CKM and $\mathcal{CP}$ violation in beauty and charm decays in LHCb

Federico Betti on behalf
of the LHCb collaboration

57th Recontres de Moriond 2023
Electroweak Interactions and Unified Theories Session

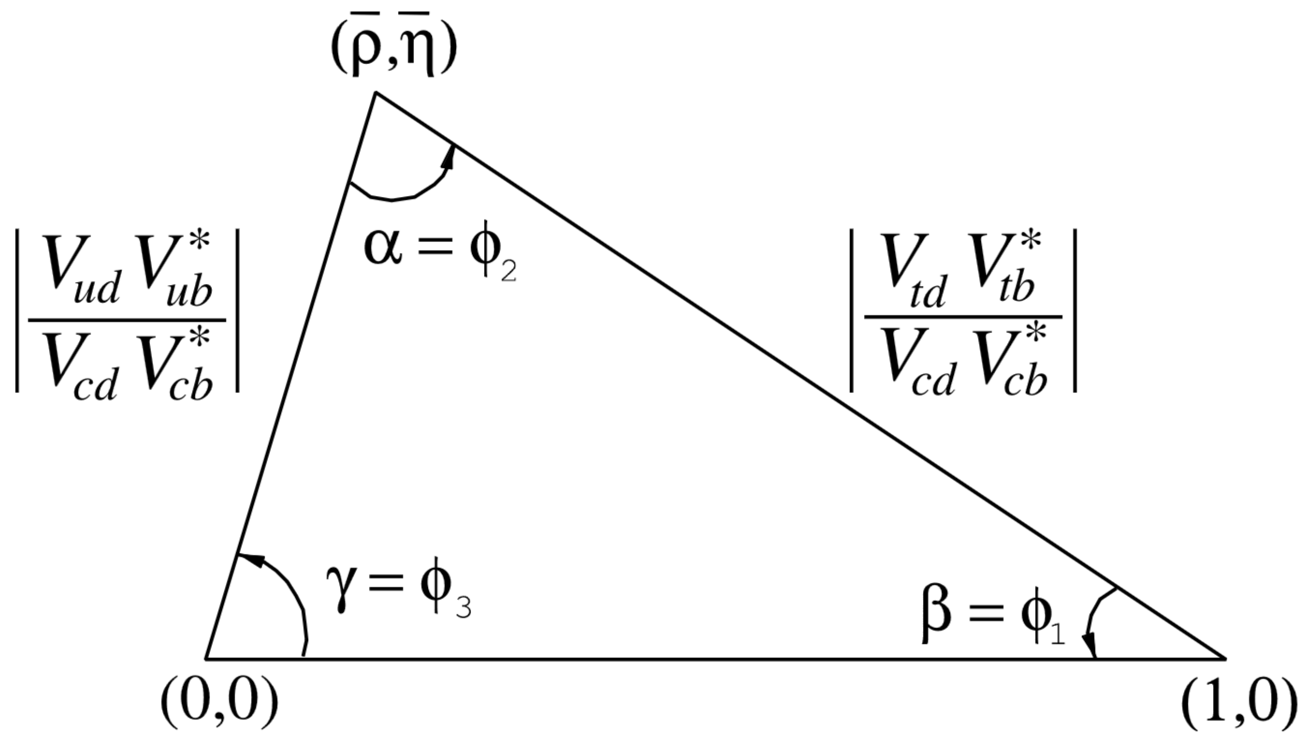
20 March 2023

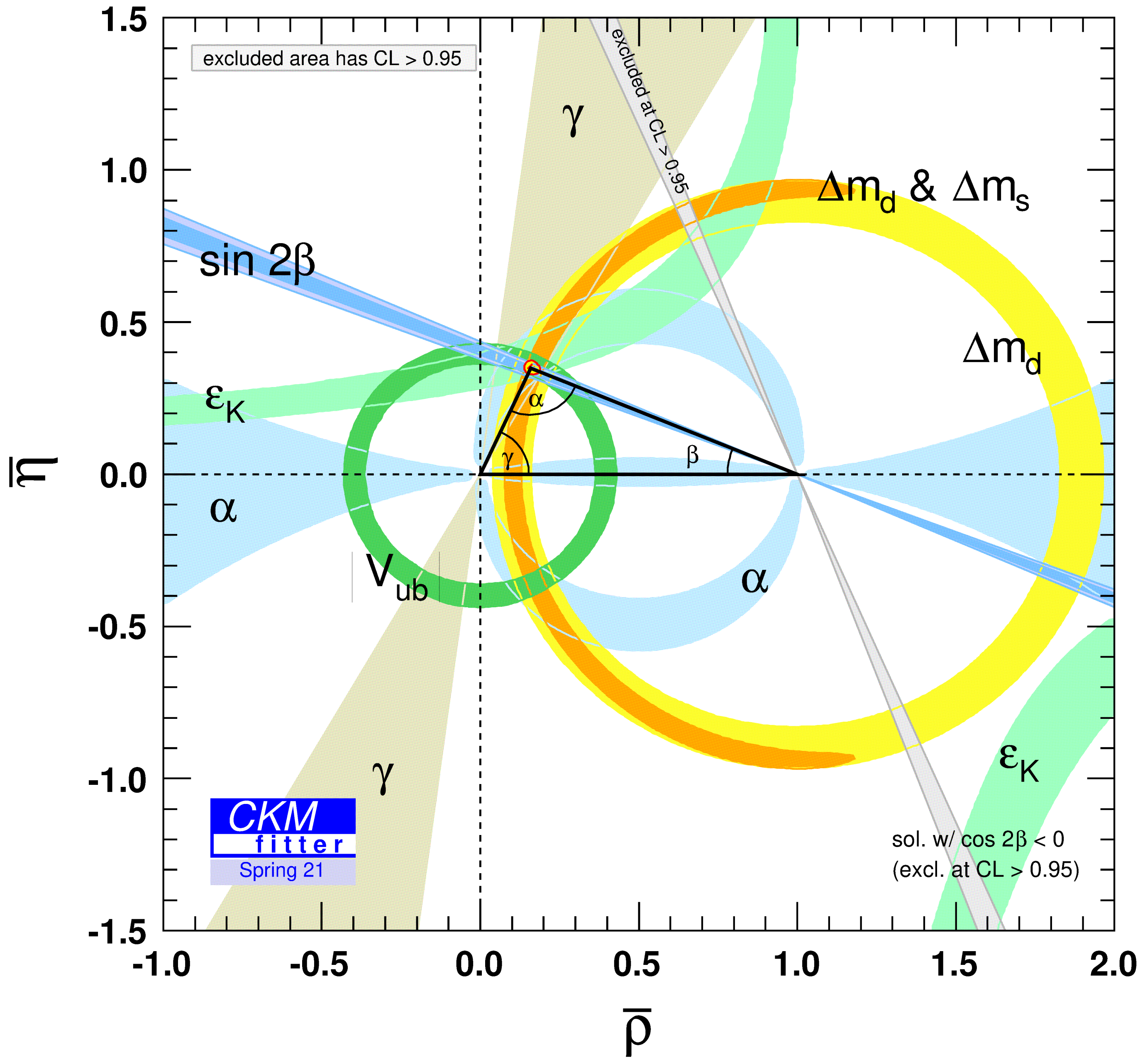
Outline

- Introduction
- Time-dependent $C\!P$ violation:
  - NEW - $B_s^0 \to \phi\phi$
  - $\tau_{\rm L}$ of $B_s^0 \to J/\psi\eta$
- Direct measurements of γ:
  - $B^\pm \to [K^\mp\pi^\pm\pi^\pm\pi^\mp]_D h^\pm$
  - $B^\pm \to [h^+h^-\pi^\pm\pi^\mp]_D h^\pm$
- $C\!P$ violation in charm:
  - local $C\!P$ violation in $D_{(s)}^+ \to K^-K^+K^+$
  - $A_{C\!P}(D^0 \to K^-K^+)$

Introduction

- CKM matrix unitarity: key test of the SM
- CKM phases responsible for $\mathcal{CP}$ violation in quark transitions
- Magnitudes of CKM matrix elements determined with branching fractions and mixing measurements
- Sensitive to New Physics
- LHCb experiment ideal place for CKM and $\mathcal{CP}$ violation measurements in beauty and charm decays





