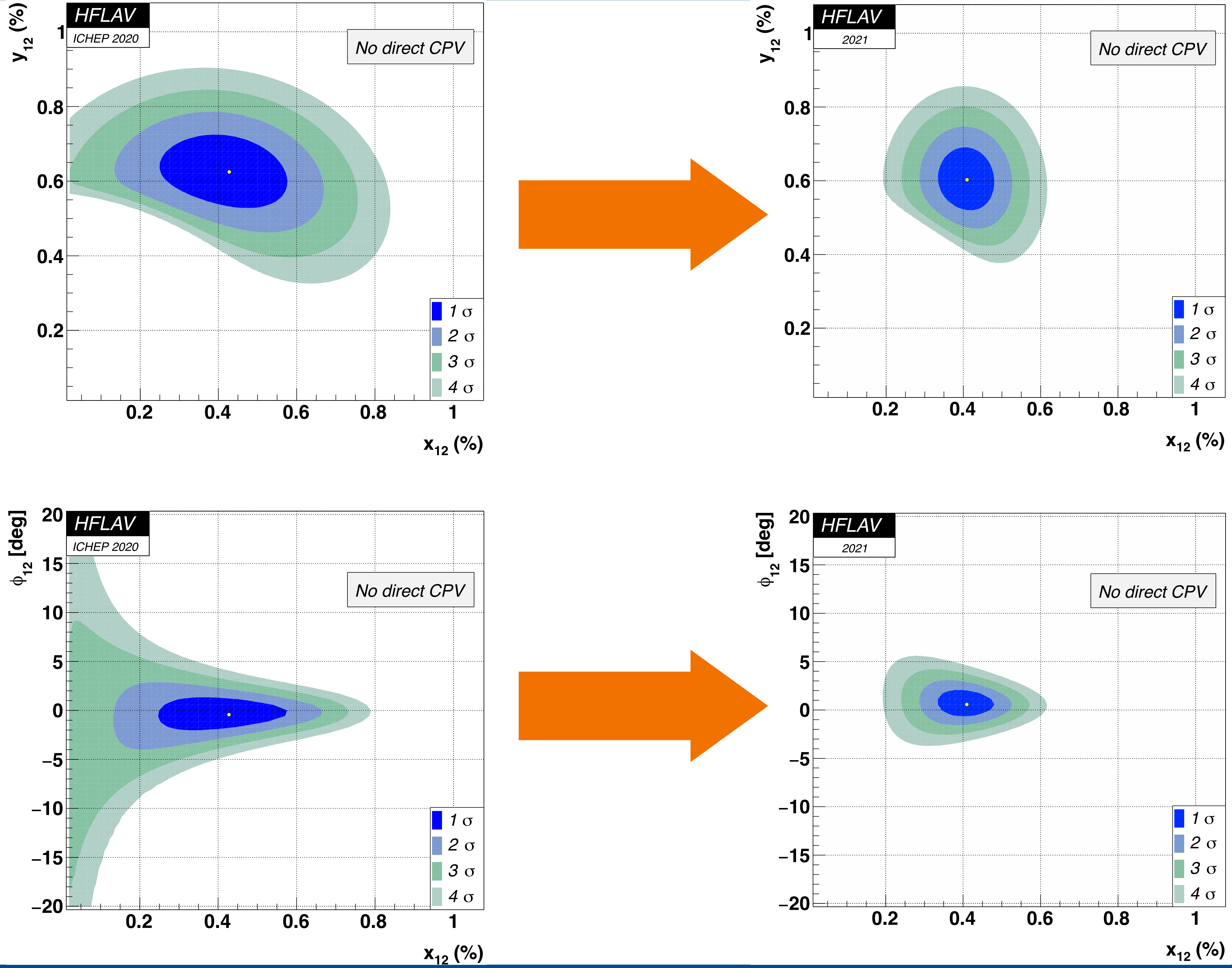
New world averages

Theoretical parametrisation

Bounds on the phase of the dispersive $\mathcal{CP}$-violating contributions to D^0 mixing are tightened

HFLAV Eur. Phys. J. C (2021) 81 226
Recently updated

See talk by Mark to see how precision further improves when including beauty observables!



