Overview of $\mathcal{CP}$ violation in charm-hadron decays

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THE UNIVERSITY of EDINBURGH

UK Research and Innovation

Outline

- Experimental techniques to study CPV in charm
- Latest results
- Future prospects

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

$C\!P$ violation in charm

- Due to smallness of involved CKM elements and GIM mechanism, $C\!P$ violation in charm decays predicted to be small: $A_{C\!P} \sim 10^{-4} - 10^{-3}$

- SM predictions difficult to calculate because of nonperturbative QCD effects

- First observation by LHCb in 2019:

$$\Delta A_{C\!P} = A_{C\!P}(D^0 \to K^-K^+) - A_{C\!P}(D^0 \to \pi^-\pi^+) = (-15.4 \pm 2.9) \times 10^{-4}$$ PRL 122 (2019) 211803

- Further measurements and theoretical improvements are needed to understand if measured $\Delta A_{C\!P}$ is consistent with SM or is affected by new physics

Experimental techniques

Charming experiments

B factories:

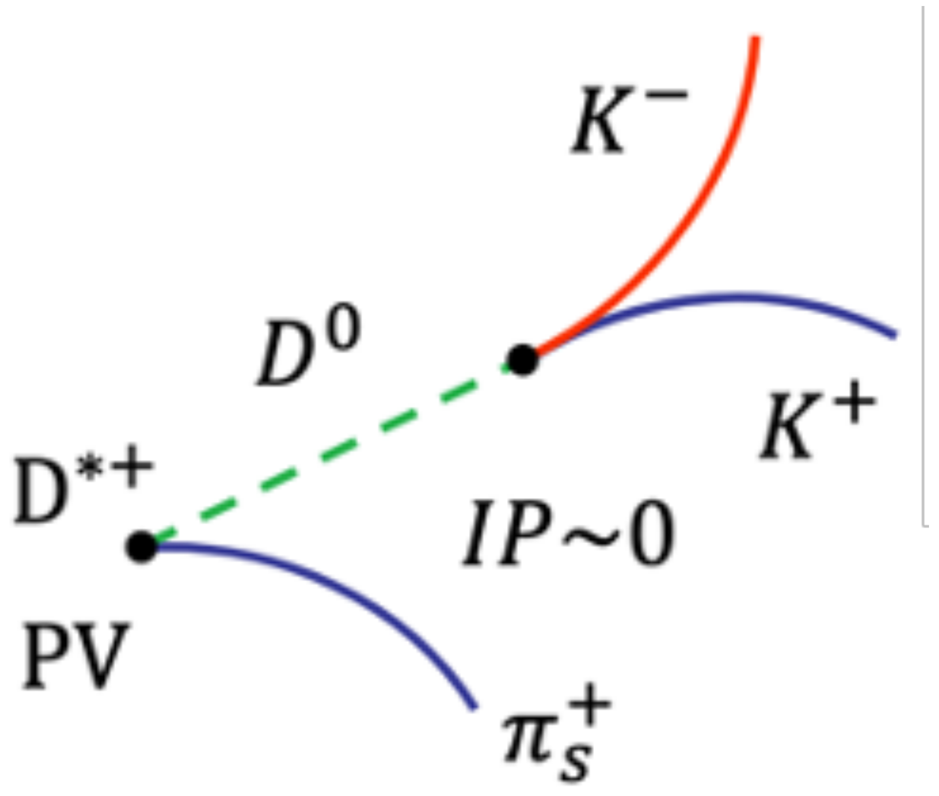
- high efficiency
- clean environment and good reconstruction of neutrals

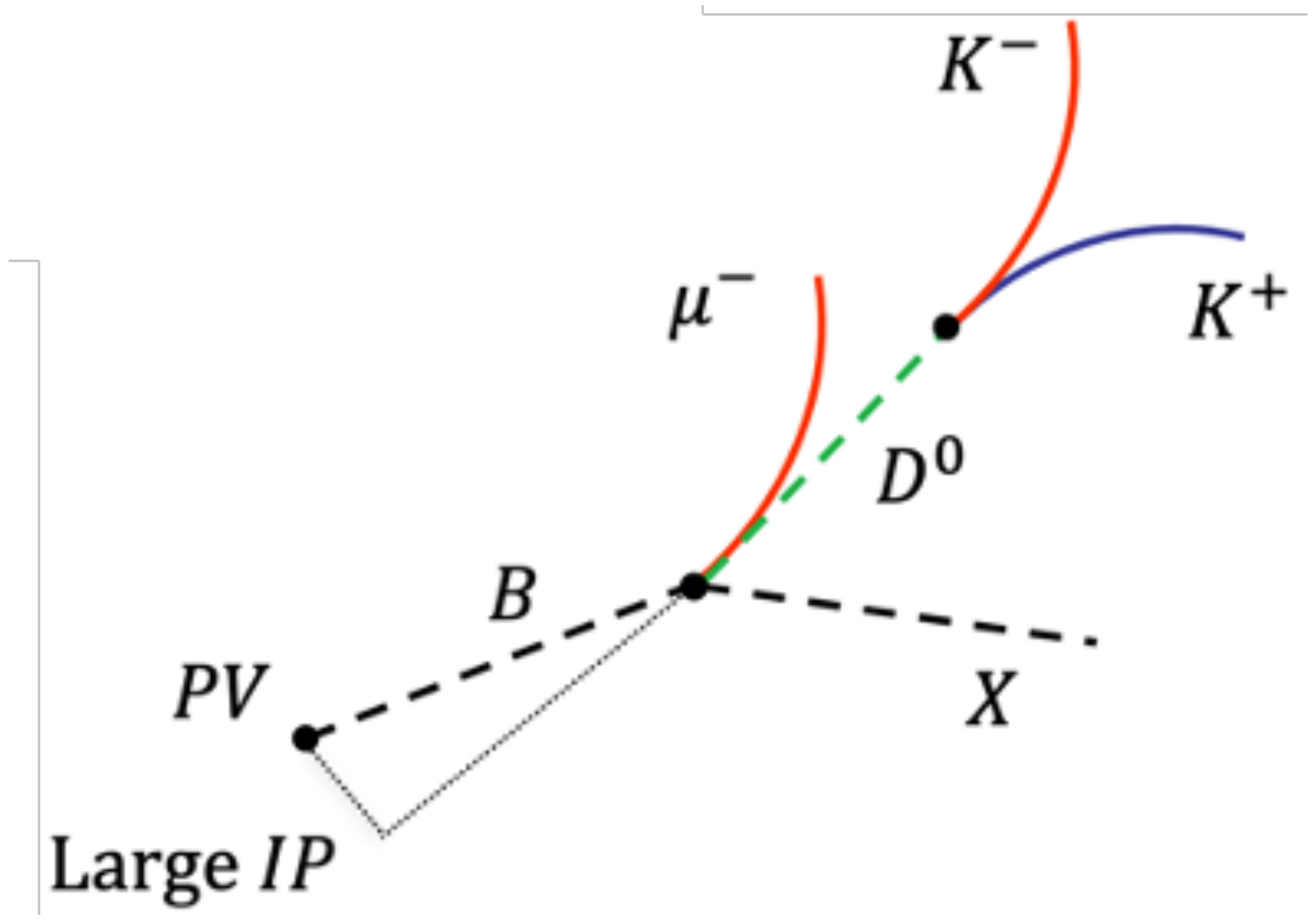
Detectors at hadron machines:

- huge cross section
- need dedicated trigger

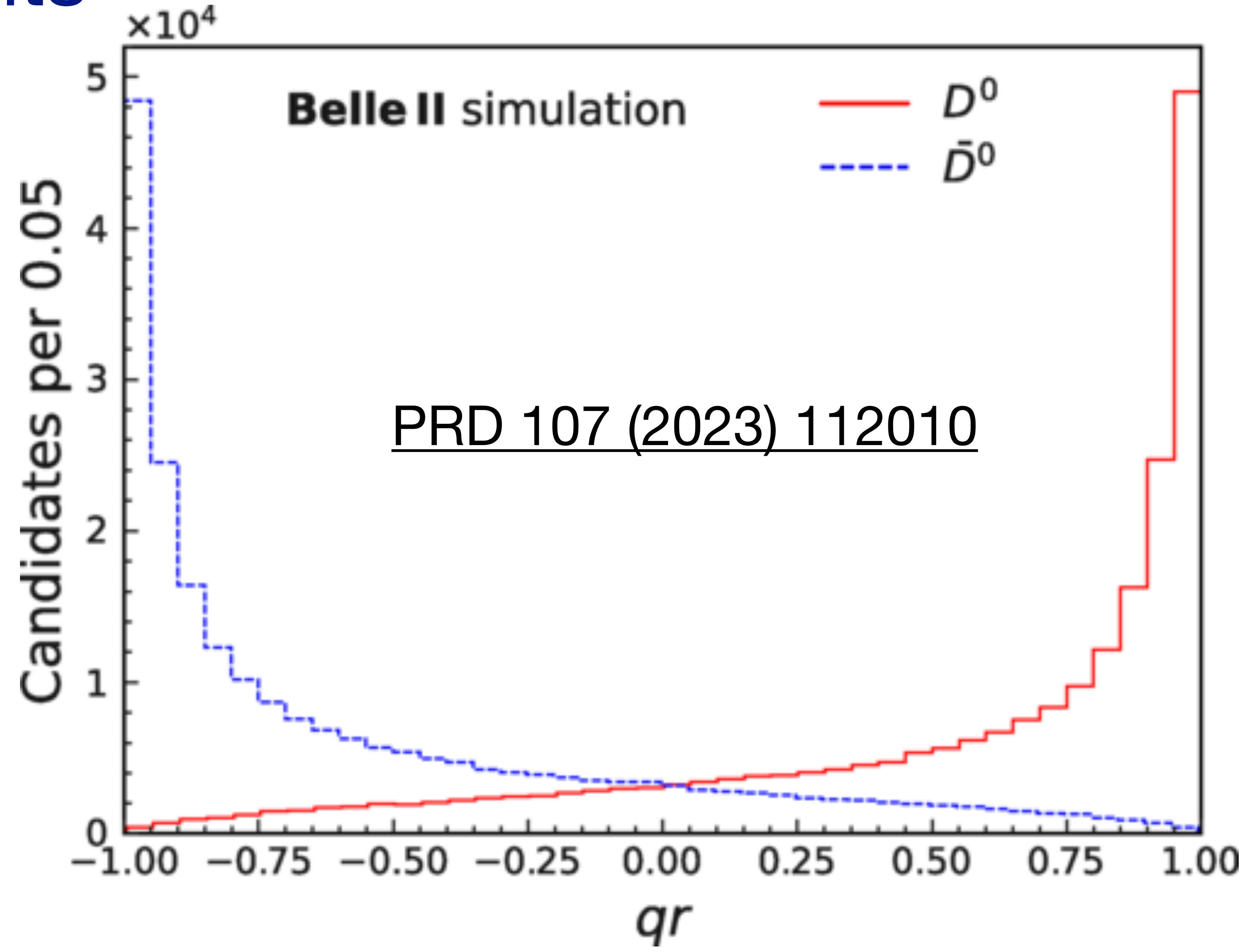
D^0 flavour tag

- Look at the charge of the accompanying particle in the decay
  - prompt tag: $D^{*\pm} \to D^0\pi^\pm$
  - semileptonic tag: $B \to D^0\mu^\pm X$





- New Charm Flavour Tagger in Belle II:
  - based on BDT
  - $\epsilon_{\rm tag}^{\rm eff} = (47.91 \pm 0.07 \pm 0.51)\,\%$
  - double size with respect to D^{*+}-tagged events



Nuisance asymmetries

up to $\mathcal{O}(10^{-6})$

$$A_{\text{raw}}(D^{*+} \to D^0(\to h^-h^+)\pi^+) \simeq A_{CP}(D^0 \to h^-h^+) + A_{\text{P}}(D^{*+}) + A_{\text{D}}(\pi^+)$$

- Production asymmetry of D^{*+} in pp collisions (LHCb)
- Forward-backward asymmetry in $e^+e^- \to c\bar{c}$ due to $\gamma - Z^0$ interference and higher-order QED effects (Belle/Belle II)

Detection asymmetry of tagging particle

- Nuisance asymmetries usually canceled with Cabibbo-favoured (no direct CPV) control modes which share common asymmetries
- Cancellation good if kinematics match between signal and control modes → kinematic weighting is needed → reduction of effective statistical power

Time-dependent $\mathcal{CP}$ asymmetries

- Consisting in measuring asymmetry or yield ratio in bins of decay time
- Less affected by nuisance (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

CPV in multibody decays

- Multibody decays: local $C\!P$ asymmetries possibly larger than integrated ones
- Local CPV can be searched with:
  - amplitude analyses → allows theorists to understand CPV per contributing amplitude, but model building is not easy
  - model-independent searches: statistical tests which provide yes/no response, but no information on internal dynamic of the decay

S_{CP} ("Miranda") method: χ^2 test to compare binned Dalitz distributions of $N^i(D^+_{(s)})$ and $N^i(D^-_{(s)})$ (yields obtained by mass fit in each bin)

$$S^i_{CP} = \frac{N^i(D^+_{(s)}) - \alpha N^i(D^-_{(s)})}{\sqrt{\alpha\left(\delta^2_{N^i(D^+_{(s)})} + \delta^2_{N^i(D^-_{(s)})}\right)}}, \quad \alpha = \frac{\sum_i N^i(D^+_{(s)})}{\sum_i N^i(D^-_{(s)})}, \quad \chi^2 = \sum_i \left(S^i_{CP}\right)^2$$

Energy test:

- unbinned method providing p-value
- it compares test statistics T observed in data with a distribution obtained from permutation samples (random flavour)
- T based on distance in phase space between candidates

$$T \equiv \frac{1}{2n(n-1)}\sum_{i,j\neq i}^{n}\psi_{ij} + \frac{1}{2\overline{n}(\overline{n}-1)}\sum_{i,j\neq i}^{\overline{n}}\psi_{ij} - \frac{1}{n\overline{n}}\sum_{i,j}^{n,\overline{n}}\psi_{ij}$$

CPV in multibody decays

- Model-independent search by measuring T-odd correlations in four-body decays using the triple product C_T and asymmetries A_T, $a_{CP}^{T-\text{odd}}$

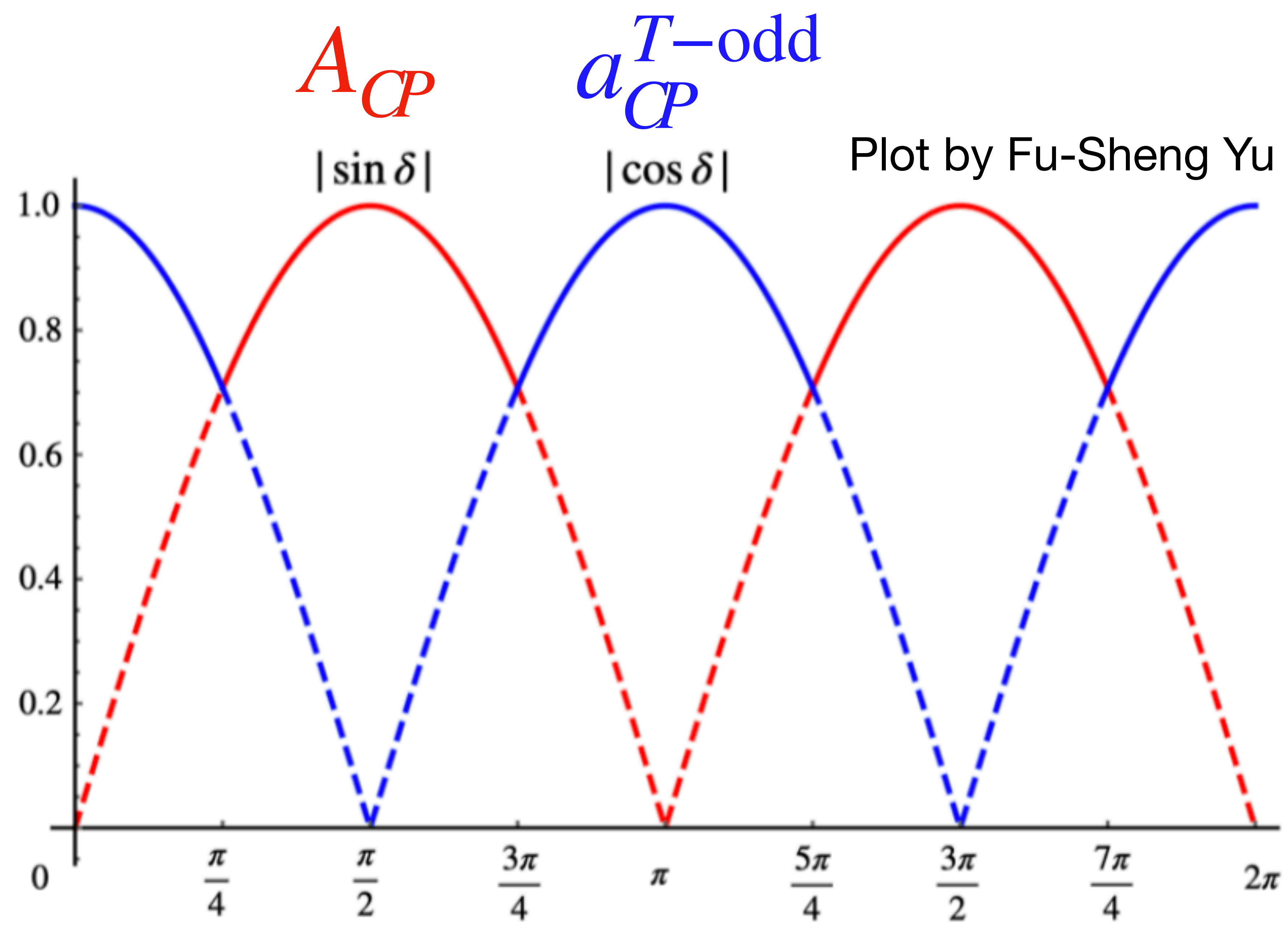
$$C_T = (\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_3$$

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)} \qquad \bar{A}_T = \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}$$

$$a_{CP}^{T-\text{odd}} = \frac{1}{2}(A_T - \bar{A}_T)$$

- $a_{CP}^{T-\text{odd}}$ unaffected by production and detection asymmetries and FSI effects

- In some cases $a_{CP}^{T-\text{odd}} \propto \sin\phi_w \cos\delta_s$, while $A_{CP} \propto \sin\phi_w \sin\delta_s \Rightarrow$ complementarity