$\mathcal{CP}$ violation in $B_s^0 \to \phi\phi$

LHCb-PAPER-2023-001 NEW

- Time-dependent $\mathcal{CP}$ violation arises from the interference between decay and mixing, characterised by phase $\phi_s^{s\bar{s}s}$ and $|\lambda|$ parameter
- In SM: $\phi_s^{s\bar{s}s}$ expected to be very close to 0 and $|\lambda|$ very close to 1
- Sensitive to NP in the penguin decay or the B_s^0 mixing
- Three linear polarisation states for $\phi\phi \Rightarrow$ NP may be polarisation-dependent
- Strategy: measure differential decay rate $\frac{\mathrm{d}^4\Gamma(t,\vec{\Omega})}{\mathrm{d}t\mathrm{d}\vec{\Omega}} \propto \sum_{k=1}^{6} h_k(t) f_k(\vec{\Omega})$

$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + b_k \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) + Q c_k \cos(\Delta m_s t) + Q d_k \sin(\Delta m_s t)\right]$$

N_k, a_k, b_k, c_k, d_k are function of amplitude magnitudes, phases, $\phi_{s,i}$ and $|\lambda_i|$ $(i = 0, \parallel, \perp)$

Q is the initial B_s^0 flavour

$f_k(\vec{\Omega})$ are functions of the helicity angles

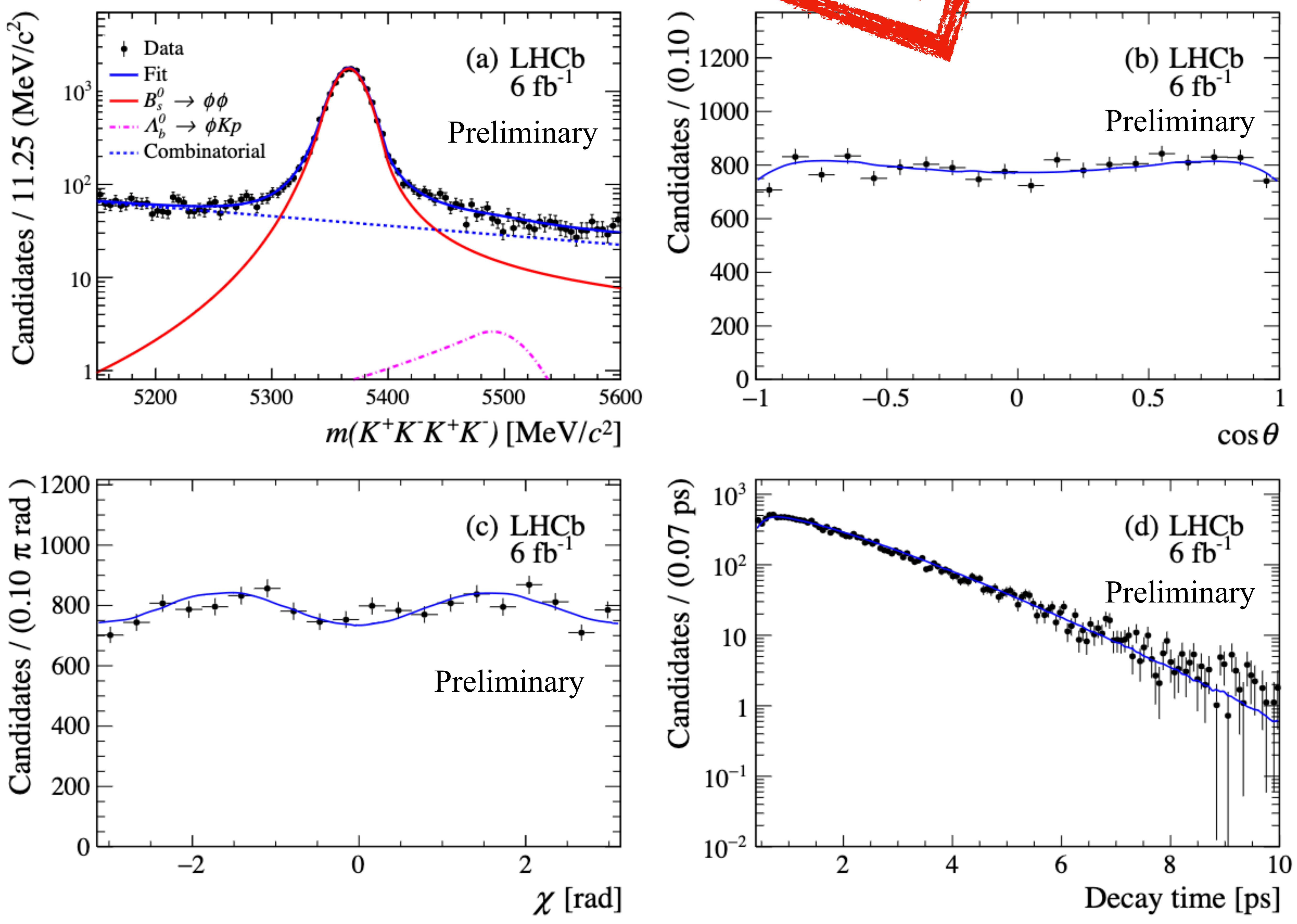
JHEP 12 (2019) 155

CP violation in $B_s^0 \to \phi\phi$

LHCb-PAPER-2023-001

NEW

- LHCb Run 2 data sample
- Angular and decay-time acceptance are obtained from simulation $\Rightarrow$ for angular acceptance, iterative procedure to correct for simulation-data differences, based on the agreement of $p_{\mathrm{T}}(K)$
- Flavour taggers are calibrated on $B^+ \to J/\psi K^+$ and $B_s^0 \to D_s^- \pi^+$ samples
- Both polarisation-dependent and polarisation-independent ($\phi_{s,i} = \phi_s^{s\bar{s}s}$ and $|\lambda_i| = |\lambda|$) fits are performed
- Dominant systematics: time resolution, flavour tagging, angular acceptance



CP violation in $B_s^0 \to \phi\phi$

NEW

LHCb-PAPER-2023-001

Run 2 results

Polarisation independent

$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009 \text{ rad}$$
$$|\lambda| = 1.004 \pm 0.030 \pm 0.009\,,$$