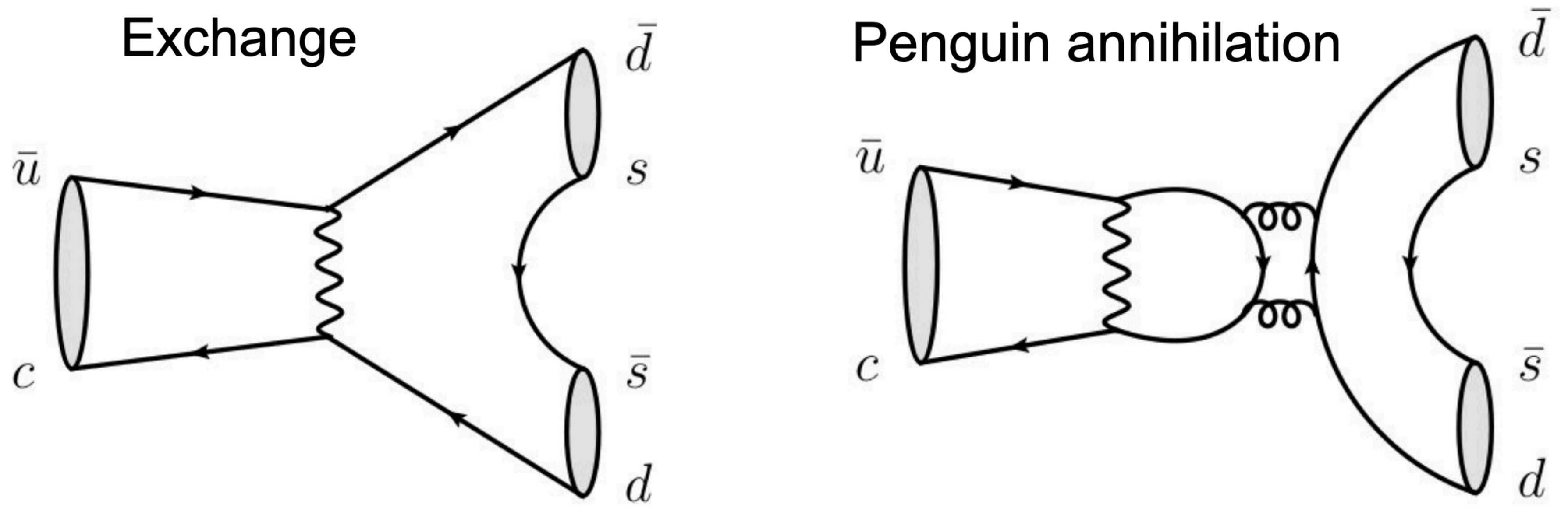
Future prospects and conclusions

Conclusions

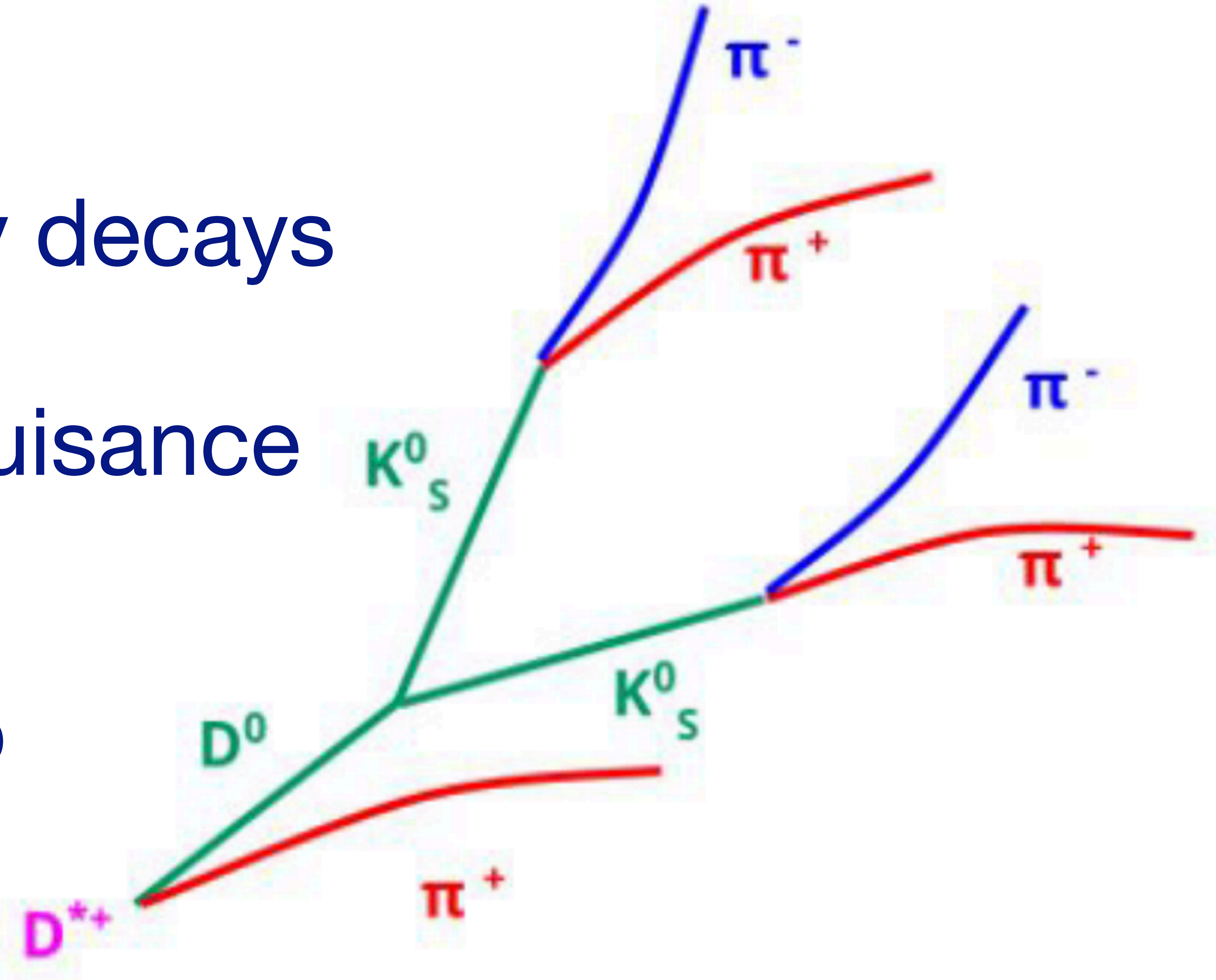
- Most precise determination of $A_{CP}(D^0 \to K_s^0 K_s^0)$ and measured $A_{CP}(D^+_{(s)} \to h^+\pi^0, h^+\eta)$ with an uncertainty of $\mathcal{O}(10^{-2})$
- Observation of a nonzero difference between D^0 mass eigenstates ➡ more than 7 standard deviations of significance
- Most precise measurement of time-dependent CP asymmetry in D^0 decays, improving by nearly a factor 2 the precision of the world average of ΔY
- Soon new measurements with Run 2 data - stay tuned
- The statistical uncertainty of many CP violating observables in charm will be reduced by ~1 order of magnitude with the LHCb Upgrade I and II

Backup

$A_{CP}(D^0 \to K_s^0 K_s^0)$



- A_{CP} expected to be as large as ~1% PRD 92 (2015) 054036
- K_s^0 challenging ➡ need to consider separately K_s^0 reconstructed from long pions (L) and downstream pions (D)
- Consider D^{*+} produced both in prompt and secondary decays
- $D^0 \to K^+K^-$ used as a calibration sample to cancel nuisance detection and production asymmetries
- Raw asymmetry obtained from a multidimensional fit to $\Delta m = m(D^{*+}) - m(D^0)$ and $m(K_s^0)$



arXiv:2105.01565

$A_{CP}(D^0 \to K^0_s K^0_s)$

Sample	2015 + 2016 (2 fb^{-1}) Yield	$\mathcal{A}^{CP}$ [%]	2017 + 2018 (4 fb^{-1}) 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	$-35 \pm 47 \pm 6$