Latest results

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

$A_{CP}(K^-K^+)\,|\,D^+ = (13.6 \pm 8.8 \pm 1.6) \times 10^{-4}$

$A_{CP}(K^-K^+)\,|\,D_s^+ = (2.8 \pm 6.7 \pm 2.0) \times 10^{-4}$

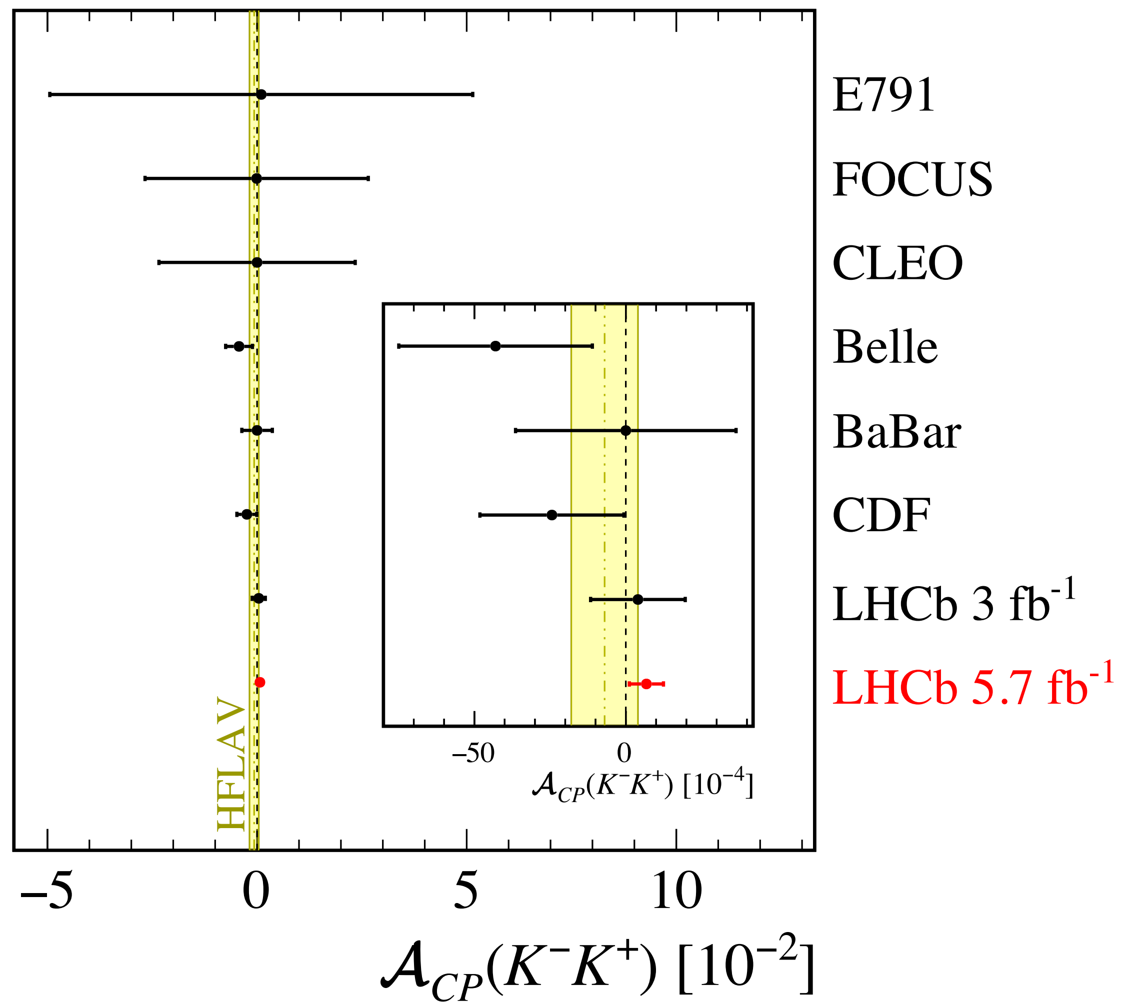
$\rho_{\text{stat}} = 0.05$

$\rho_{\text{syst}} = 0.28$

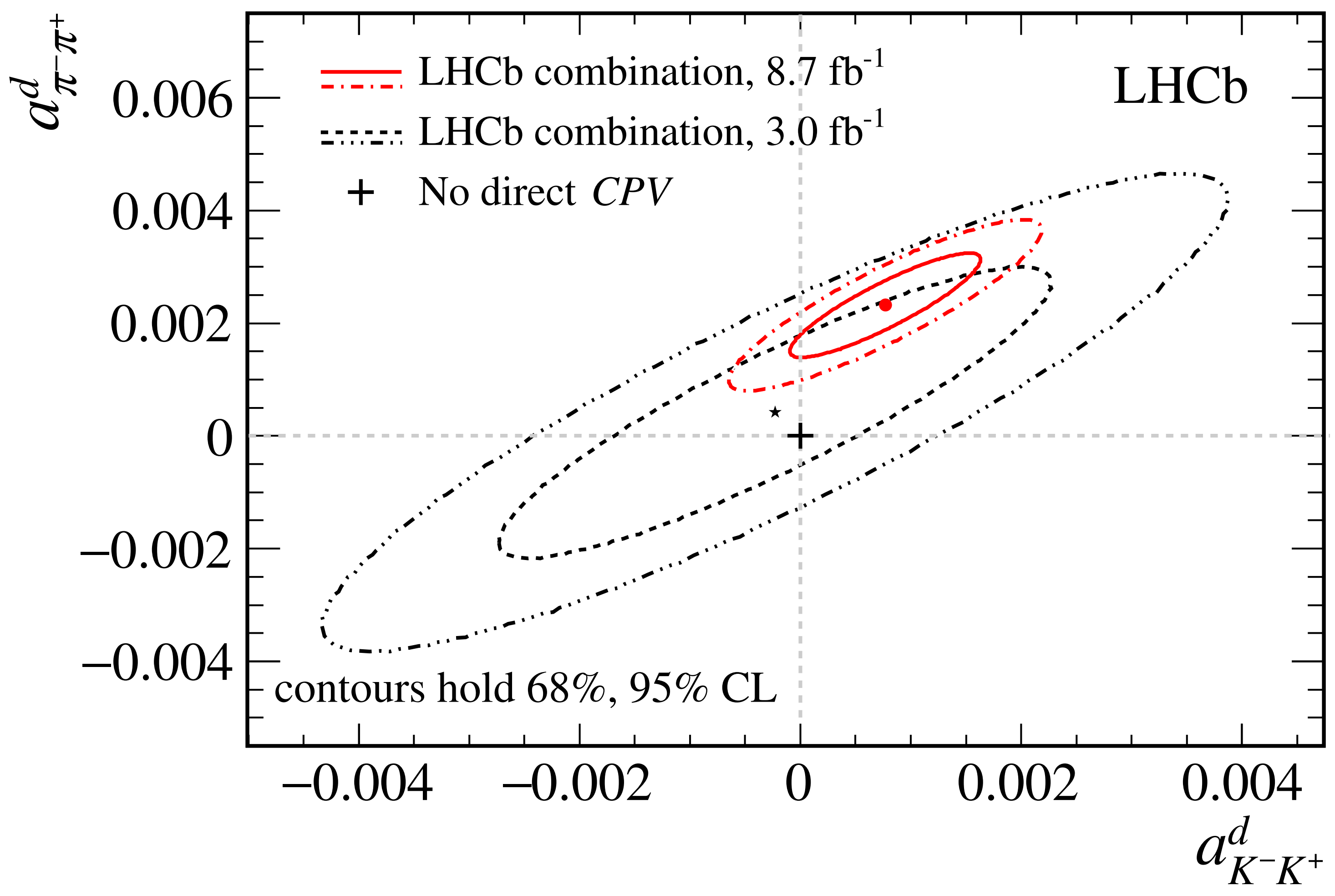
PRL 131 (2023) 091802

LHCb 2015-2018 data sample

Uncertainty about half of the previous world average



By combining all LHCb measurements of $A_{CP}(K^-K^+)$, ΔA_{CP}, ΔY and $\langle t \rangle_{h^-h^+}$, using $A_{CP}(h^-h^+) = a^d_{h^-h^+} + \frac{\langle t \rangle_{h^-h^+}}{\tau_{D^0}} \Delta Y$



$a^d_{KK} = (7.7 \pm 5.7) \times 10^{-4}$

$a^d_{\pi\pi} = (23.2 \pm 6.1) \times 10^{-4}$

$\rho(a^d_{KK}, a^d_{\pi\pi}) = 0.88$

- Evidence of direct CP violation in $D^0 \to \pi^-\pi^+$ at 3.8σ level
- Exceeds at 2σ level SM expectations of U-spin symmetry breaking

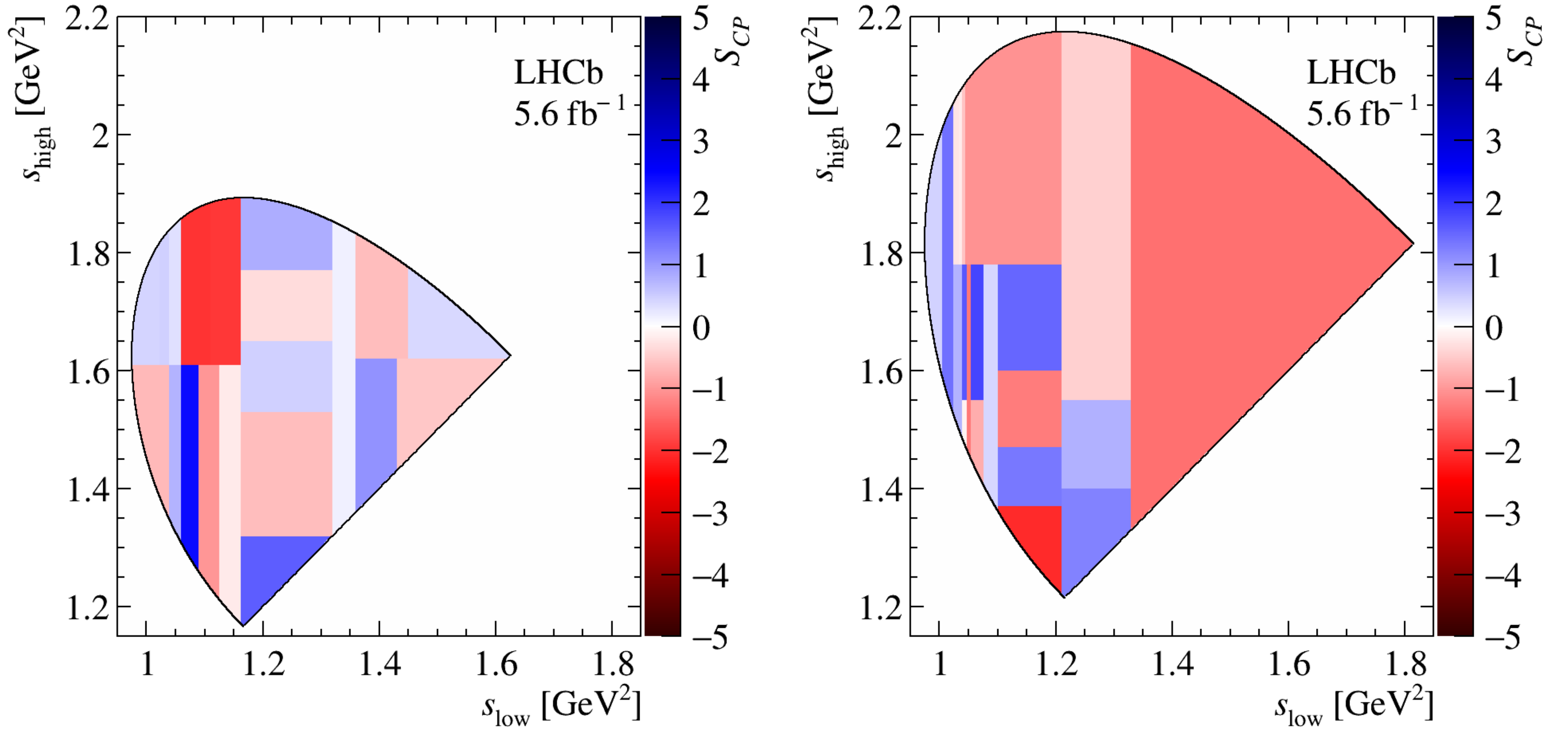
Search for local $C\!P$ violation in $D^+_{(s)} \to K^-K^+K^+$

[JHEP 07 (2023) 067]

- $D_s^+ \to K^-K^+K^+$: Singly Cabibbo-suppressed → might show $C\!P$ violation
- $D^+ \to K^-K^+K^+$: Doubly Cabibbo-suppressed → no $C\!P$ violation in SM
- Search with $S_{C\!P}$ method
- Dalitz plot divided in 21 bins that reproduce the pattern of the main resonances (≃ constant strong phase)
- Control samples: Cabibbo-favoured $D^+ \to K^-\pi^+\pi^+$ and $D_s^+ \to K^-K^+\pi^+$
- D_s^+ mode: p-value = 13.3%
- D^+ mode: p-value = 31.6%

⇒ no local $C\!P$ violation observed

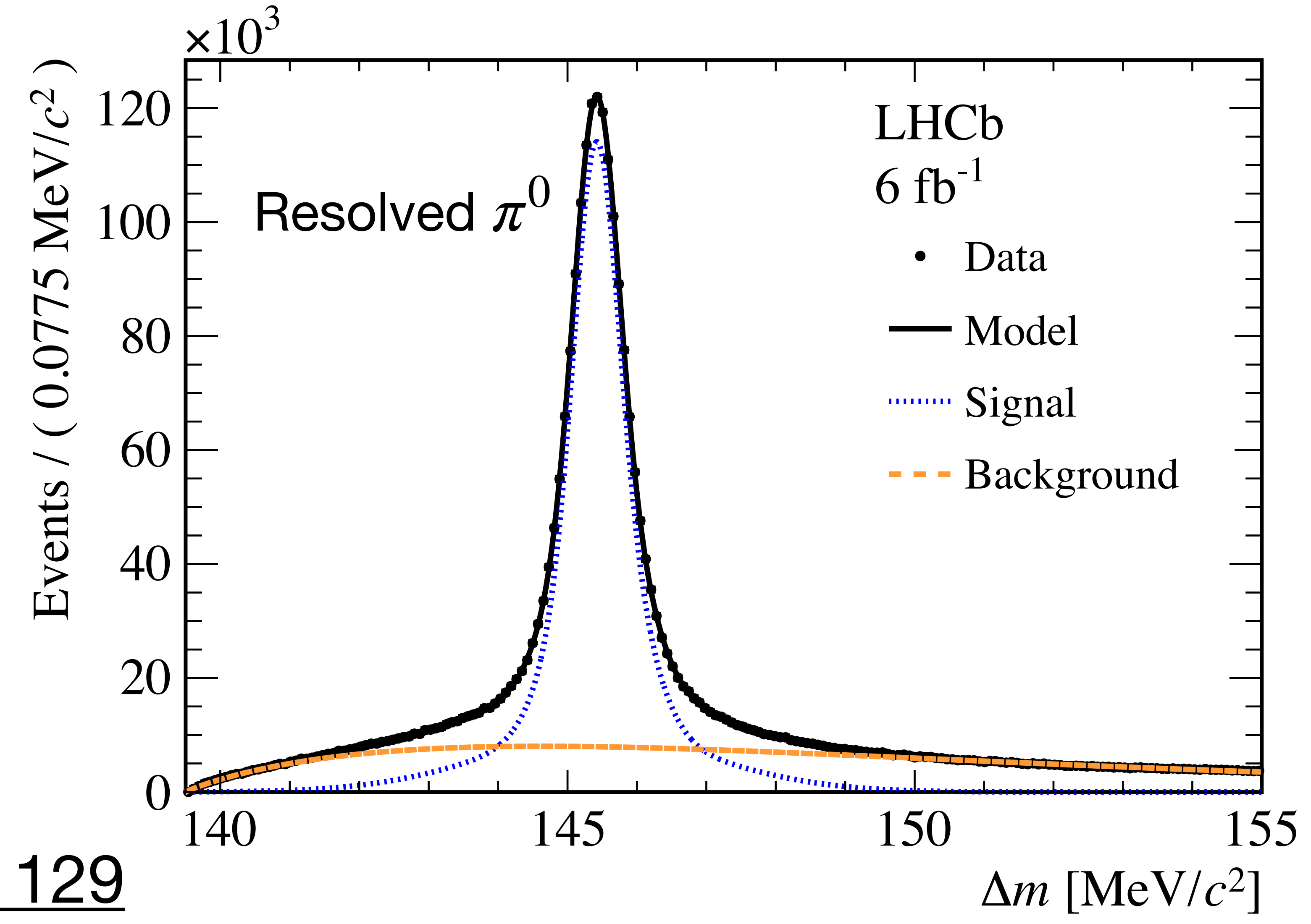
LHCb 2016-2018 data sample



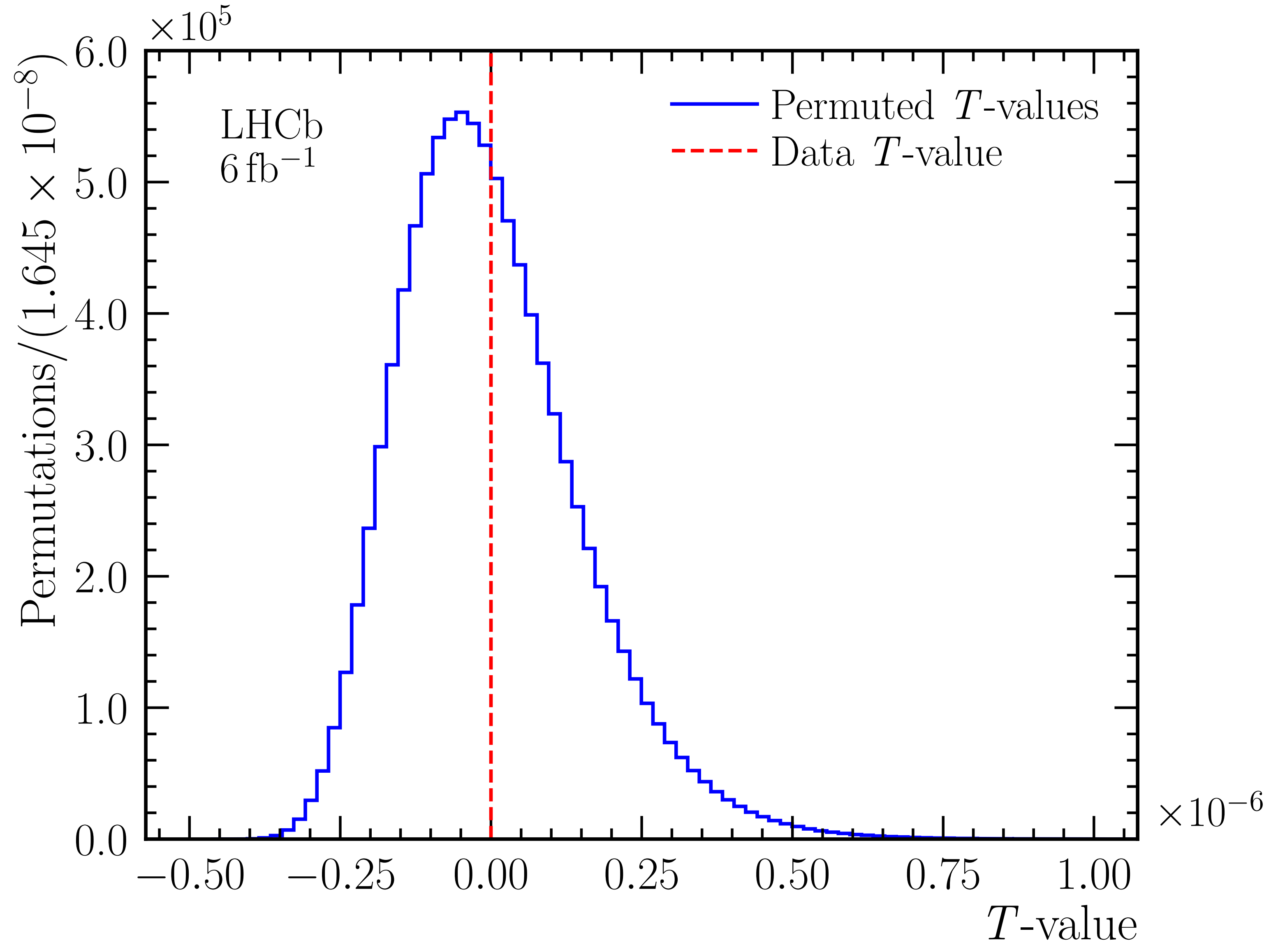
Search for local *CP* violation in $D^0 \to \pi^-\pi^+\pi^0$