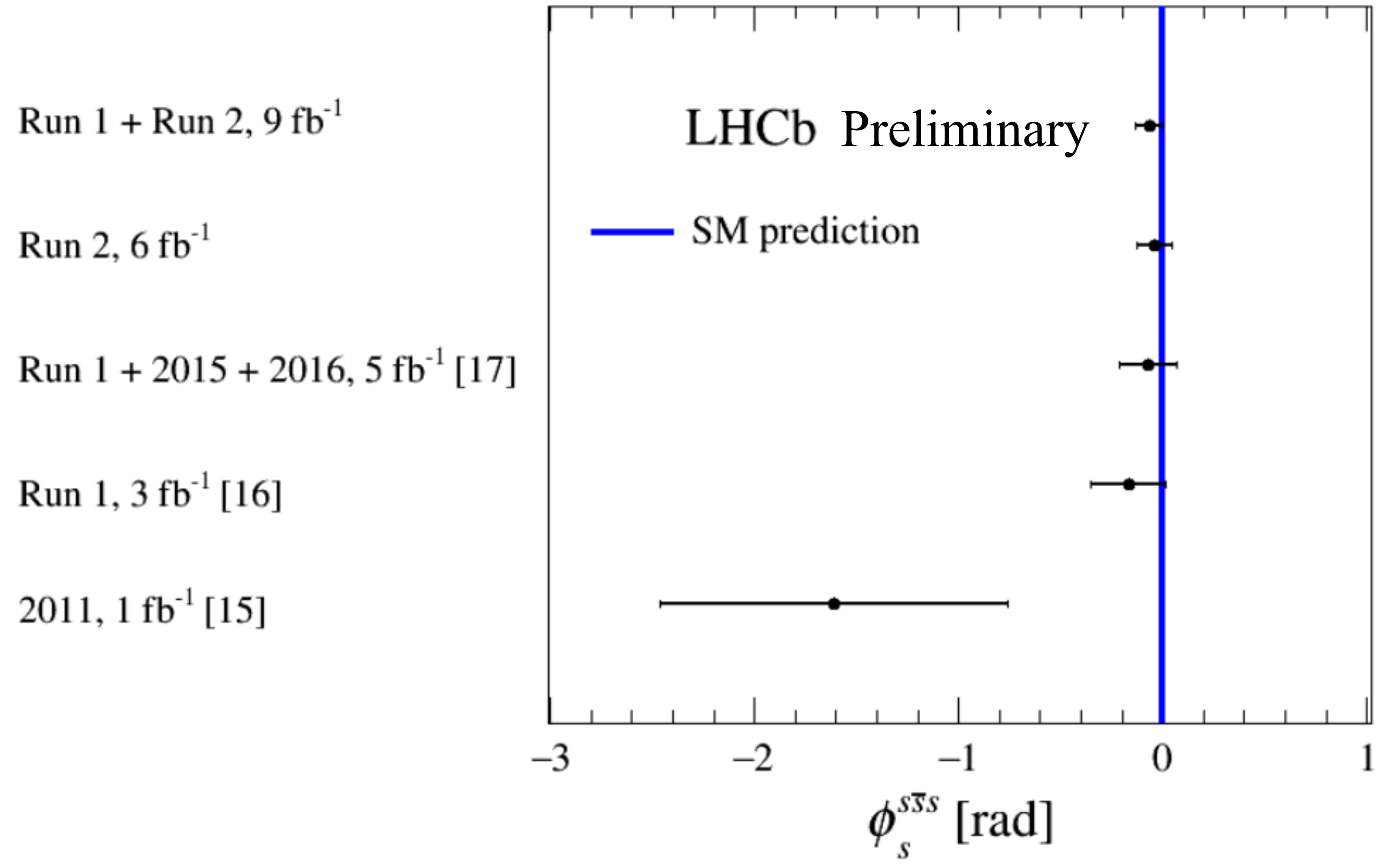
Polarisation dependent

$$|\lambda_0| = 1.02 \pm 0.17 \qquad \phi_{s,0} = -0.18 \pm 0.09 \text{ rad}$$
$$|\lambda_\perp/\lambda_0| = 0.97 \pm 0.22 \qquad \phi_{s,\parallel} - \phi_{s,0} = 0.12 \pm 0.09 \text{ rad}$$
$$|\lambda_\parallel/\lambda_0| = 0.78 \pm 0.21 \qquad \phi_{s,\perp} - \phi_{s,0} = 0.17 \pm 0.09 \text{ rad}$$

Combination with Run 1 gives:

$$\phi_s^{s\bar{s}s} = (-0.074 \pm 0.069) \text{ rad}$$
$$|\lambda| = 1.009 \pm 0.030$$

- Agreement with the SM
- Most precise measurement of time-dependent CP asymmetry in $B_s^0 \to \phi\phi$
- Polarisation-dependent CP-violation parameters are measured for the first time
  $\Rightarrow$ no difference observed between different polarisation states