Systematic uncertainties for:

- Residual background in $D^0 \to K^+K^-$
- Fit model
- Difference in secondaries fraction between signal and calibration

arXiv:2105.01565

$A_{CP}(D^+_{(s)} \to h^+\pi^0, h^+\eta)$

- In the SM, $A_{CP} \sim 10^{-3} - 10^{-4}$ for SCS $D_s^+ \to K^+\pi^0$, $D_s^+ \to K^+\eta$ and $D^+ \to \pi^+\eta$, and $A_{CP}(D^+ \to \pi^+\pi^0) = 0$ PRD 85 (2012) 034036
- h^0 reconstructed in $\gamma(\to e^+e^-)\gamma$ or $e^+e^-\gamma$ final states to reconstruct the secondary vertex
  ➡ useful to suppress background from pp
- Raw asymmetry obtained from multidimensional fit to $m(e^+e^-\gamma)$ and $m(h^+h^0)$
- $D^+_{(s)} \to K^0_s h^+$ used as a calibration sample to cancel nuisance detection and production asymmetries

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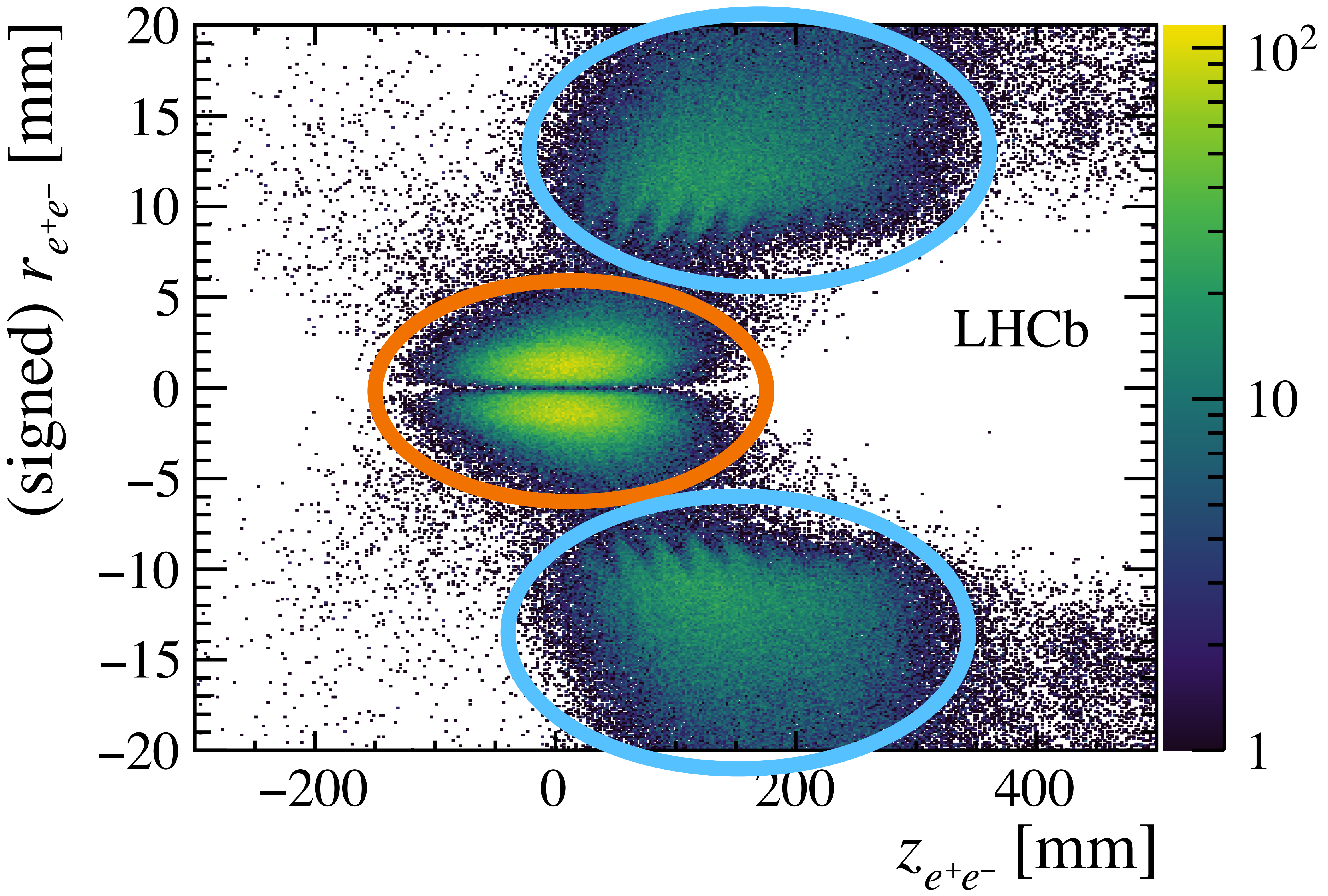