- Singly Cabibbo-suppressed decay
- 3% p-value for *CP*-symmetry hypothesis in Run 1 measurement PLB 740 (2015) 158
- Dominated by ρ resonances
- Search with energy test
- Method validated with $D^0 \to K^-\pi^+\pi^0$ control sample
- p-value = 62%

LHCb 2015-2018 data sample



JHEP 09 (2023) 129

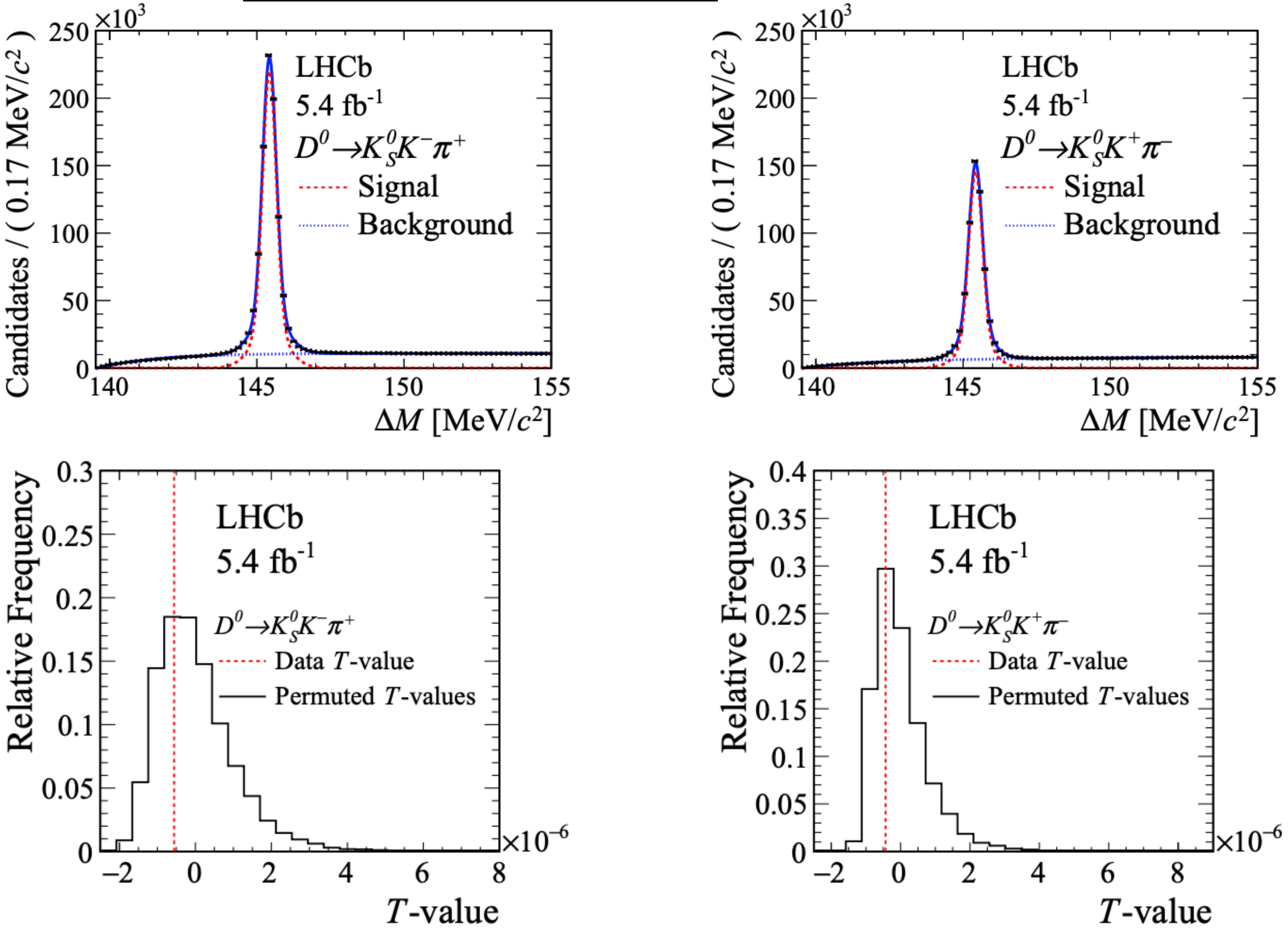


Search for local CP violation in $D^0 \to K_S^0 K^\pm \pi^\mp$

- Singly Cabibbo-suppressed decay
- Model-dependent study already performed with Run 1 measurement
  PRD 93 (2016) 052018
- Search with energy test
- Method validated with $D^0 \to K^- \pi^+ \pi^- \pi^+$ and $D^0 \to K_S^0 \pi^+ \pi^-$ control samples
- p-values = 70% ($K_S^0 K^- \pi^+$) and 66% ($K_S^0 K^+ \pi^-$)

LHCb 2016-2018 data sample

arXiv:2310.19397

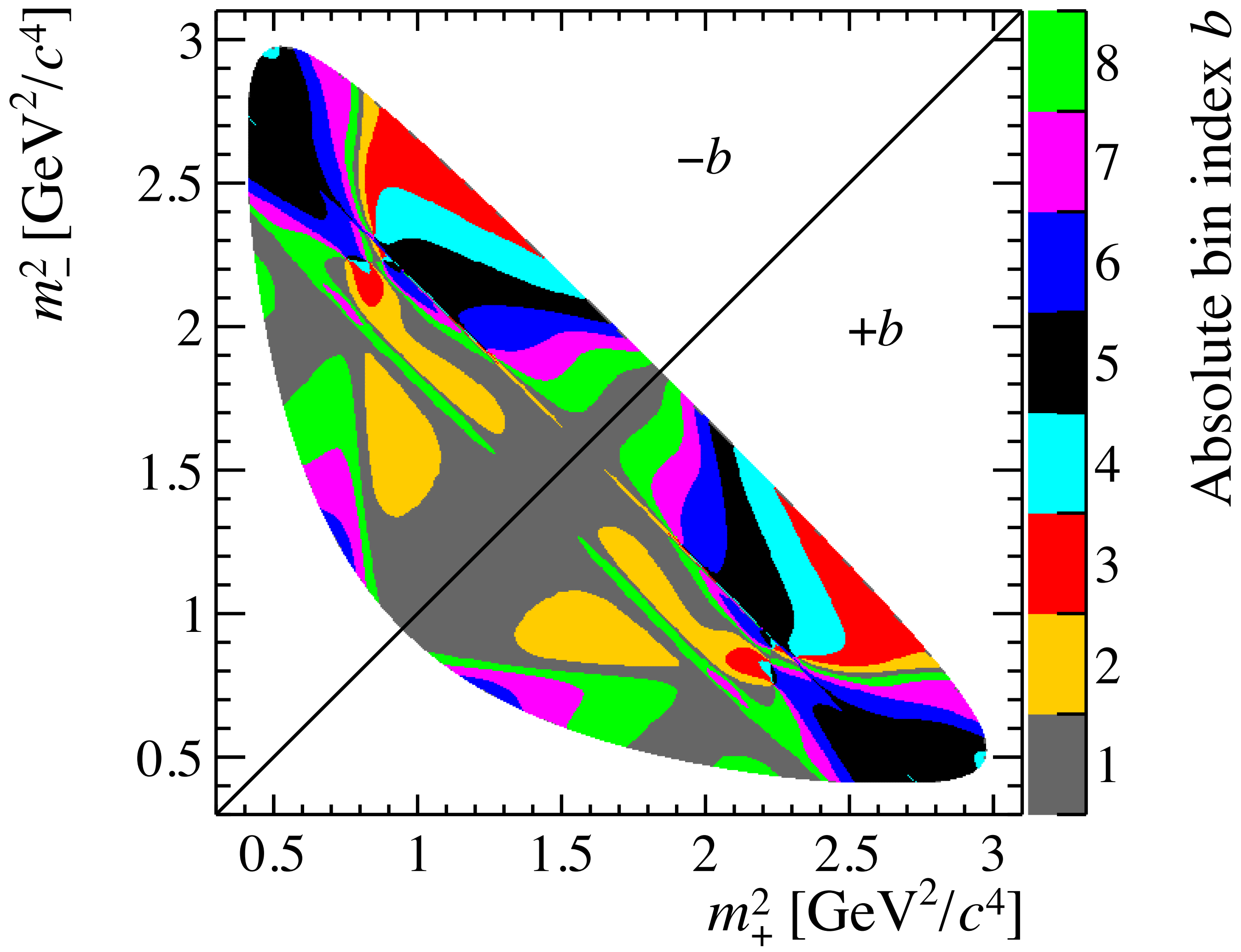


Mixing and CPV with $D^0 \to K^0_s \pi^+ \pi^-$

- $D^0 \to K^0_s \pi^+ \pi^-$ is particularly sensitive to x
- Analysis performed with model-independent *bin-flip* method, which does not require accurate modelling of the efficiency
- Prompt tag: led to observation of $x \neq 0$
- Semileptonic tag: allows to probe the low decay-time region

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

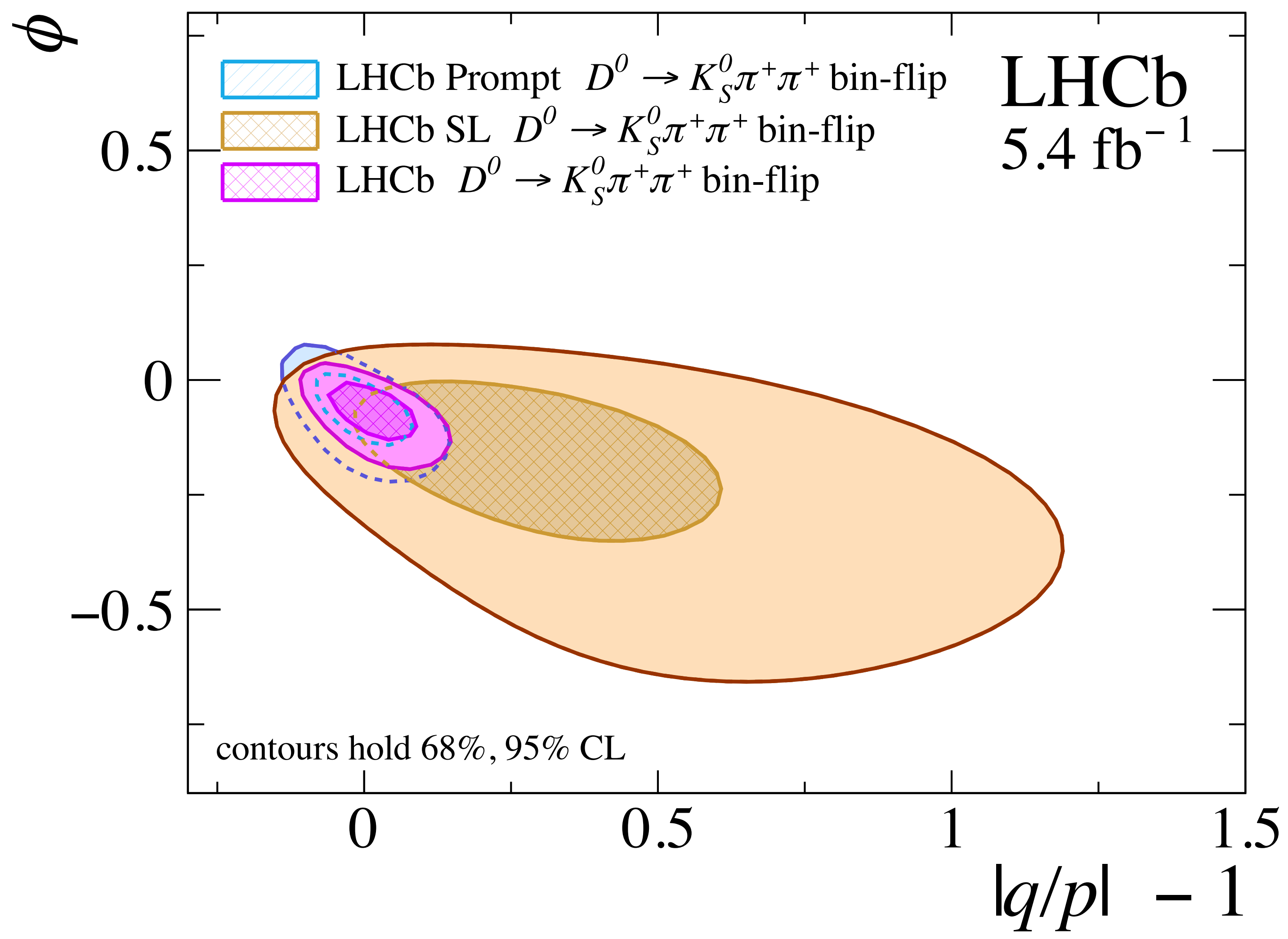
PRL 127 (2021) 111801 PRD 108 (2023) 052005

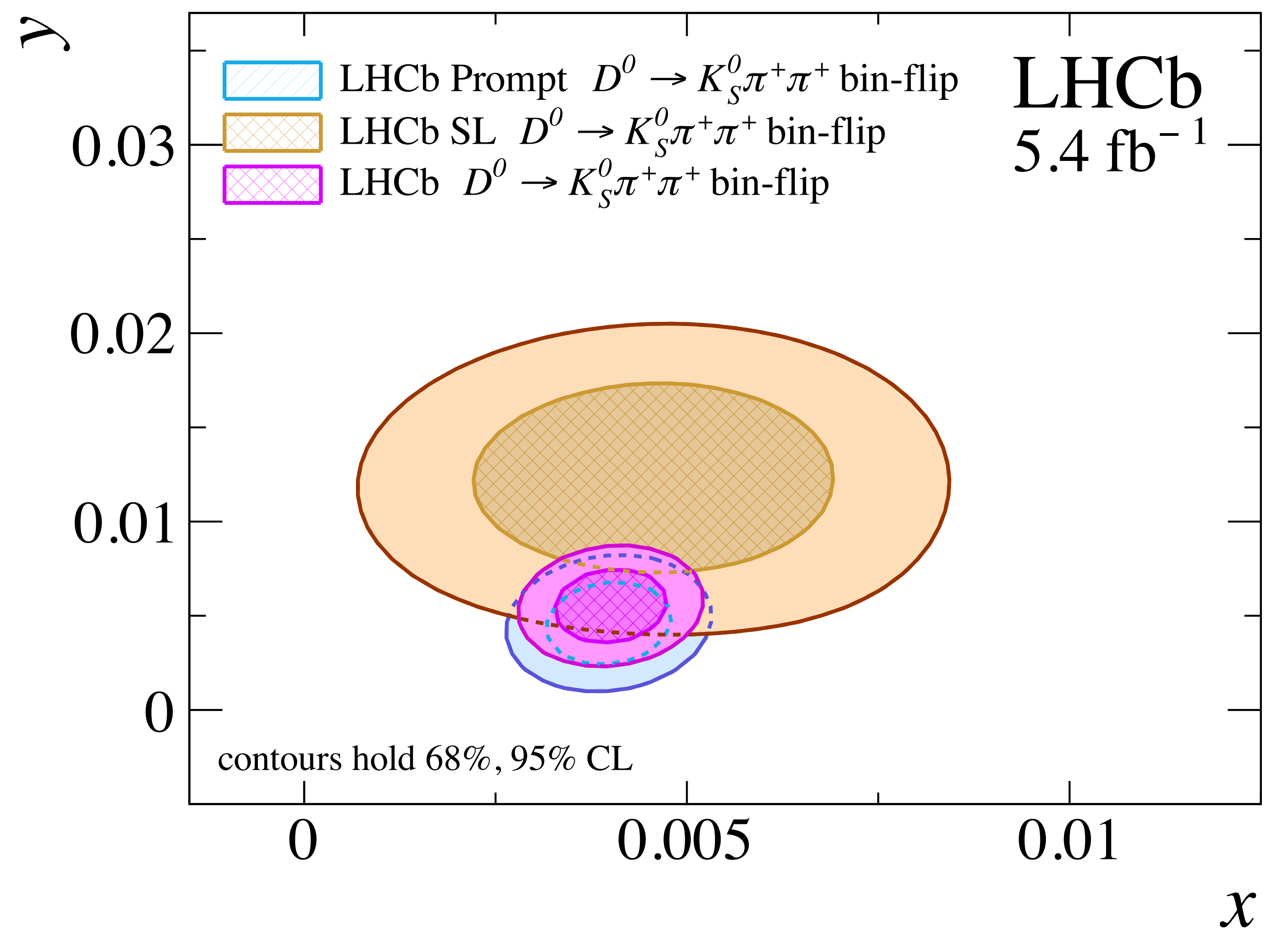


Almost constant strong-phase difference in each Dalitz bin ➡ external inputs from CLEO and BESIII