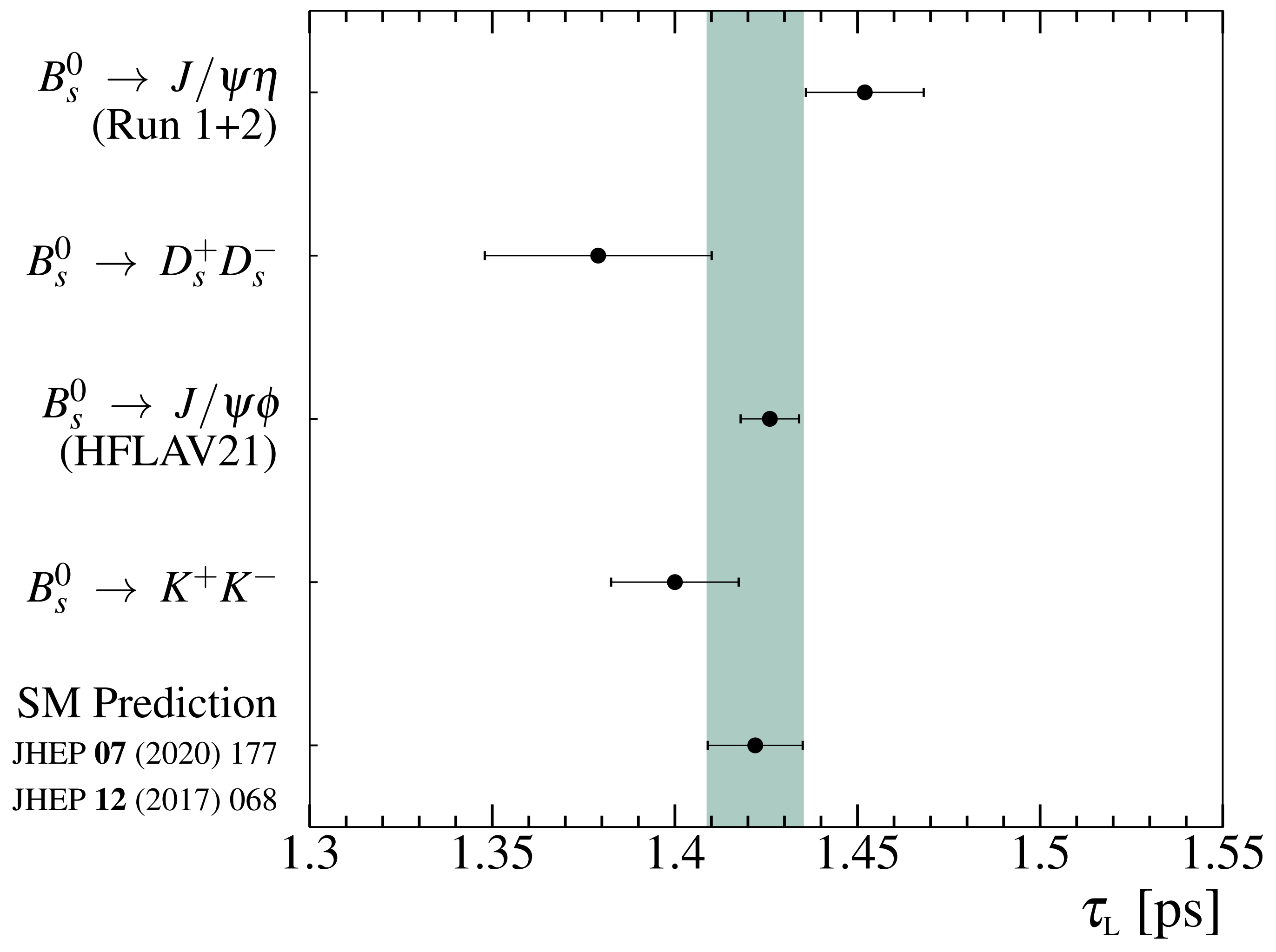


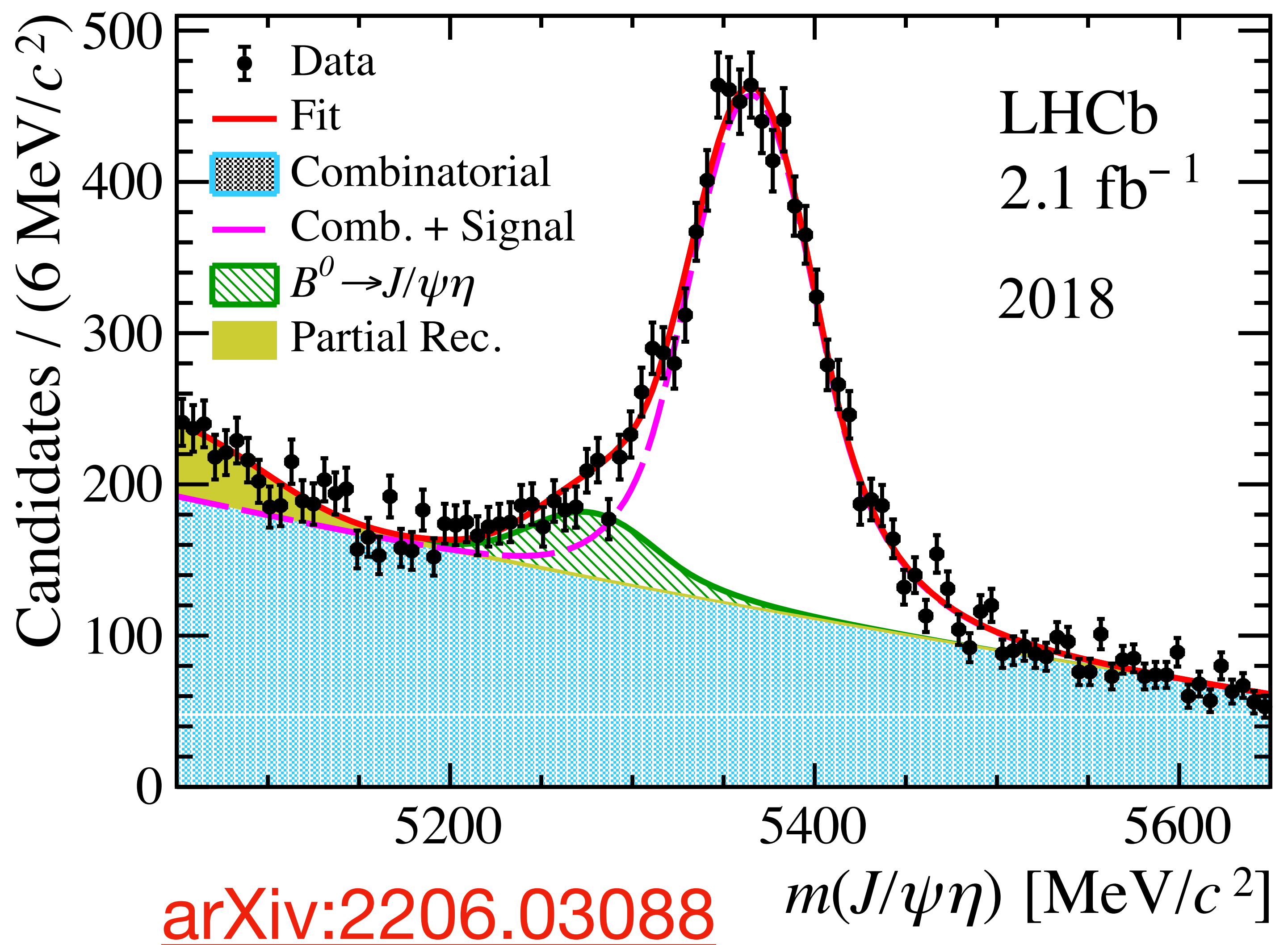
τ_L of $B_s^0 \to J/\psi\eta$

- $C\!P$ violation in $B_s^0 - \overline{B}_s^0$ mixing small $\Rightarrow$ effective lifetime in $C\!P$-even modes determines $\tau_\mathrm{L} = 1/\Gamma_\mathrm{L}$
- Stringent test of consistency between direct measurements of $\Delta\Gamma_s$ and those inferred from effective lifetimes
- Run 2 result: $\tau_\mathrm{L} = (1.445 \pm 0.016 \pm 0.008)$ ps
- Combination with Run 1: $\tau_\mathrm{L} = (1.452 \pm 0.014 \pm 0.007 \pm 0.002)$ ps

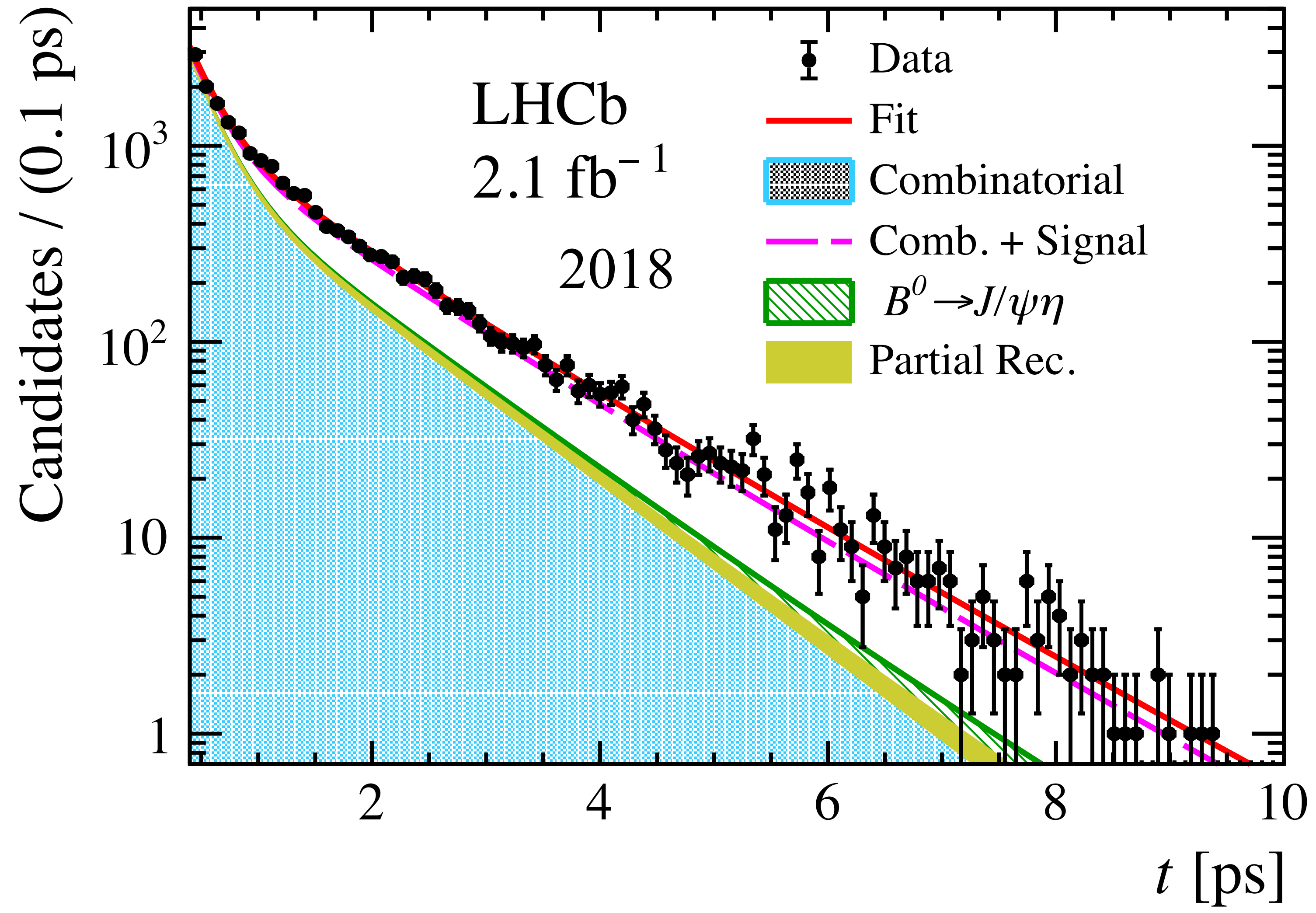
correlated syst. (0.007) — uncorrelated syst. (0.002)

- Future improvements expected with other final states with $\eta^{(\prime)}$ and Run 2 $B_s^0 \to D_s^+ D_s^-$