$A_{CP}(D^+_{(s)} \to h^+\pi^0, h^+\eta)$

Systematic uncertainties

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Source	$D^+ \to \pi^+\pi^0$	$D^+ \to K^+\pi^0$	$D^+_s \to K^+\pi^0$
Fit model	0.59	1.55	1.01
PID asymmetry	0.06	0.27	0.15
Secondary decays	< 0.01	0.01	0.02
Combined A_{Raw} Run 1 and Run 2	0.23	0.65	0.30
Control modes	0.03	1.18	0.59
$A_{\mathrm{Mix}}(K^0)$	< 0.01	< 0.01	< 0.01
$\mathcal{A}_{CP}(D^+_{(s)} \to K^0_S h^+)$	0.12	0.08	0.26
Total	0.65	2.07	1.24

Source	$D^+ \to \pi^+\eta$	$D^+_s \to \pi^+\eta$	$D^+ \to K^+\eta$	$D^+_s \to K^+\eta$
Fit model	0.35	0.15	4.04	1.08
PID asymmetry	0.06	0.01	0.87	0.16
Secondary decays	< 0.01	0.02	0.01	0.04
Control modes	0.05	0.39	0.14	0.12
$A_{\mathrm{Mix}}(K^0)$	< 0.01	< 0.01	< 0.01	< 0.01
$\mathcal{A}_{CP}(D^+_{(s)} \to K^0_S h^+)$	0.12	0.20	0.08	0.26
Total	0.38	0.46	4.13	1.13