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

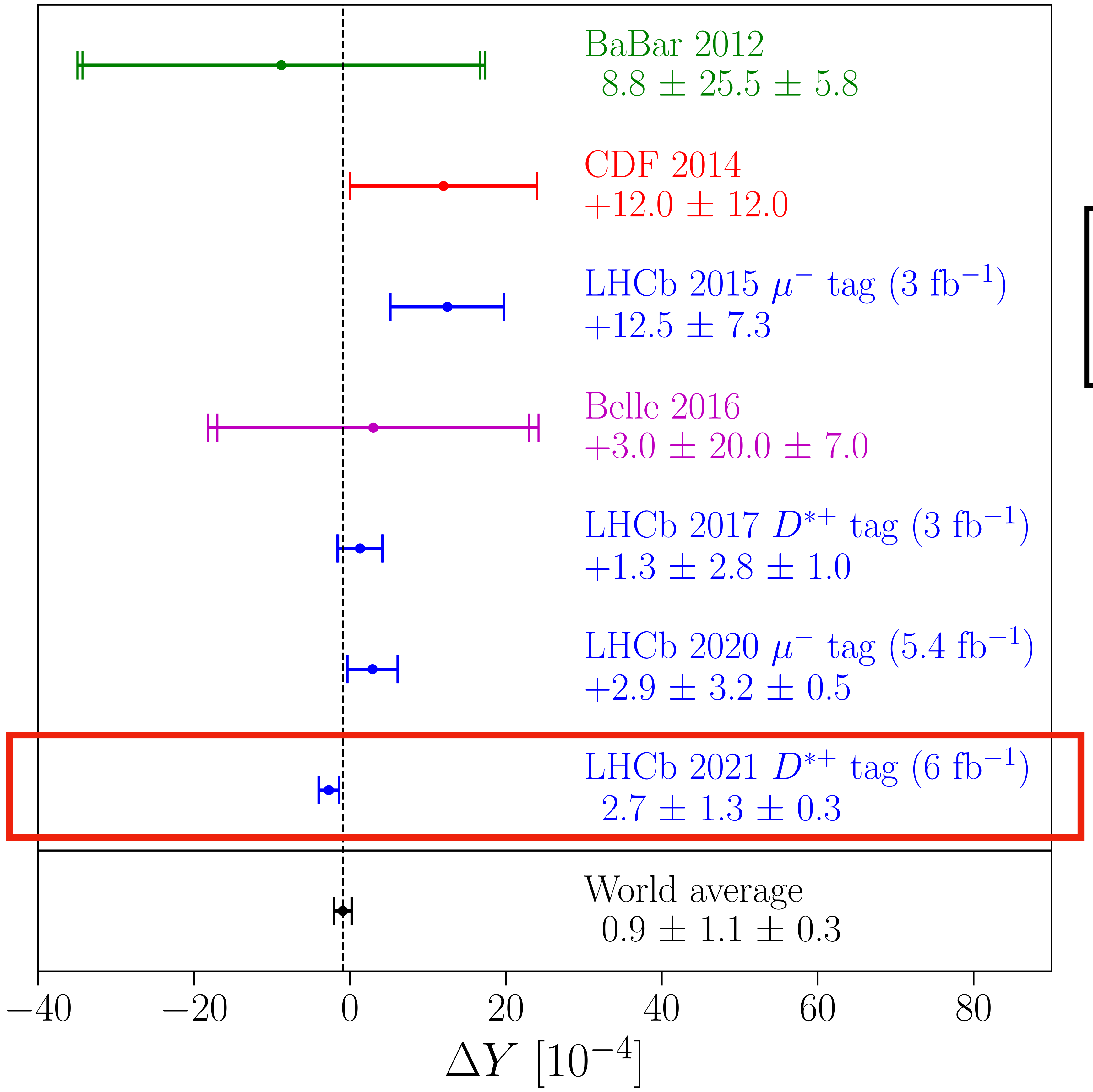
LHCb 2016-2018 data sample





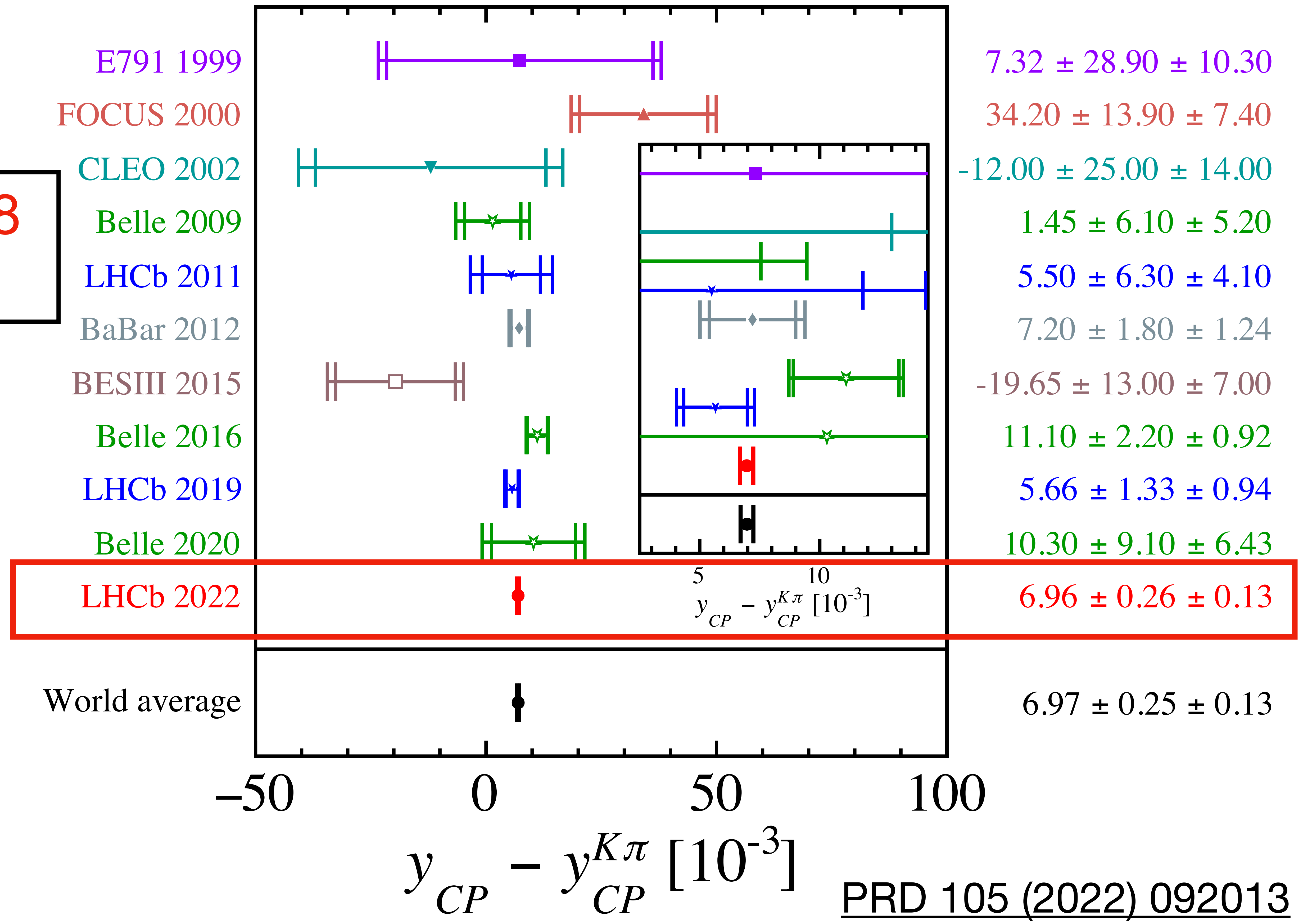
ΔY and $y_{CP} - y_{CP}^{K\pi}$

Precision on ΔY world average improved by nearly a factor 2 PRD 104 (2021) 072010



LHCb 2015-2018 data sample

Latest determination of $y_{CP} - y_{CP}^{K\pi}$ four times more precise than previous world average



PRD 105 (2022) 092013

CPV in $D^0 \to K_S^0 K_S^0 \pi^+ \pi^-$

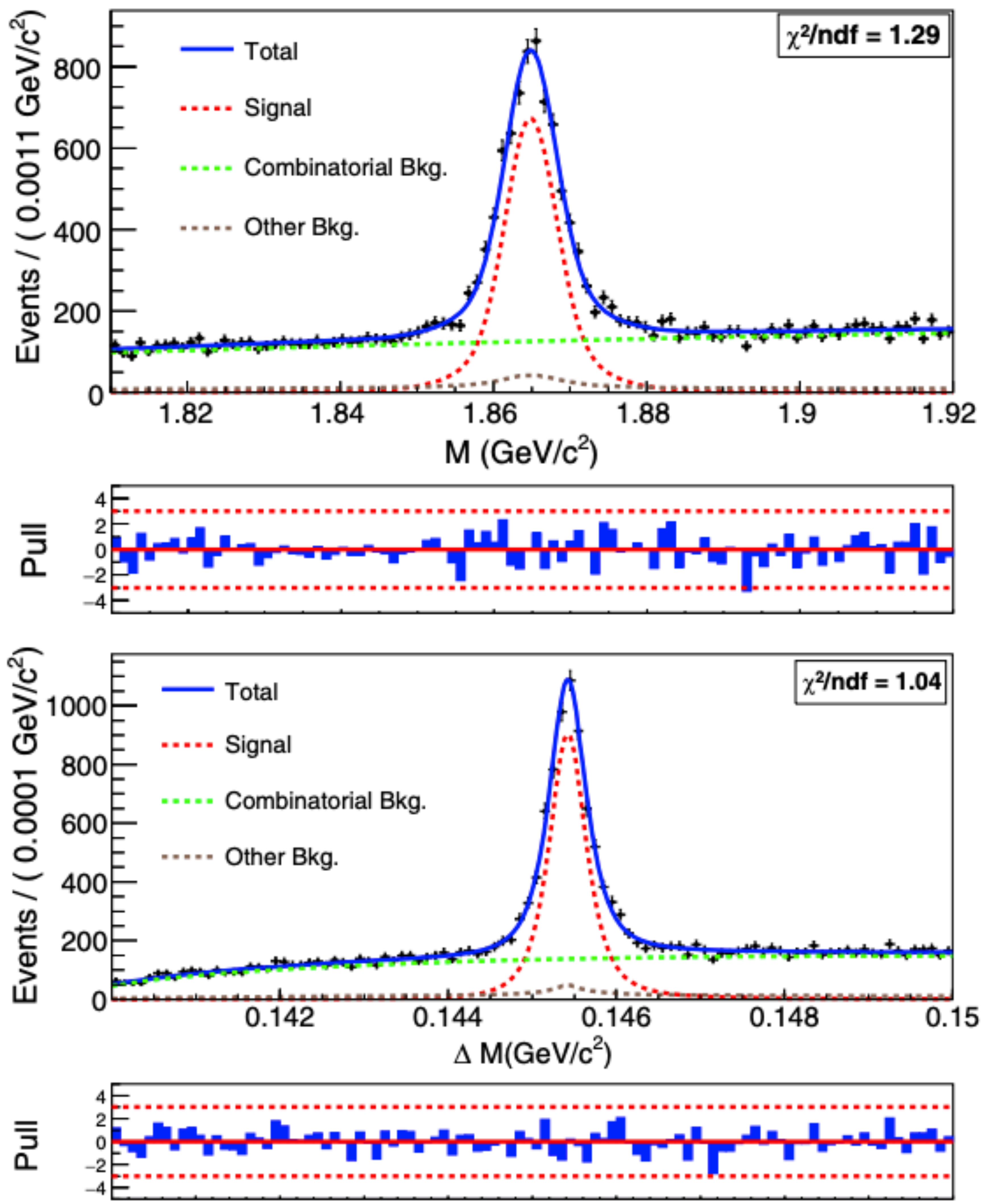
- First measurements of A_{CP} and $a_{CP}^{T\text{-odd}}$ for this decay:

Full Belle data sample ($922\ \text{fb}^{-1}$)

$$A_{CP} = (-2.51 \pm 1.44^{+0.11}_{-0.10})\ \%$$

$$a_{CP}^{T\text{-odd}} = (-1.95 \pm 1.42^{+0.14}_{-0.12})\ \%$$

- For A_{CP}:
  - ➡ Detection asymmetry corrected with untagged $D^0 \to K^-\pi^+$ decays
  - ➡ A_{FB} corrected by averaging A_{raw} over D^* polar angle
- Most precise determination of branching fraction up to date



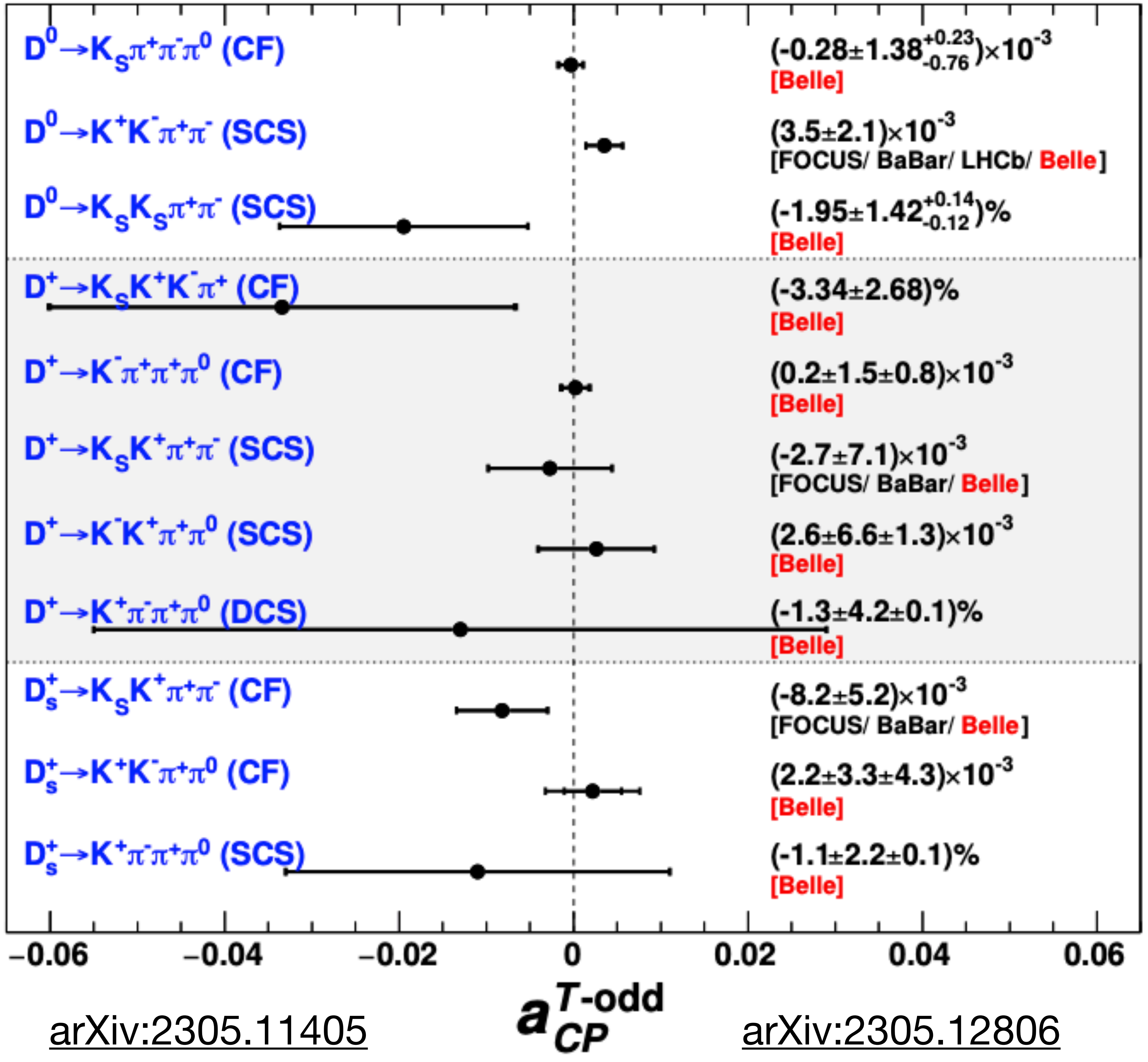
PRD 107 (2023) 052001

T-odd correlations in D^+ and D_s^+ four-body decays

- A_T and $a_{CP}^{T-\mathrm{odd}}$ obtained by simultaneous fit to subsamples divided by D flavour and C_T charge
- First or most precise determinations of these quantities
- $a_{CP}^{T-\mathrm{odd}}$ measured also in subregions of phase space

Full Belle data sample ($980\ \mathrm{fb}^{-1}$)