arXiv:2206.03088

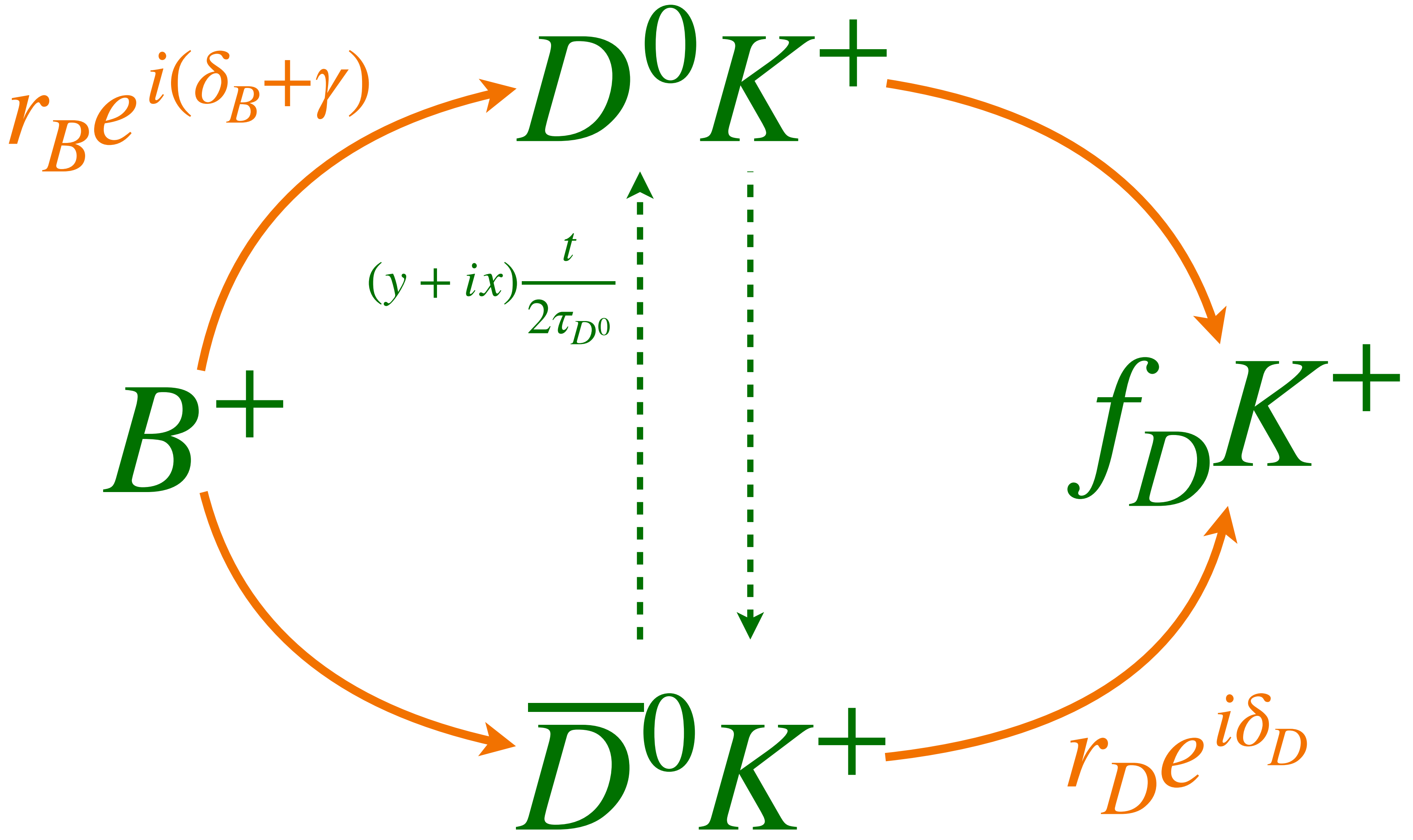


Direct measurements of γ

$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- γ measured in tree-level decays sensitive to interference between $b \to cW$ and $b \to uW$ transition amplitudes

- Golden modes: $B^\pm \to DK^\pm$



$$\Gamma(B^\pm \to f_D h^\pm) \propto r_D^2 + r_B^2 + 2r_D r_B R_D \cos(\delta_B + \delta_D \pm \gamma)$$
$$- r_D R_D (y\cos\delta_D - x\sin\delta_D) + \frac{1}{2}(x^2+y^2)$$
$$- r_B[y\cos(\delta_B \pm \gamma) + x\sin(\delta_B \pm \gamma)]$$

- R_D coherence factor → suppresses interference and reduces sensitivity

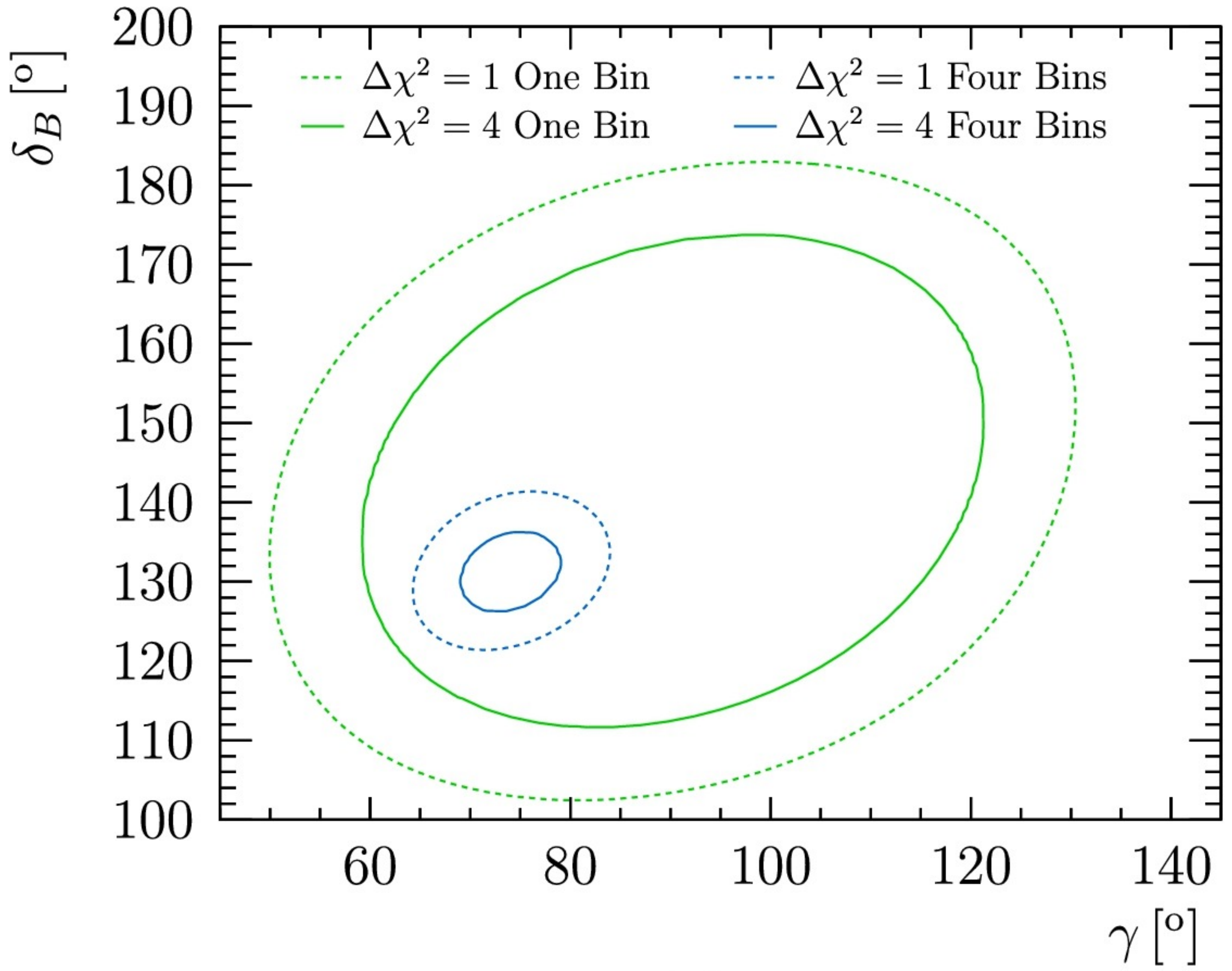
Measurement of γ with $B^{\pm} \to [K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]_D h^{\pm}$

arXiv:2209.03692

- $R_{K3\pi} \simeq 0.4$, but in decay phase-space bins $R^i_{K3\pi}$ can reach also 1 $\Rightarrow$ increased sensitivity with binned measurement