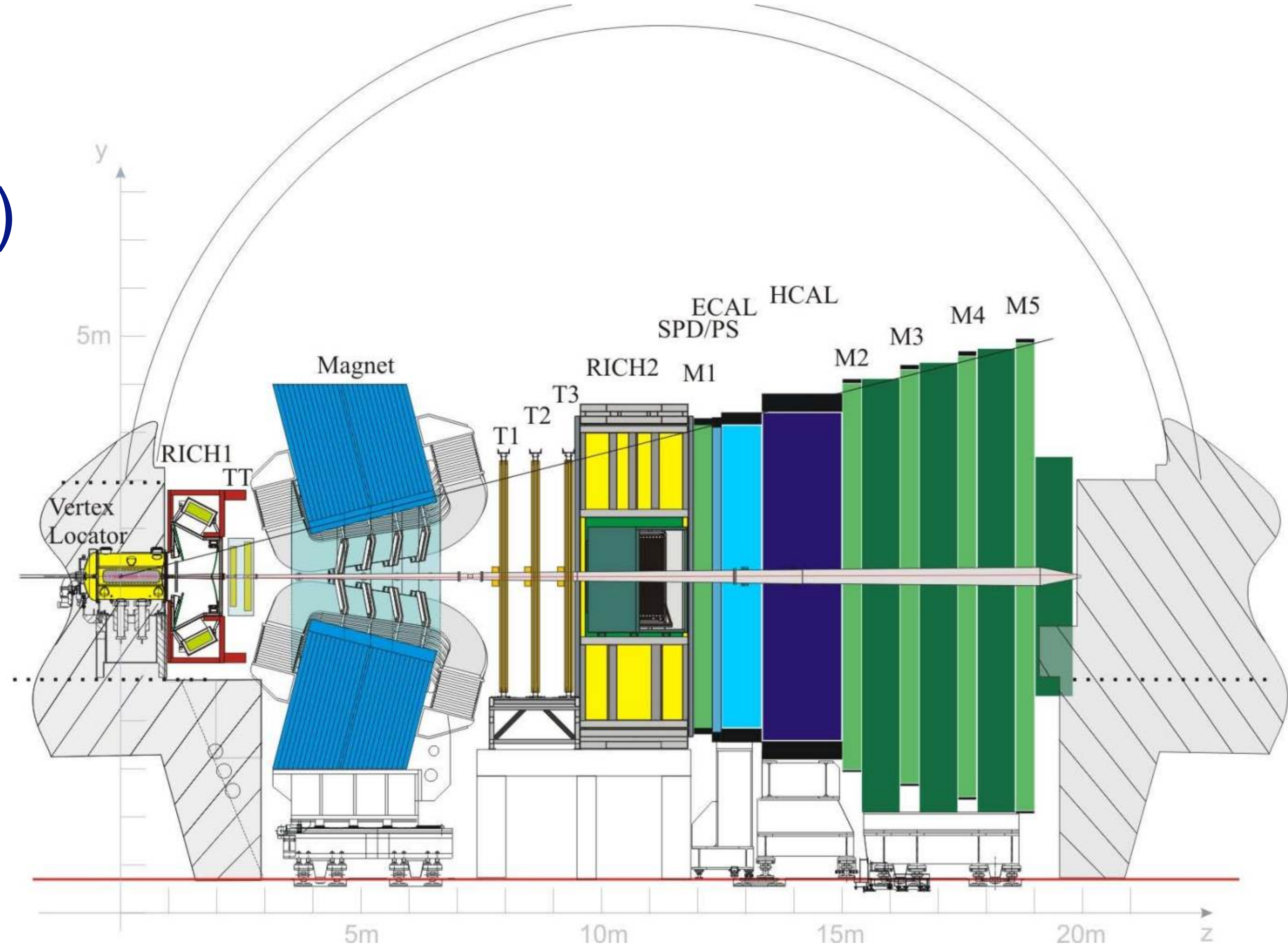
Charm at LHCb

- Large $c\bar{c}$ production cross section
  $\sigma(pp \to c\bar{c}X)_{\sqrt{s}=13\ \text{TeV}} = (2369 \pm 3 \pm 152 \pm 118)\ \mu\text{b}$

JHEP 05 (2017) 074

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

- 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%)



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

arXiv:2105.09889

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

arXiv:2105.09889

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

D^0 mixing parameters with $D^0 \to K_s^0 \pi^+ \pi^-$

arXiv:2106.03744

Systematic uncertainties (in units of 10^{-3})

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

Future prospects

- Some key measurements still to be performed with Run 2 data, such as:
  - $A_{CP}(D^0 \to K^+K^-)$ ➡ expected uncertainty 7×10^{-4}
  - $y_{CP}(D^0 \to h^+h^-)$
- With Upgrade I and II, LHCb will be able to reduce the statistical uncertainty of the CP violating observables in charm by ~ 1 order of magnitude
- No systematic uncertainties are known to have irreducible contributions which exceed the ultimate statistical precision
  ➡ strong potential of probing SM and characterise new physics contributions to CP violation in the charm sector with future upgrades

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

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°

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$$\Delta Y$$

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 %