made by Longke Li



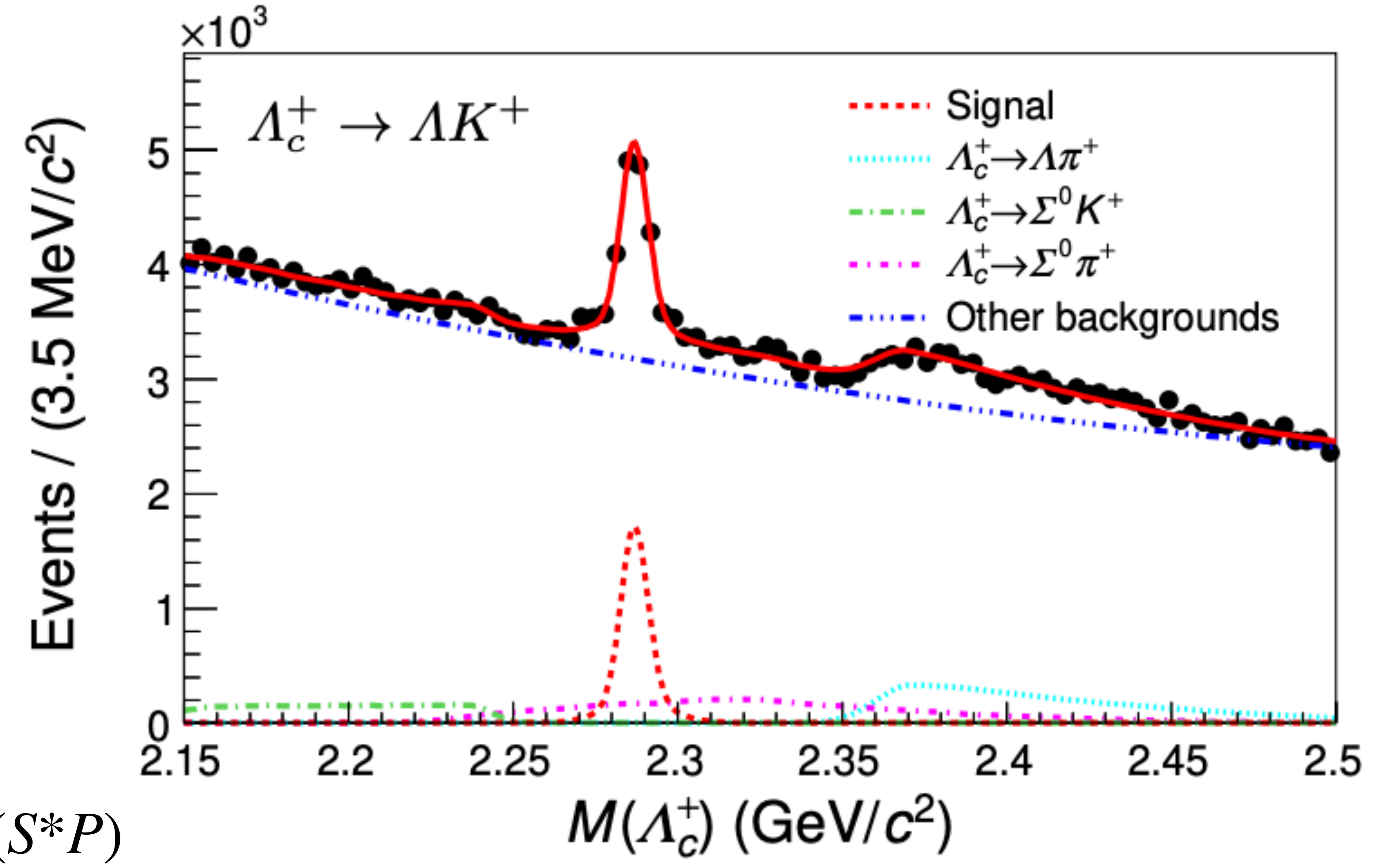
arXiv:2305.11405 arXiv:2305.12806

CPV in Λ_c decays

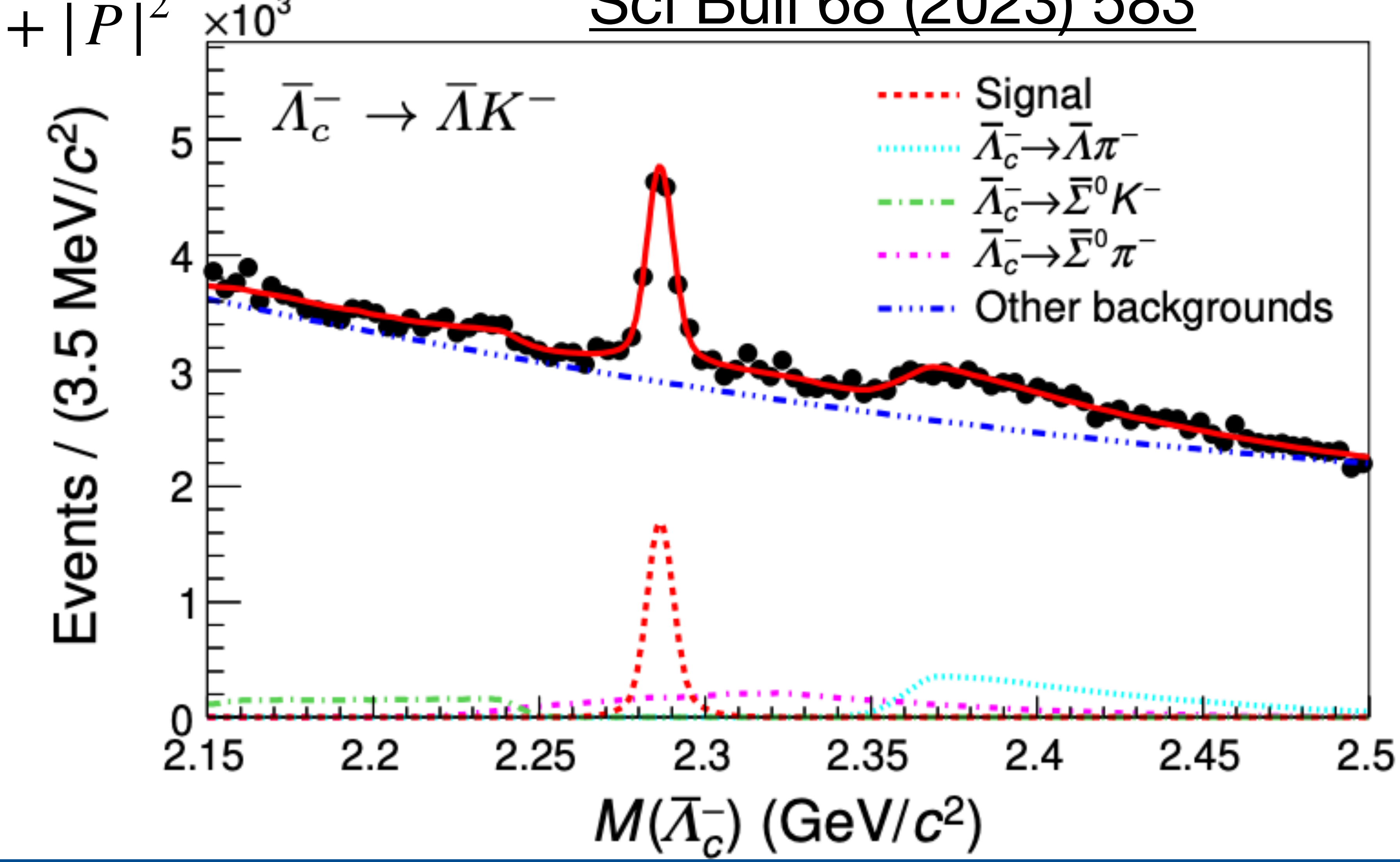
- First measurement of direct and α-induced CP asymmetry in singly Cabibbo-suppressed Λ_c decays:

$$A_{CP}(\Lambda_c^+ \to \Lambda K^+) = 0.021 \pm 0.026 \pm 0.001$$
$$A_{CP}(\Lambda_c^+ \to \Sigma^0 K^+) = 0.025 \pm 0.054 \pm 0.004$$
$$A_{CP}^{\alpha}(\Lambda_c^+ \to \Lambda K^+) = -0.023 \pm 0.086 \pm 0.071$$
$$A_{CP}^{\alpha}(\Lambda_c^+ \to \Sigma^0 K^+) = 0.08 \pm 0.35 \pm 0.14$$

$$A_{CP}^{\alpha} = \frac{\alpha_{\Lambda_c^+} + \alpha_{\overline{\Lambda}_c^-}}{\alpha_{\Lambda_c^+} - \alpha_{\overline{\Lambda}_c^-}}, \alpha = \frac{2\Re(S^*P)}{|S|^2 + |P|^2}$$



Sci Bull 68 (2023) 583



- Detection asymmetries corrected with Cabibbo-favoured D and Λ_c^+ decays

- Method to measure A_{CP}^{α} promising for future studies of other hyperons

Full Belle data sample (980 fb^{-1})

Future prospects

Future direct CPV with LHCb

- 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

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

LHCB-PUB-2018-009

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

Future time-dependent CPV with LHCb

- 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°

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

LHCB-PUB-2018-009

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 %

Future direct CPV with Belle II

- General improvement by one order of magnitude, and $\sigma < 10^{-3}$ for most of the measurements
- $\sigma(A_{CP}(D^0 \to K^+K^-))$ will have the same magnitude as LHCb $23\ \text{fb}^{-1}$
- $\sigma(\Delta A_{CP})$ will be in the same ballpark as the current one
- Belle II will dominate the knowledge of decays involving neutrals
- Disclaimer: improvements in reconstruction wrt Belle not taken into account here, including new CFT

Mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%) (Belle existing measurement)	Belle II 50 ab^{-1}
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \to K^0_S \pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.02
$D^0 \to K^0_S K^0_S$	921	$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	± 0.23
$D^0 \to K^0_S \eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K^0_S \eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	± 0.13
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	± 0.40
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	± 0.33
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
$D^+ \to \pi^+\pi^0$	921	$+2.31 \pm 1.24 \pm 0.23$	± 0.17
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \to K^0_S \pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.02
$D^+ \to K^0_S K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.04
$D^+_s \to K^0_S \pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D^+_s \to K^0_S K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

PTEP 12 (2019) 123C01

Future time-dependent CPV with Belle II

- Improvement by a factor 6-7
- Knowledge of binned strong phases expected to be improved by BESIII → systematic uncertainty will be reduced
- Disclaimer: improvements in reconstruction wrt Belle not taken into account here, including new CFT and better time resolution

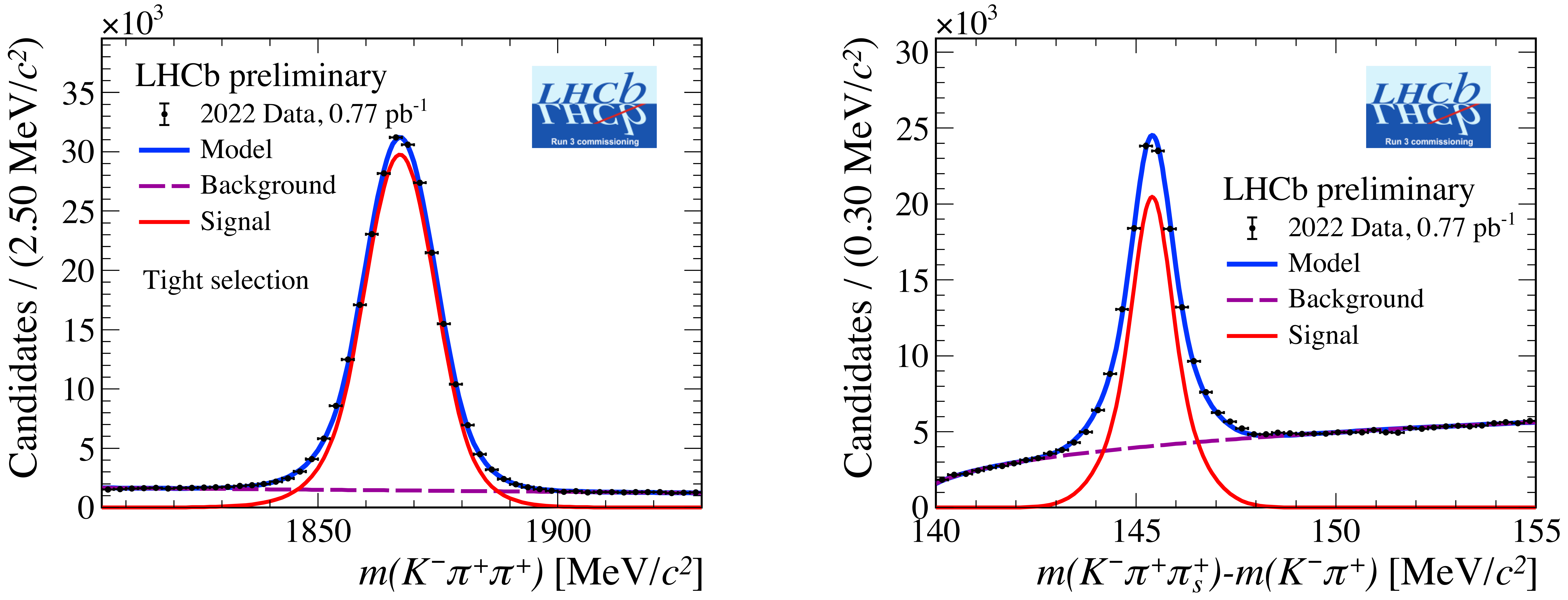
$D^0 \to K_s^0\pi^+\pi^-$

Data	Stat.	Syst. Red.	Syst. Irred.	Total	Stat.	Syst. Red.	Syst. Irred.	Total
	σ_x (10^{-2})				σ_y (10^{-2})			
976 fb^{-1}	0.19	0.06	0.11	0.20	0.15	0.06	0.04	0.16
5 ab^{-1}	0.08	0.03	0.11	0.14	0.06	0.03	0.04	0.08
50 ab^{-1}	0.03	0.01	0.11	0.11	0.02	0.01	0.04	0.05
	$\|q/p\|$ (10^{-2})				ϕ (°)			
976 fb^{-1}	15.5	5.2–5.6	7.0–6.7	17.8	10.7	4.4–4.5	3.8–3.7	12.2
5 ab^{-1}	6.9	2.3–2.5	7.0–6.7	9.9–10.1	4.7	1.9–2.0	3.8–3.7	6.3–6.4
50 ab^{-1}	2.2	0.7–0.8	7.0–6.7	7.0–7.4	1.5	0.6	3.8–3.7	4.0–4.2