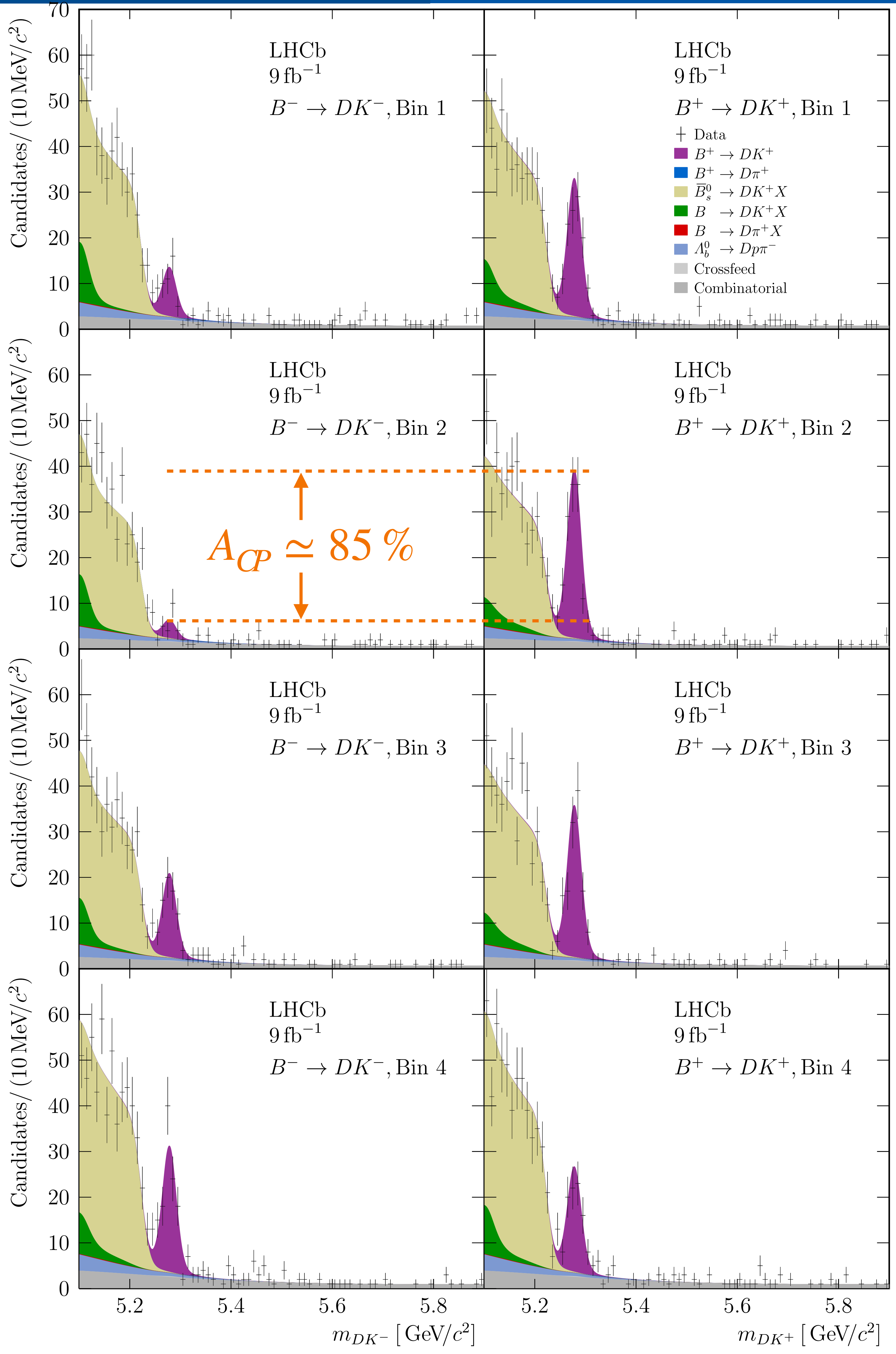
EPJC 78 (2018) 6, 443

- 4 bins chosen according to LHCb amplitude analysis
- LHCb Run 1 + Run 2 data sample



Bin	Measured $R^i_{K3\pi}$	Measured $\delta^i_{K3\pi}$
1	$0.61^{+0.28}_{-0.54}$	$\left(100^{+55}_{-18}\right)^\circ$
2	$1.00^{+0.00}_{-0.40}$	$\left(131^{+34}_{-12}\right)^\circ$
3	$0.53^{+0.34}_{-0.21}$	$\left(157^{+77}_{-36}\right)^\circ$
4	$0.19^{+0.32}_{-0.18}$	$\left(26^{+67}_{-90}\right)^\circ$

PLB 802 (2020) 135188



Measurement of γ with $B^{\pm} \to [K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]_D h^{\pm}$

arXiv:2209.03692

$$\gamma = \left(54.8^{+6.0+0.6+6.7}_{-5.8-0.6-4.3}\right)^{\circ}$$

- γ obtained using external inputs for:
  - Hadronic D decay parameters from model-independent determinations by CLEO-c and BESIII JHEP 05 (2021) 164
  - $D^0 - \overline{D}^0$ mixing parameters by LHCb PRL 116 (2016) 241801
- 2nd most precise determination of γ from single D-decay mode
- Large improvement expected from incoming BESIII $\psi(3770)$ data ($20\ \mathrm{fb}^{-1}$) and LHCb measurement of D^0 mixing with promptly-produced D^0