PTEP 12 (2019) 123C01

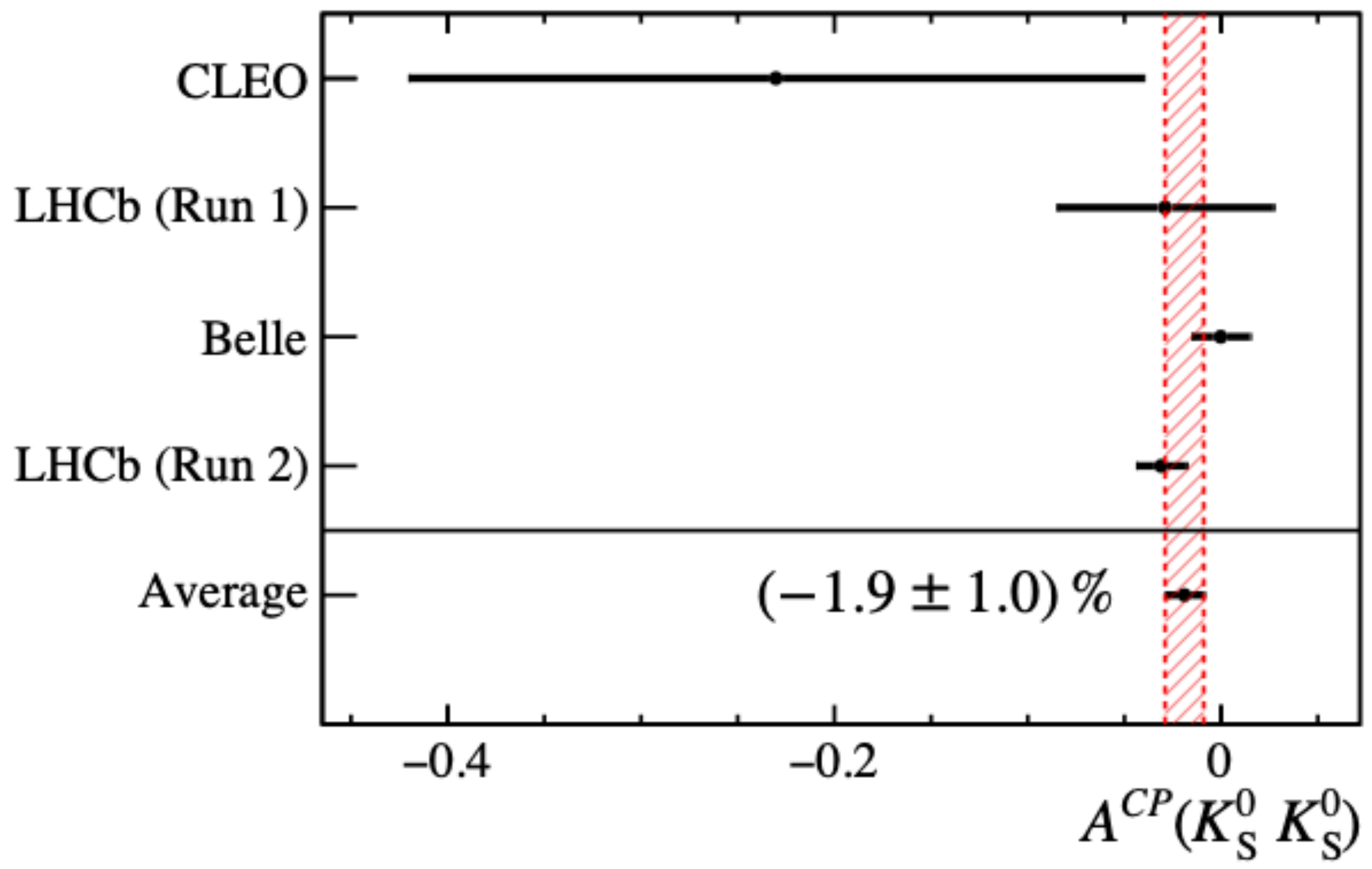
First Run 3 LHCb charm mass peaks

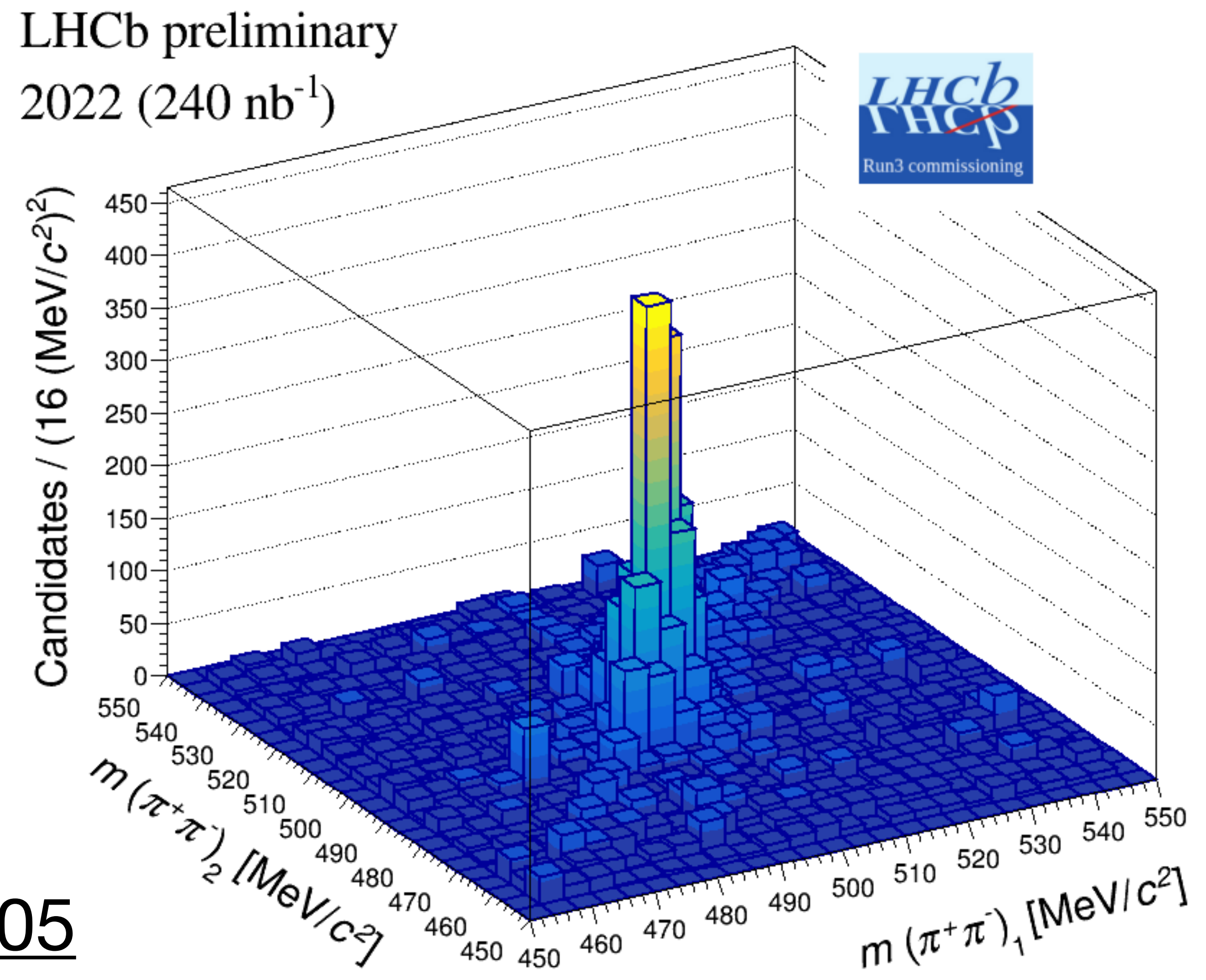
LHCB-FIGURE-2023-011



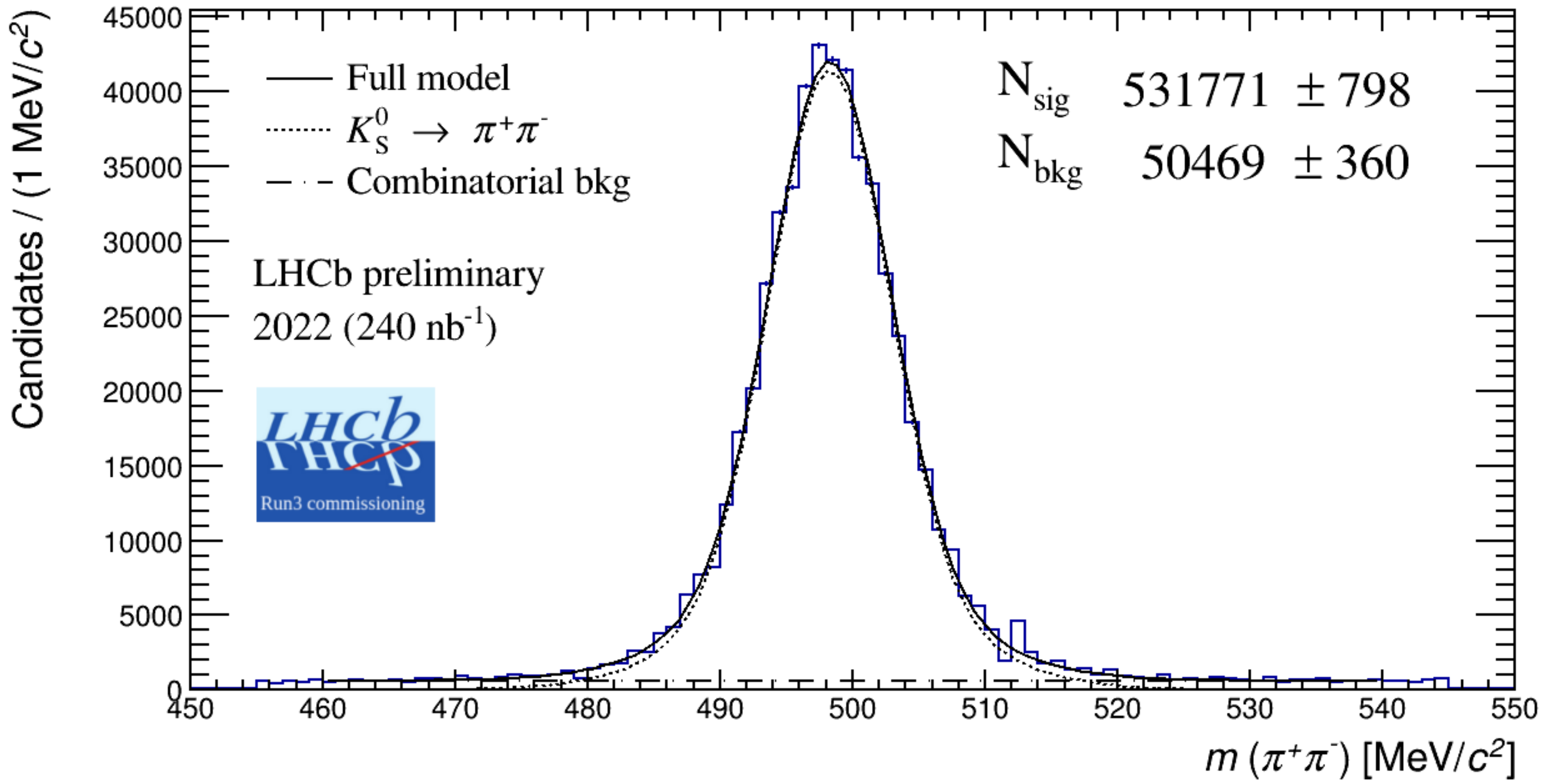
New Hlt1 K_s^0 lines in LHCb

- New dedicated selection for single and di-K_s^0
- Expected 2.6x improvement on efficiency on $D^0 \to K_s^0 K_s^0$
- Important step to get to $\sigma(A_{CP}) \sim 10^{-3}$





LHCB-FIGURE-2023-005



Future challenges

- In these measurements, systematics scale with statistics, but we will reach a point where $\sigma_{\text{stat}} \sim \sigma_{\text{syst}}$
- Nuisance asymmetries currently corrected for with Cabibbo-favoured decays → kinematic weighting applied → systematic associated
  ⇒ should we start measuring A_P and A_D (or even absolute efficiencies) separately?
- Measurements with π^0 ($D^+ \to \pi^+\pi^0, D^+ \to \pi^0\pi^0, \ldots$) challenging at LHCb → we should work hard to improve the π^0 reconstruction, especially in future upgrades
- Multibody decays: crucial to choose powerful, interpretable observables: robust experimentally, impactful theoretically → synergy with theory community is needed!
- QCD strongly affects SM calculations → what can we do to help theory community in improving their predictions?

Conclusions

- After discovery of CPV in D^0 decays, many other $C\!P$ measurements have been performed in D decays
- First evidence of $a^d_{C\!P}(D^0 \to \pi^-\pi^+) \neq 0$
- Mixing and CPV-in-mixing parameters measured with impressive precision in D^0 system
- New searches for CPV in four-body decays
- Future measurements with LHCb Upgrades and Belle II will further increase knowledge of CPV in charm and clarify the global picture

Backup

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

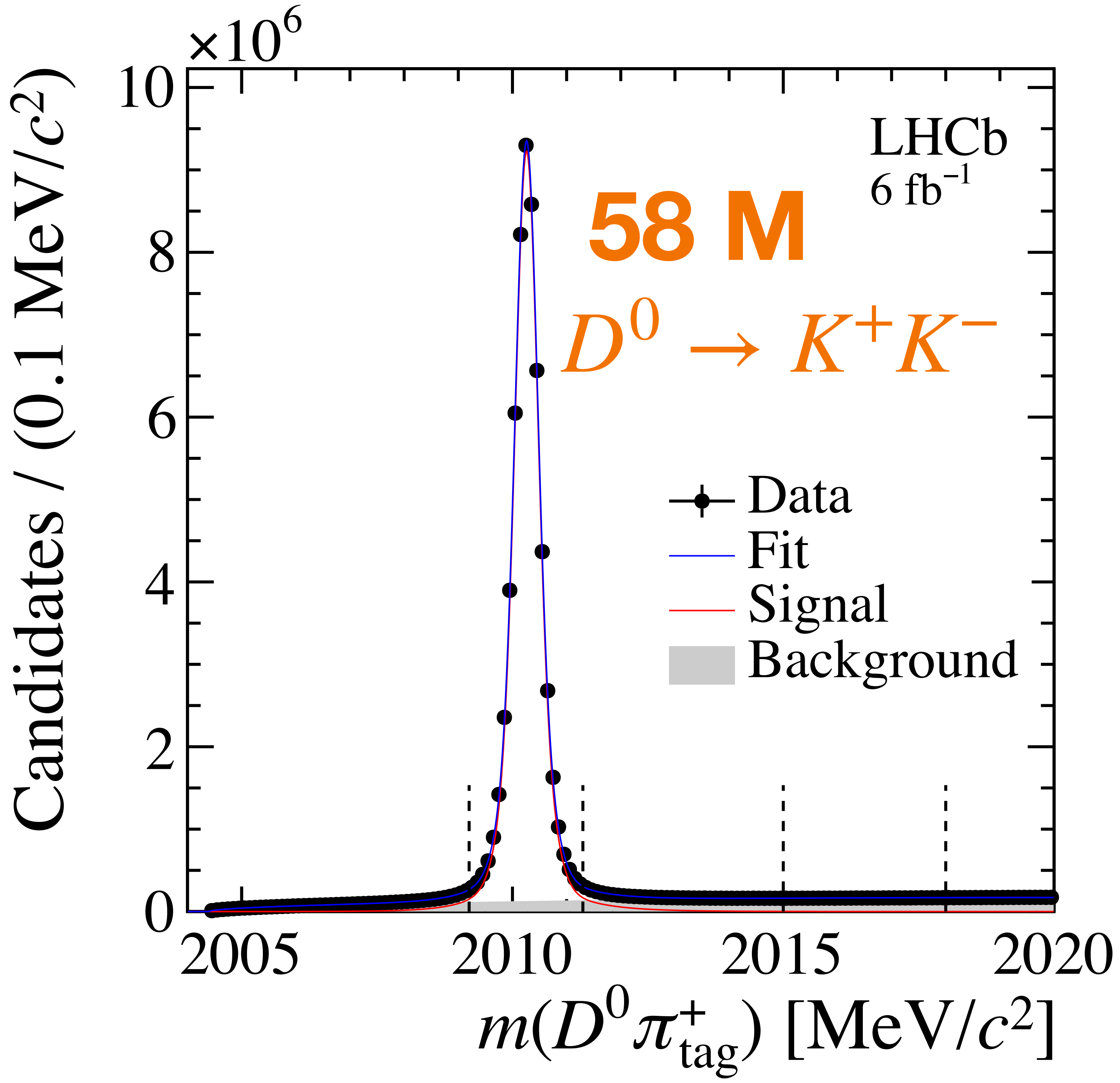
$$\phi_f^M \equiv \arg\left(\frac{M_{12}A_f}{\bar{A}_f}\right) \simeq \phi_{12}$$

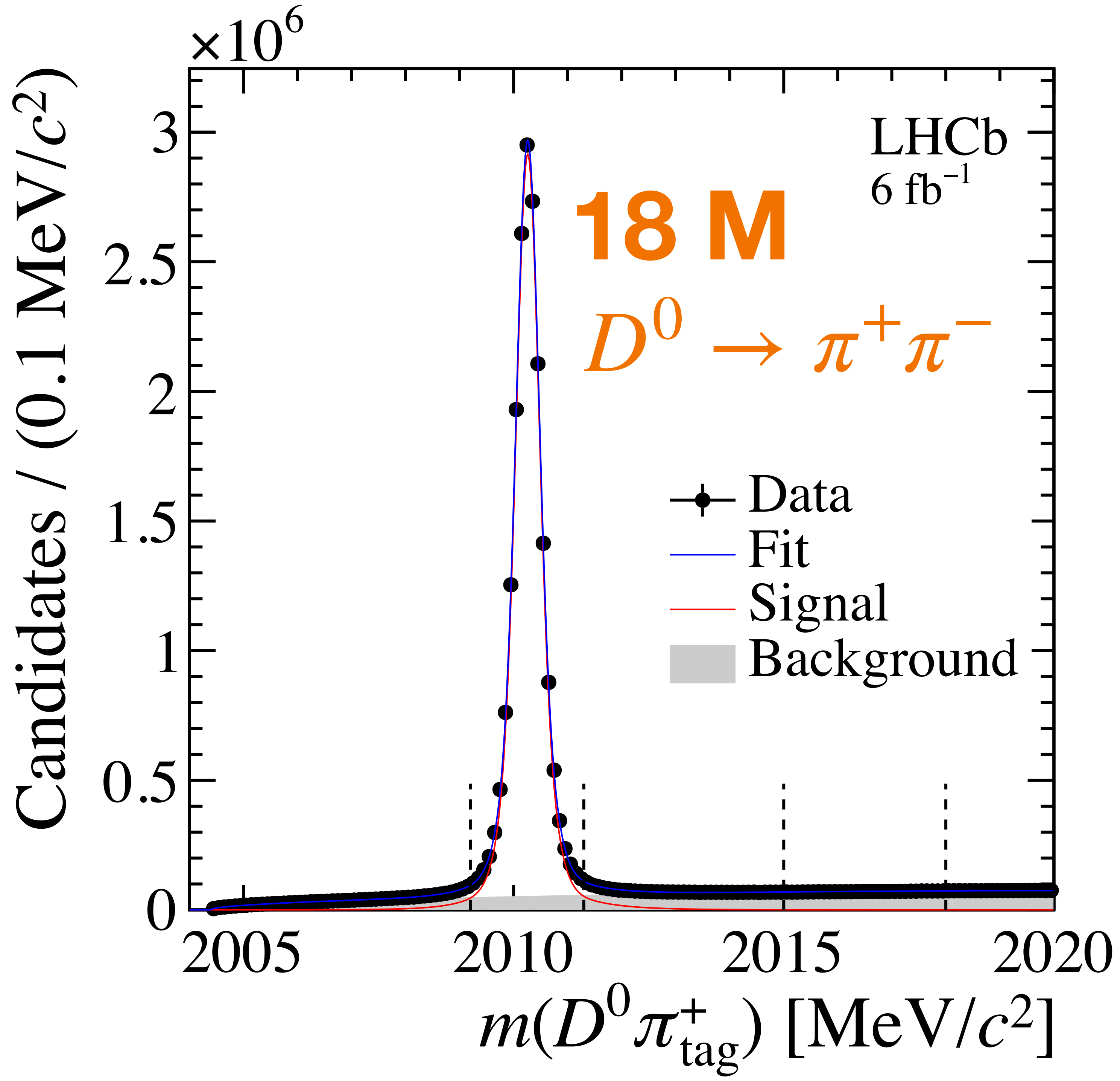
Superweak approximation

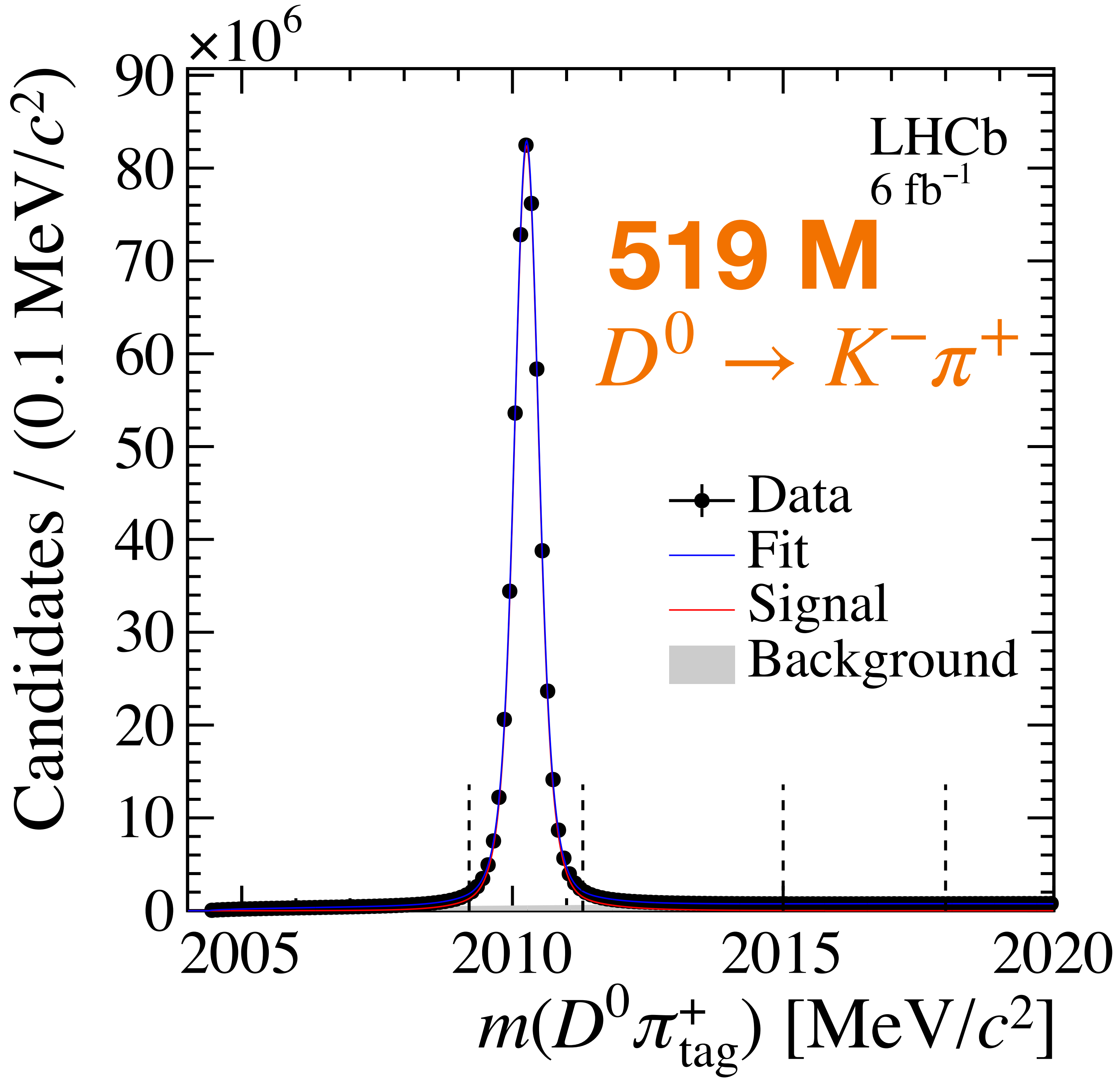
- $\Delta Y_{K^+K^-} = \Delta Y_{\pi^+\pi^-} = \Delta Y$ at current level of precision
- SM expectation $\sim 2 \times 10^{-5}$ PRD 103 (2021) 053008 PLB 810 (2020) 135802
- Strategy: measure asymmetry in bins of D^0 decay time and measure the linear slope
- Selection induces correlations between kinematics 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