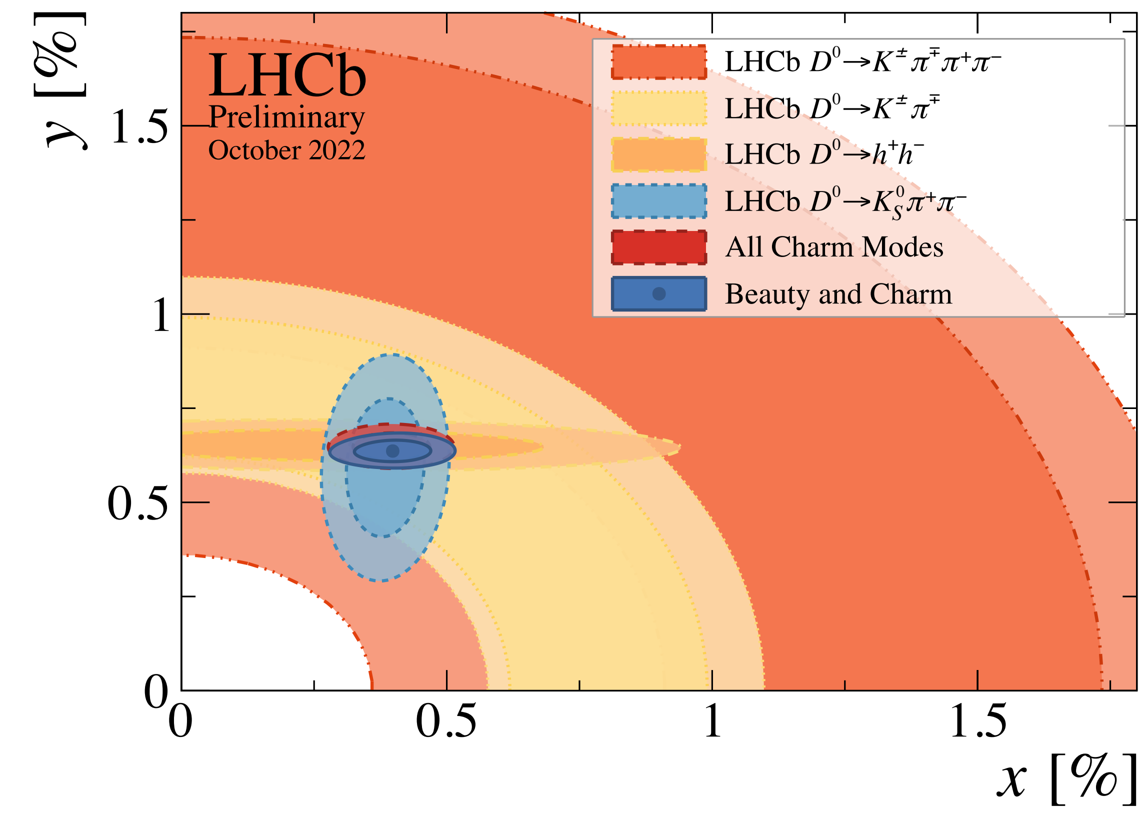
γ + charm combination

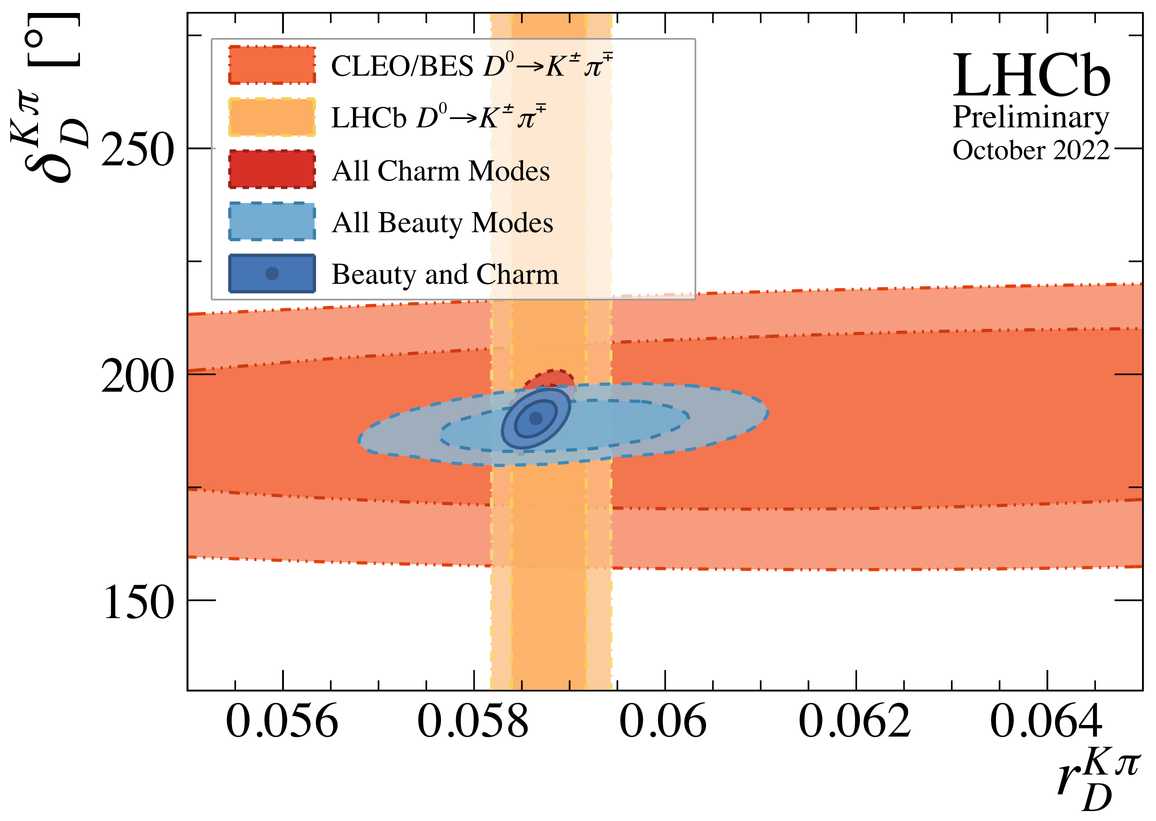
LHCb-CONF-2022-003

- Latest LHCb combination includes new and updated measurements of:
  - $B^{\pm} \to [h^{\pm}h'^{\mp}\pi^0]_D h^{\pm}$ arXiv:2112.10617
  - $B^{\pm} \to [K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]_D h^{\pm}$ arXiv:2209.03692
  - y_{CP} in $D^0 \to h^+h^-$ PRD 105 (2022) 092013
  - x_{CP}, y_{CP}, δx, δy in $\overline{B} \to D^0(\to K_s^0\pi^+\pi^-)\mu^-\overline{\nu}_{\mu}X$ arXiv:2208.06512
  - $A_{CP}(D^0 \to K^-K^+)$ arXiv:2209.03179

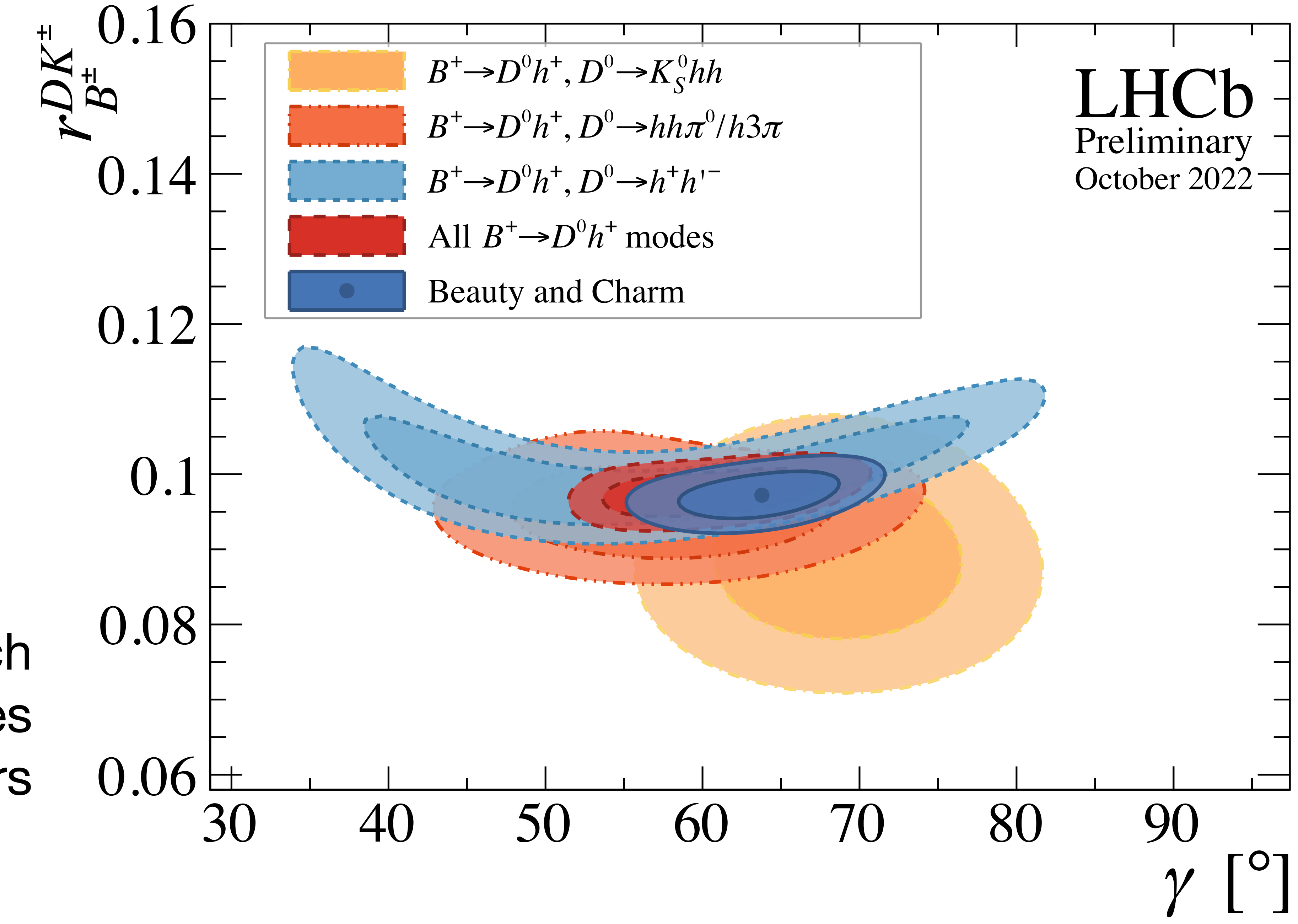
- Compatibility with indirect determinations
  - $\gamma = \left(65.7^{+0.9}_{-2.7}\right)^{\circ}$ CKMfitter
  - $\gamma = \left(65.8 \pm 2.2\right)^{\circ}$ UTFit