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

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

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

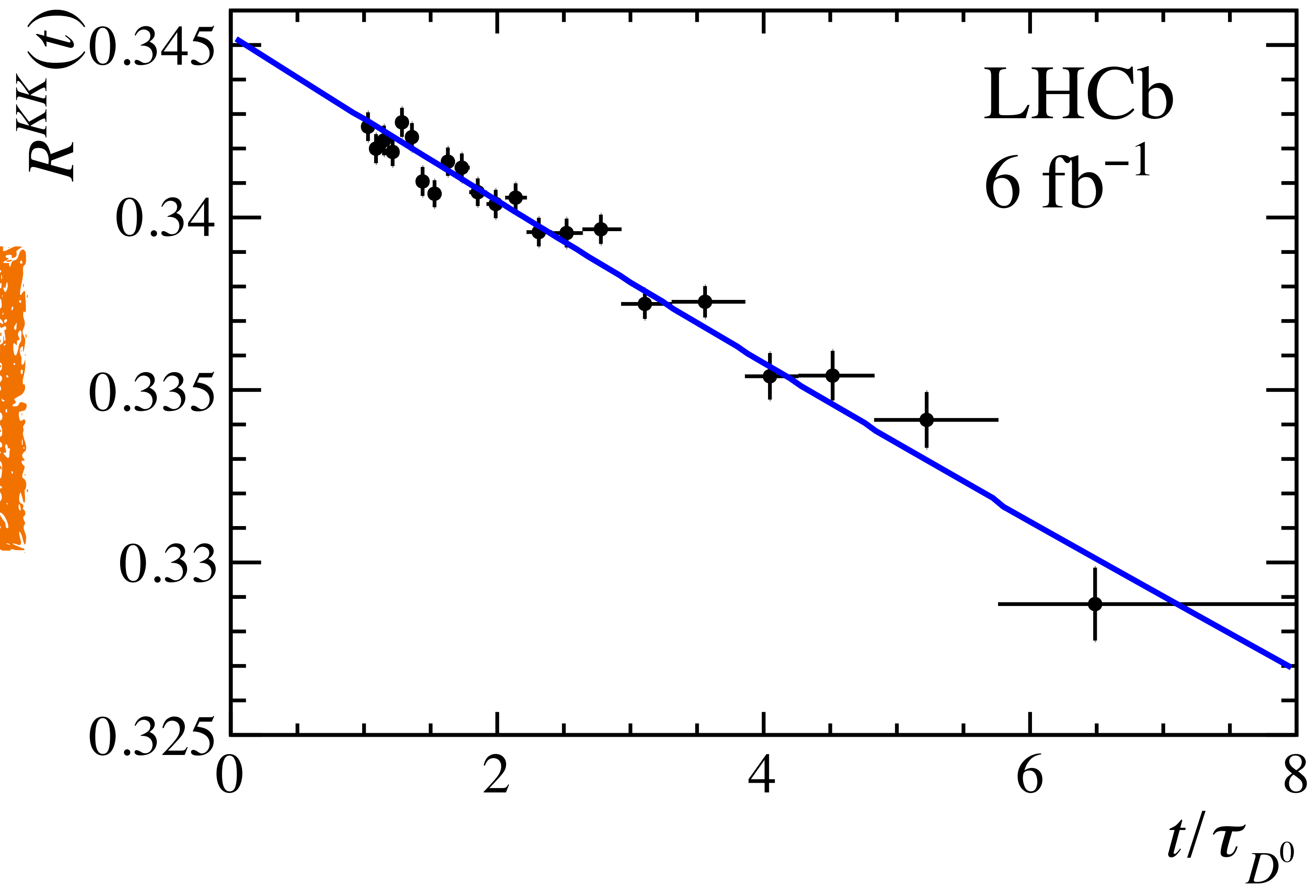
PRD 105 (2022) 092013

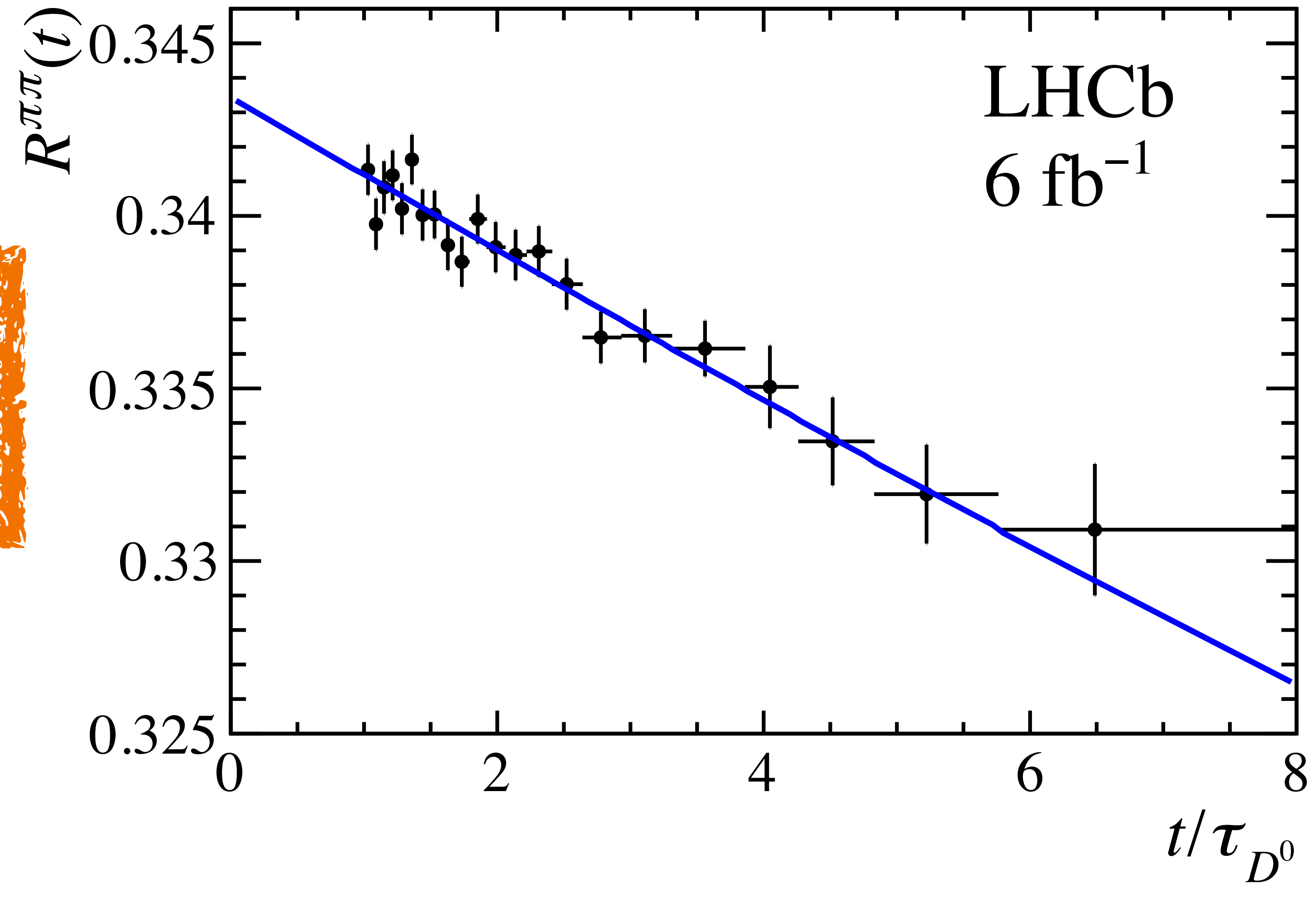
$$y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3}$$

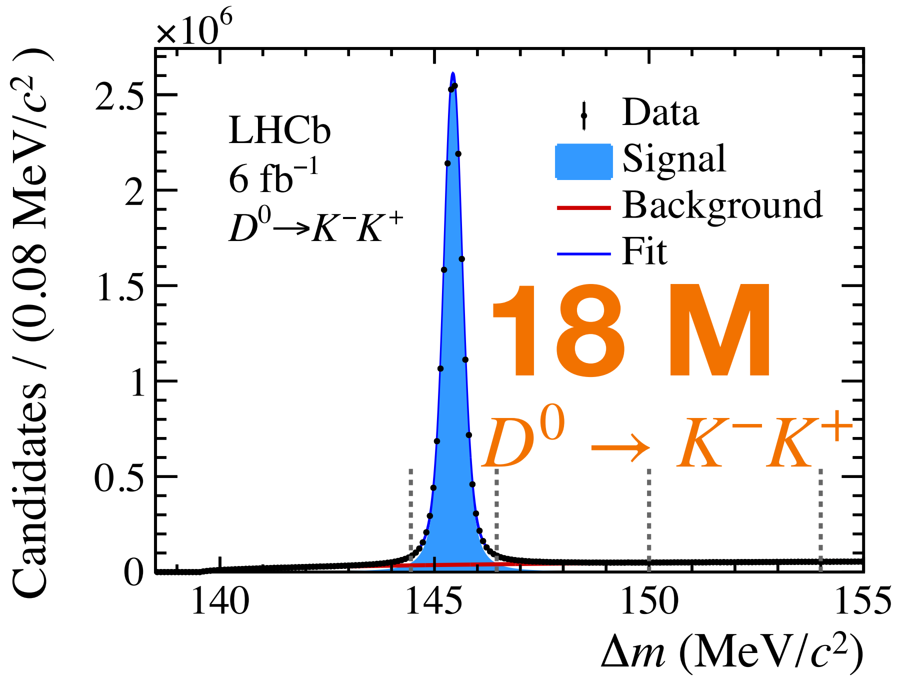
$$y_{CP}^{CC} = (0.15 \pm 0.36) \times 10^{-3}$$

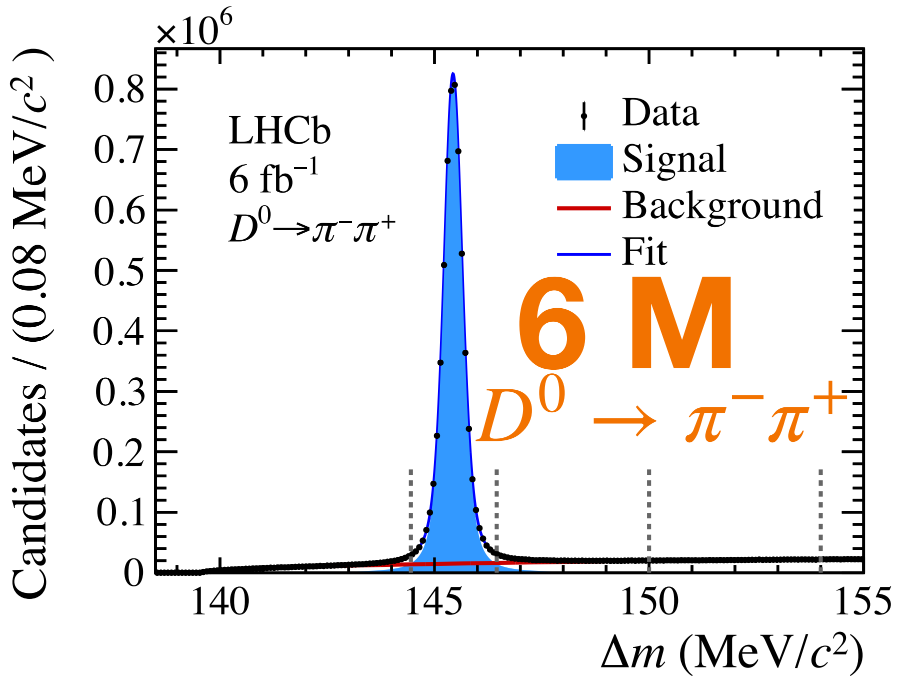
→ compatible with 0

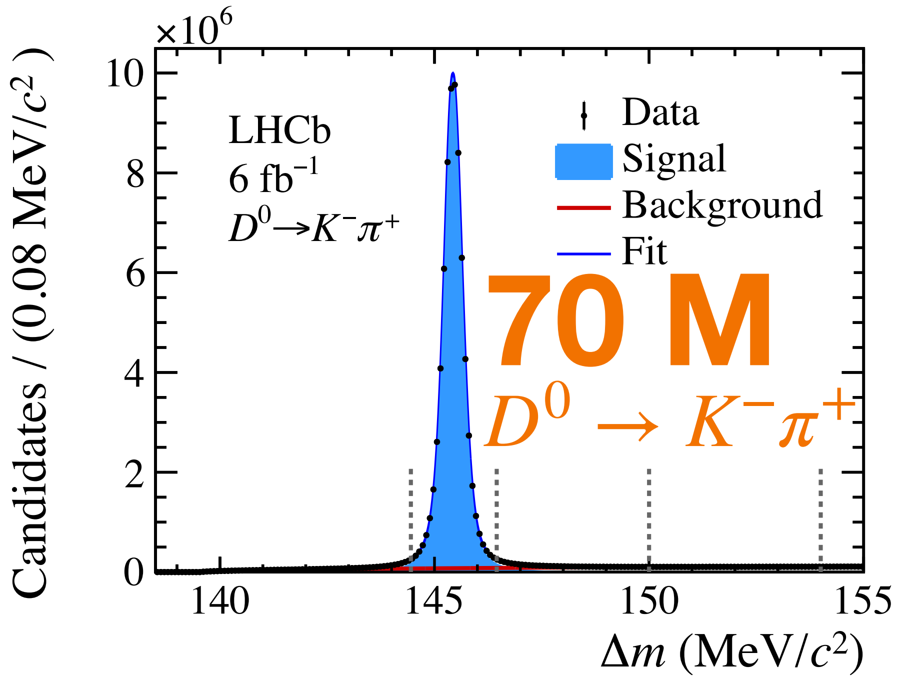
$$y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3}$$











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
- Analysis performed with model-independent *bin-flip* method, which does not require accurate modelling of the efficiency PRD 99 (2019) 012007
- 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

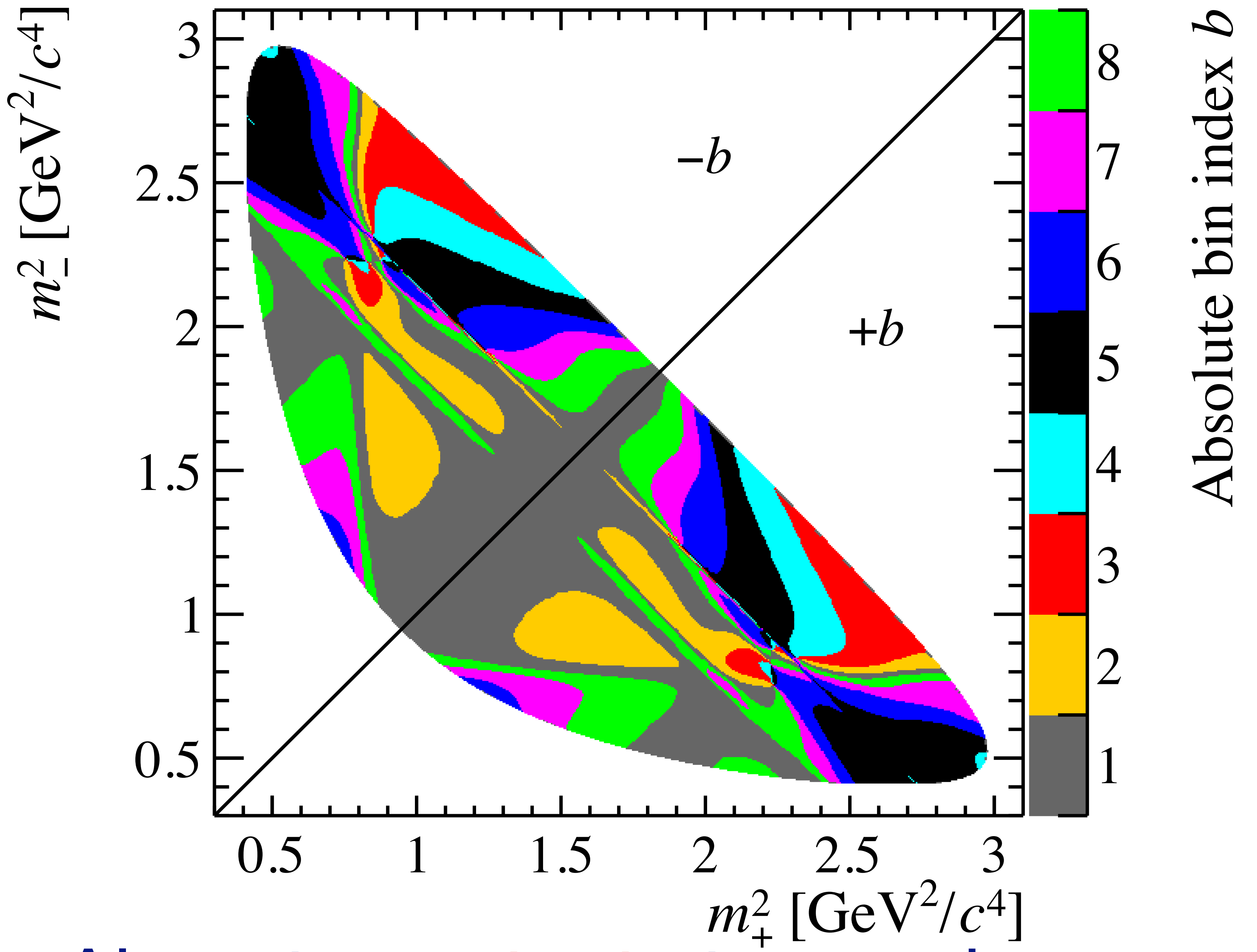
$$x_{CP} = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

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

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

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

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



PRD 82 (2010) 112006

PRD 101 (2020) 112002

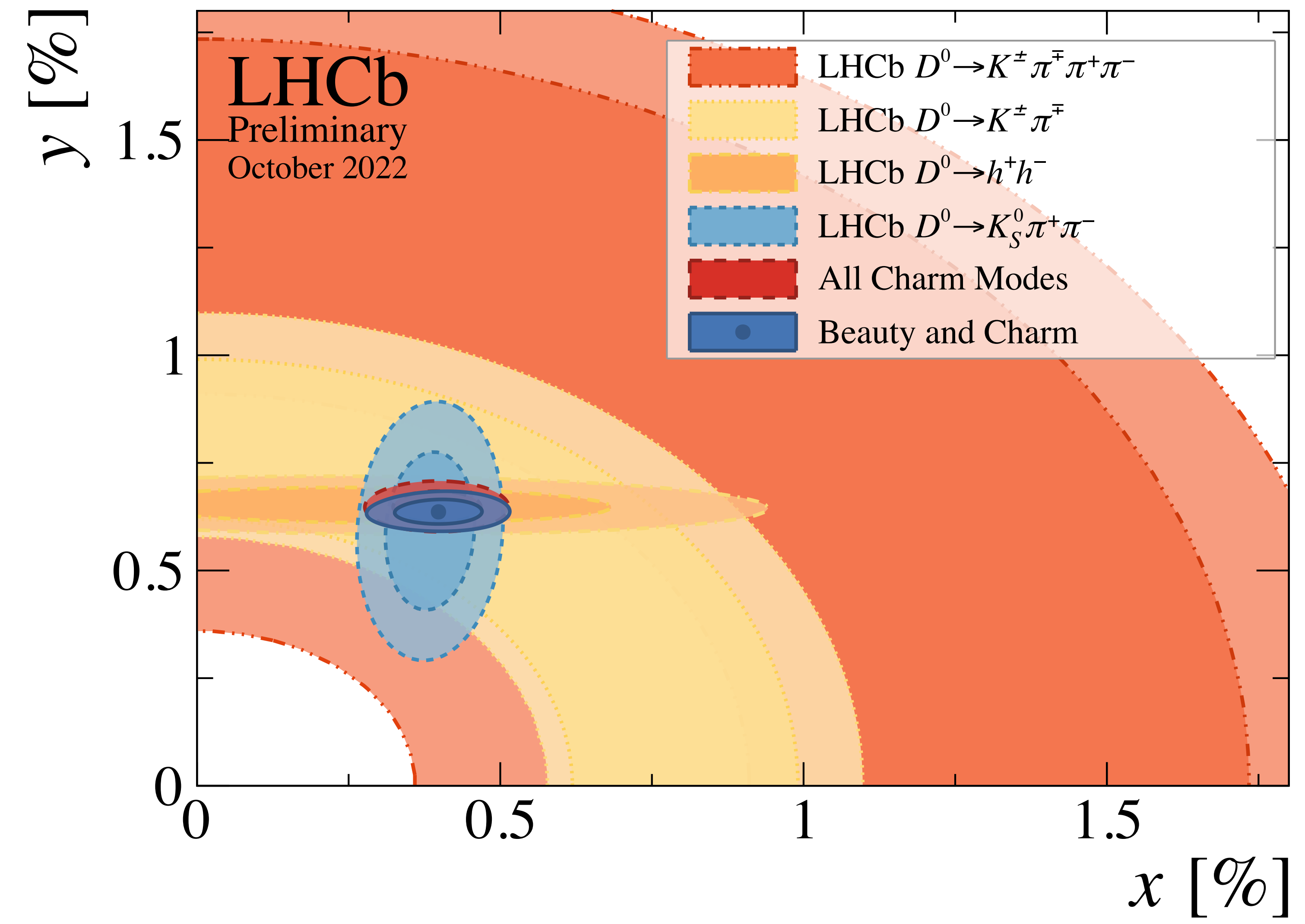
Almost constant strong-phase difference in each Dalitz bin ➡ external inputs from CLEO and BESIII

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

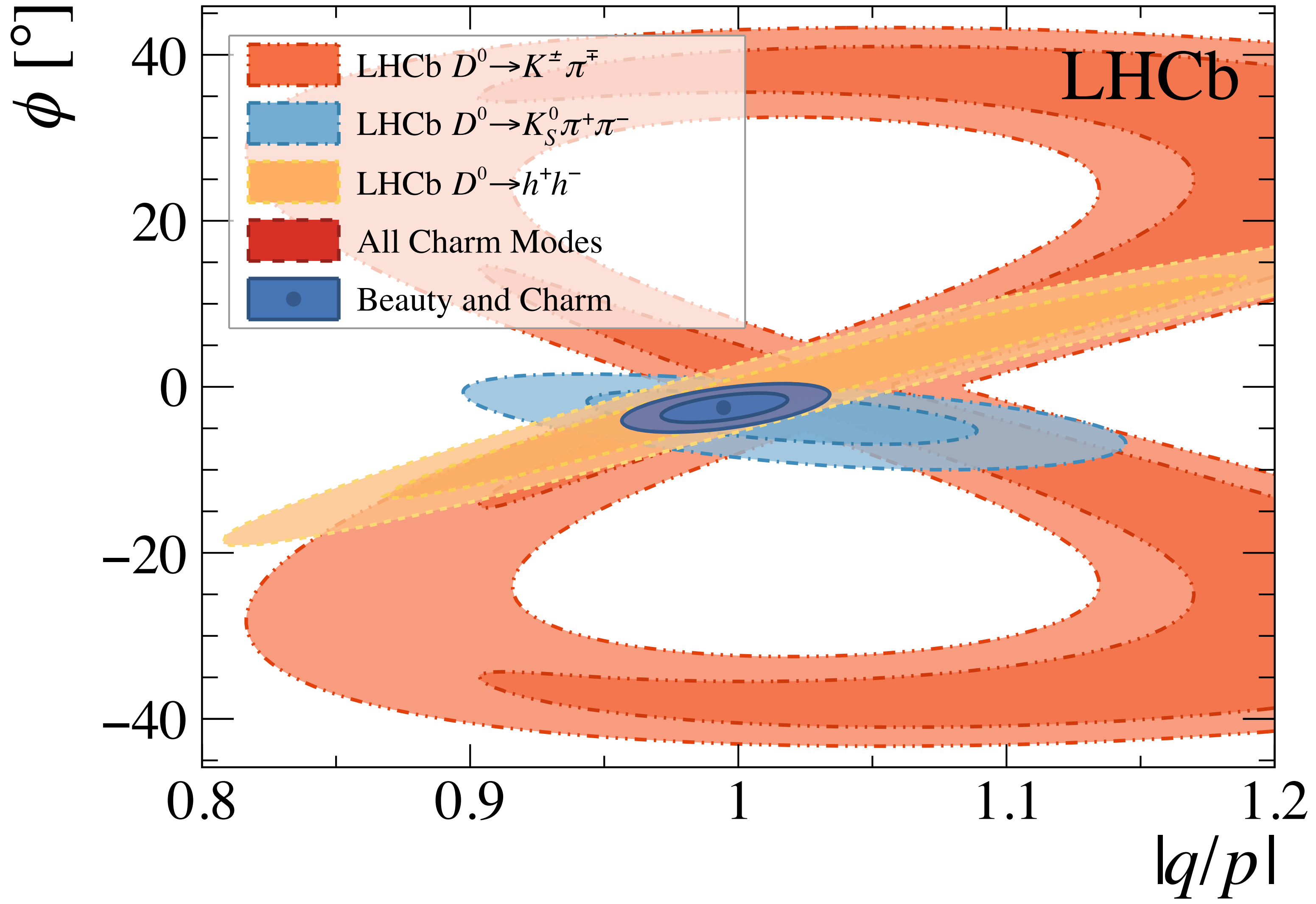
- All previously mentioned measurements are included in the latest combination



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	$^{+0.020}_{-0.019}$	$[0.617, 0.656]$	$^{+0.041}_{-0.039}$	$[0.597, 0.677]$
$\lvert q/p \rvert$	0.995	$^{+0.015}_{-0.016}$	$[0.979, 1.010]$	$^{+0.032}_{-0.032}$	$[0.963, 1.027]$
$\phi[°]$	-2.5	$^{+1.2}_{-1.2}$	$[-3.7, -1.3]$	$^{+2.4}_{-2.5}$	$[-5.0, -0.1]$



γ + charm combination

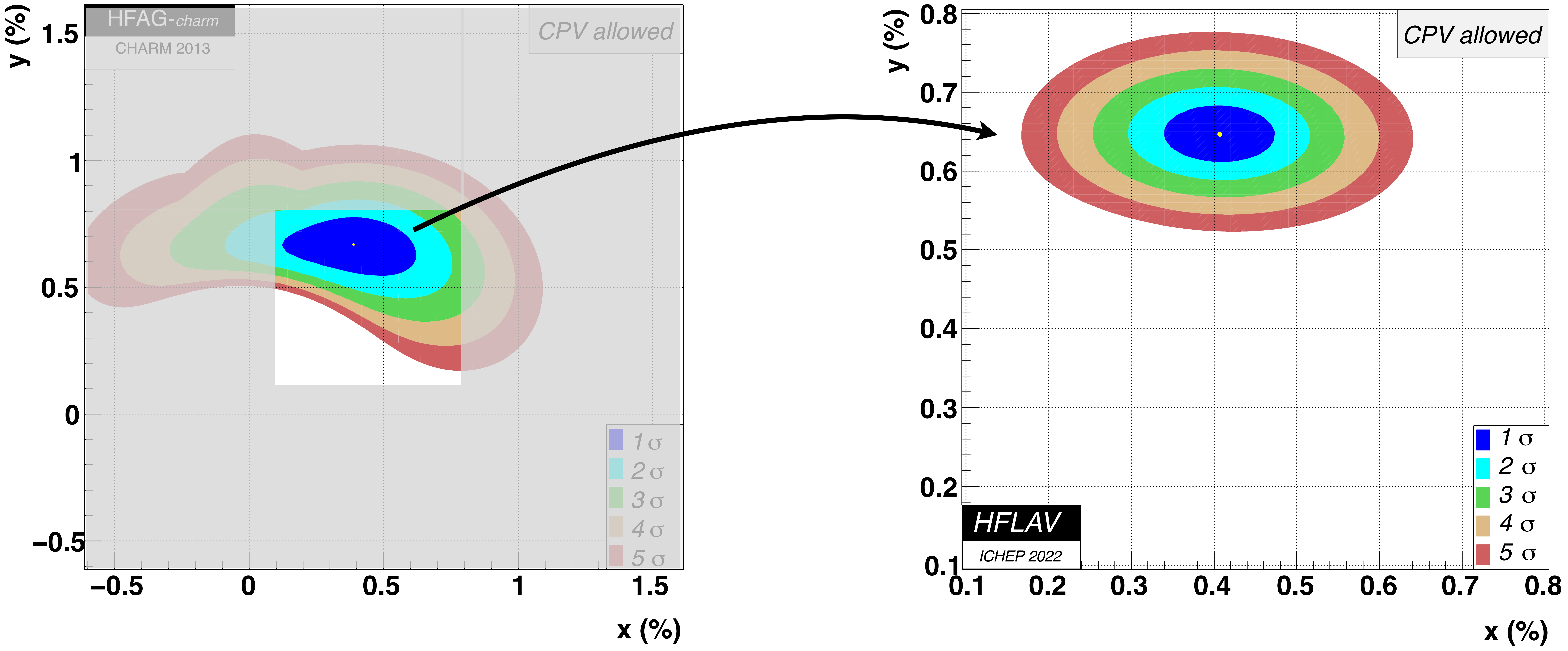
LHCb-CONF-2022-003

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

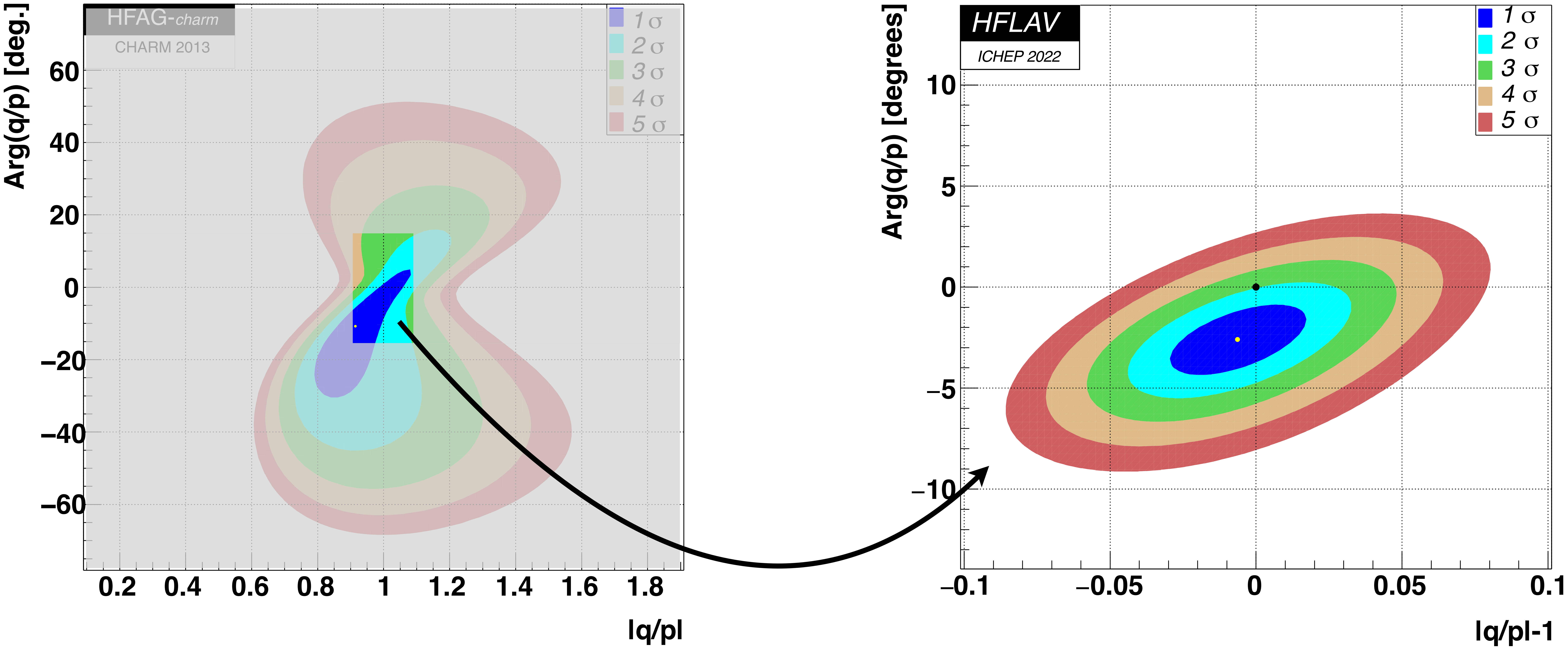
D decay	Observable(s)	Ref.	Dataset	Status since Ref. [14]
$D^0 \to h^+h^-$	ΔA_{CP}	[24, 40, 41]	Run 1&2	As before
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[16, 24, 25]	Run 2	**New**
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[42]	Run 1	As before
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[15]	Run 2	**New**
$D^0 \to h^+h^-$	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 Uncertainty	68.3% CL Interval	95.4% CL Uncertainty	95.4% CL 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]
$r_{B^0_s}^{D_s^\mp K^\pm}$	0.310	$^{+0.096}_{-0.094}$	[0.216, 0.406]	$^{+0.20}_{-0.22}$	[0.09, 0.51]
$\delta_{B^0_s}^{D_s^\mp K^\pm}[^\circ]$	356	$^{+19}_{-18}$	[338, 375]	$^{+39}_{-38}$	[318, 395]
$r_{B^0_s}^{D_s^\mp K^\pm\pi^+\pi^-}$	0.460	$^{+0.081}_{-0.085}$	[0.375, 0.541]	$^{+0.16}_{-0.17}$	[0.29, 0.62]
$\delta_{B^0_s}^{D_s^\mp K^\pm\pi^+\pi^-}[^\circ]$	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]

Landscape after 10 years



Landscape after 10 years



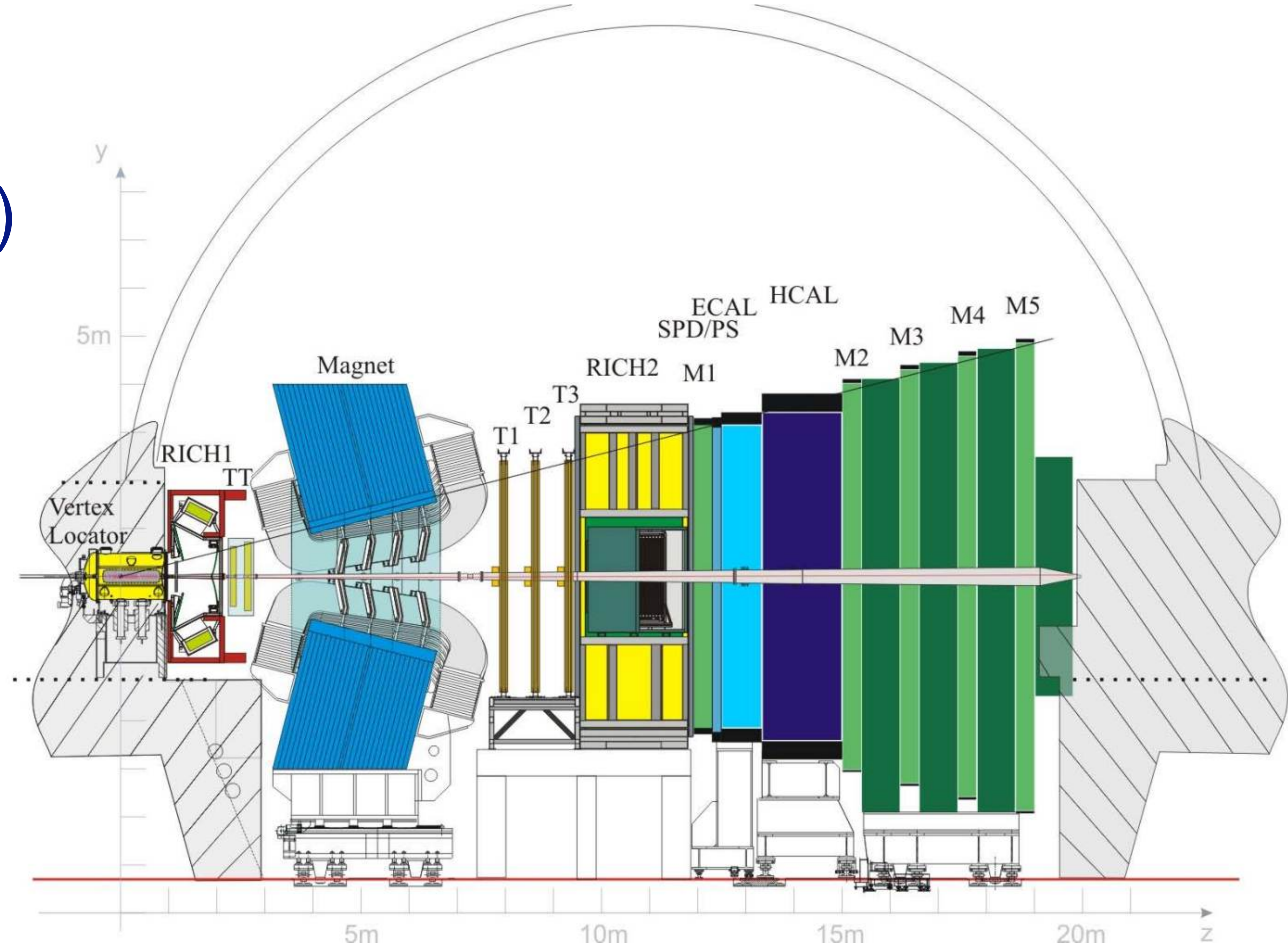
Charm at LHCb

- 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 ($13\ \mu\text{m}$ in transverse plane for PV)
  - ✦ Excellent IP resolution ($\sim 20\ \mu\text{m}$)
  - ✦ Very good momentum resolution ($\delta p/p \sim 0.5\% - 0.8\,\%$)
  - ✦ Excellent PID capabilities
  - ✦ Very good trigger efficiency (~90%)



Other future prospects (LHCb)

Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(x'^2_{K\pi})$	$\sigma(y'_{K\pi})$	$\sigma(A_D)$	$\sigma(\|q/p\|)$	$\sigma(\phi)$
Run 1–2 ($9\,\text{fb}^{-1}$)	1.8	1.5×10^{-5}	2.9×10^{-4}	0.51%	0.12	10°
Run 1–3 ($23\,\text{fb}^{-1}$)	10	6.4×10^{-6}	1.2×10^{-4}	0.22%	0.05	4°
Run 1–4 ($50\,\text{fb}^{-1}$)	25	3.9×10^{-6}	7.6×10^{-5}	0.14%	0.03	3°
Run 1–5 ($300\,\text{fb}^{-1}$)	170	1.5×10^{-6}	2.9×10^{-5}	0.05%	0.01	1°

Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(x'_{K\pi\pi\pi})$	$\sigma(y'_{K\pi\pi\pi})$	$\sigma(\|q/p\|)$	$\sigma(\phi)$
Run 1–2 ($9\,\text{fb}^{-1}$)	0.22	2.3×10^{-4}	2.3×10^{-4}	0.020	1.2°
Run 1–3 ($23\,\text{fb}^{-1}$)	1.29	0.9×10^{-4}	0.9×10^{-4}	0.008	0.5°
Run 1–4 ($50\,\text{fb}^{-1}$)	3.36	0.6×10^{-4}	0.6×10^{-4}	0.005	0.3°
Run 1–5 ($300\,\text{fb}^{-1}$)	22.5	0.2×10^{-4}	0.2×10^{-4}	0.002	0.1°

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Other future prospects (LHCb)

Sample ($\mathcal{L}$)	$D^+ \to K^-K^+\pi^+$	$D^+ \to \pi^-\pi^+\pi^+$	$D^+ \to K^-K^+K^+$	$D^+ \to \pi^-K^+\pi^+$
Run 1–2 ($9\,\text{fb}^{-1}$)	200	100	14	8
Run 1–4 ($23\,\text{fb}^{-1}$)	1,000	500	70	40
Run 1–4 ($50\,\text{fb}^{-1}$)	2,600	1,300	182	104
Run 1–6 ($300\,\text{fb}^{-1}$)	17,420	8,710	1,219	697

	$D^0 \to \pi^+\pi^-\pi^+\pi^-$		$D^0 \to K^+K^-\pi^+\pi^-$	
Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(a_{CP}^{\widehat{T}\text{-odd}})$	Yield ($\times 10^6$)	$\sigma(a_{CP}^{\widehat{T}\text{-odd}})$
Run 1–2 ($9\,\text{fb}^{-1}$)	13.5	2.4×10^{-4}	4.7	5.4×10^{-4}
Run 1–3 ($23\,\text{fb}^{-1}$)	69	1.1×10^{-4}	12	3.4×10^{-4}
Run 1–4 ($50\,\text{fb}^{-1}$)	150	7.5×10^{-5}	26	2.3×10^{-4}
Run 1–5 ($300\,\text{fb}^{-1}$)	900	2.9×10^{-5}	156	9.4×10^{-5}

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Other future prospects (Belle II)

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

Parameter	$5\,\text{ab}^{-1}$	$20\,\text{ab}^{-1}$	$50\,\text{ab}^{-1}$
$\delta x'^2$ (10^{-5})	6.2	3.2	2.0
$\delta y'$ (%)	0.093	0.047	0.029
$\delta x'$ (%)	0.32	0.22	0.13
$\delta y'$ (%)	0.23	0.15	0.097
$\delta\|q/p\|$	0.174	0.073	0.043
$\delta\phi$ (°)	13.2	8.4	5.4