$$\gamma = \left(63.8^{+3.5}_{-3.7}\right)^{\circ}$$



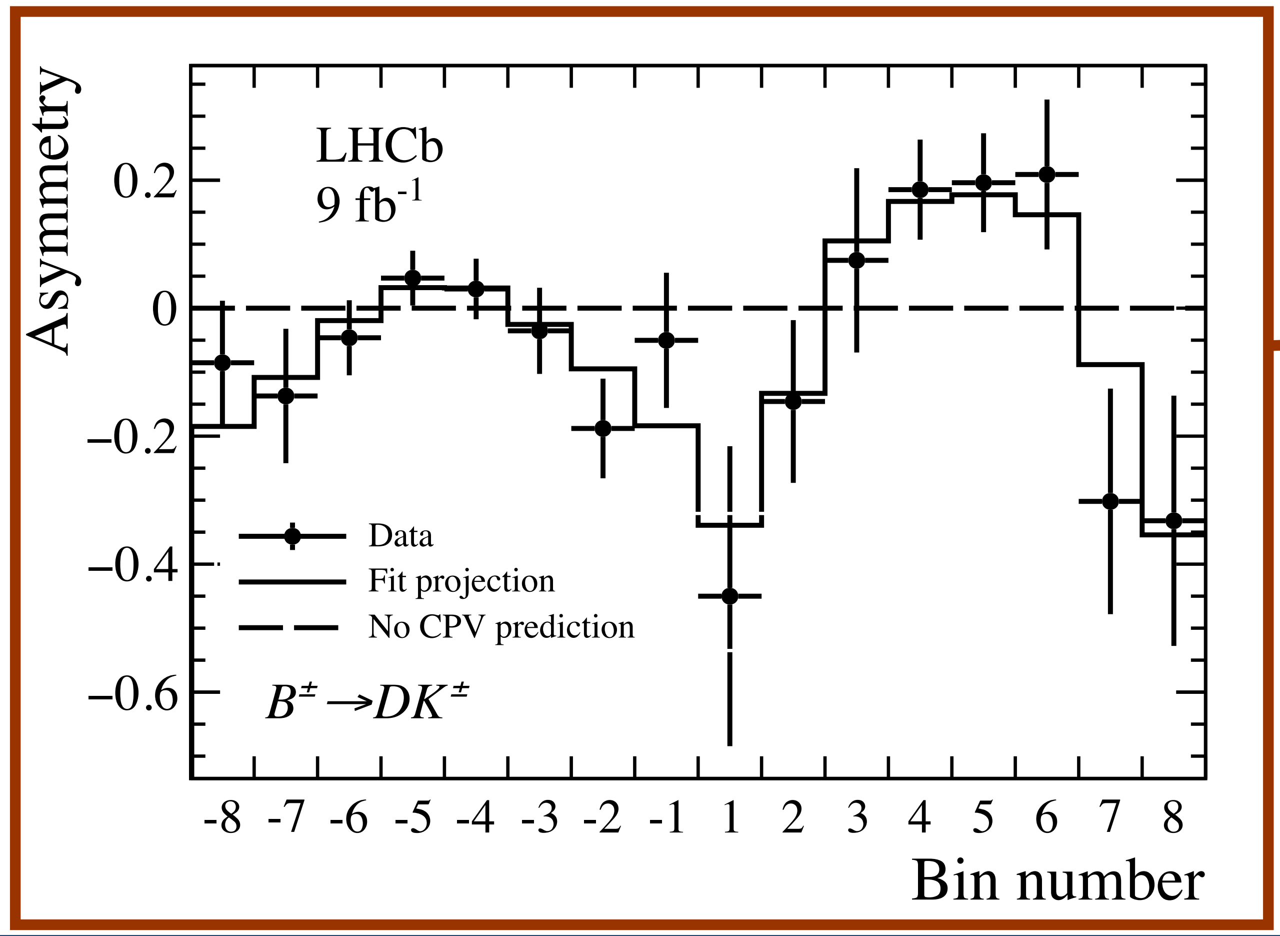


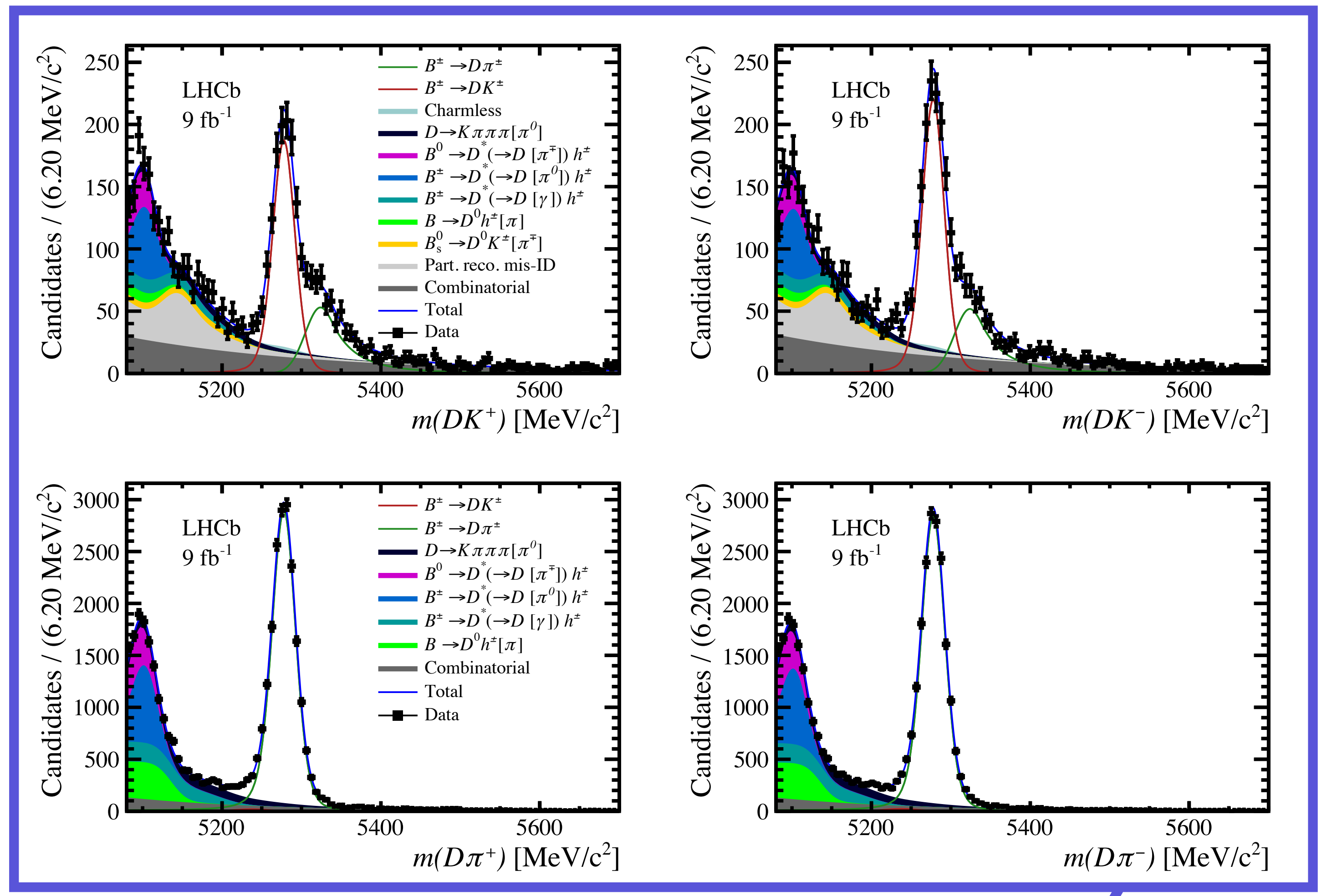
Frequentist approach
173 observables
52 parameters



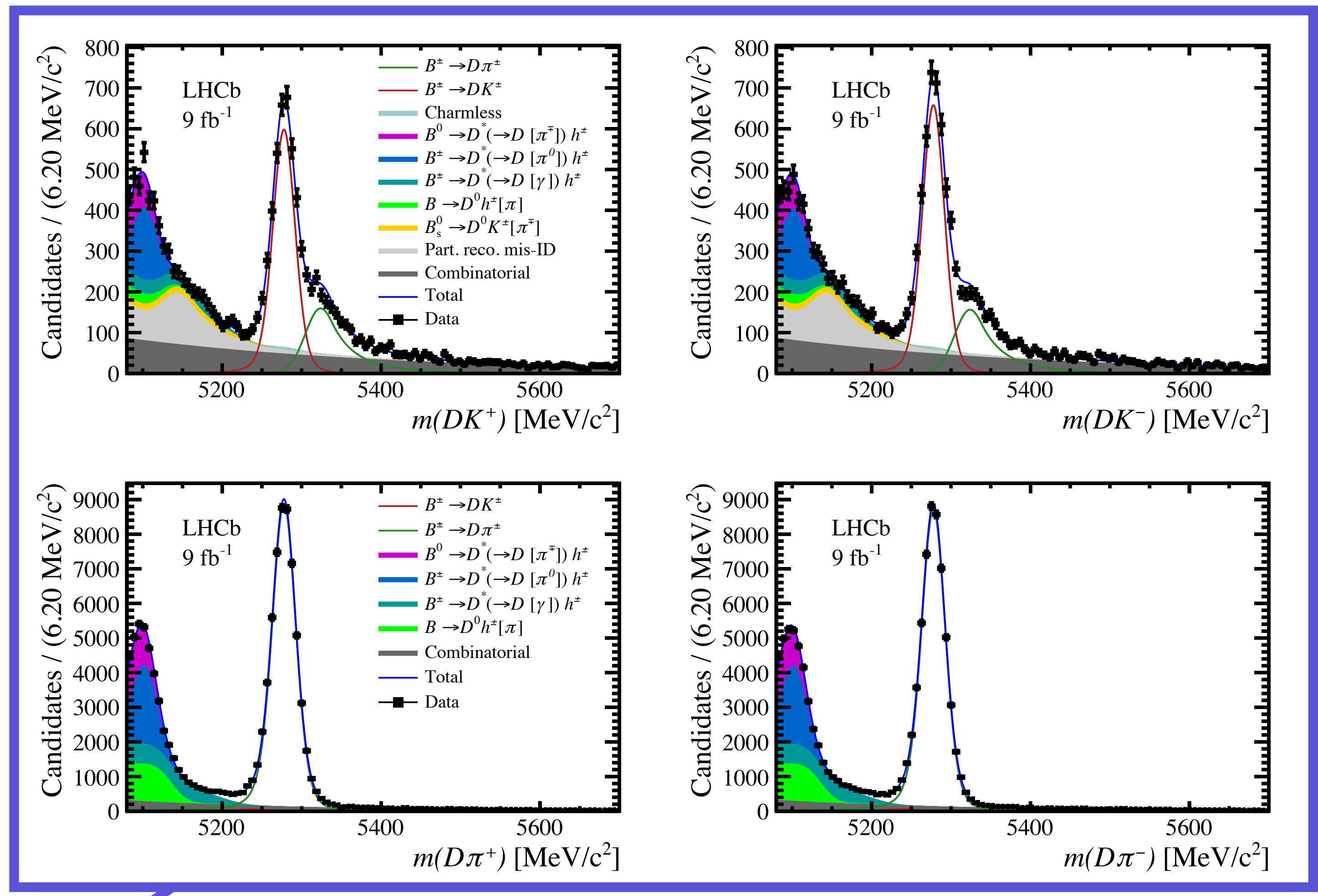
Measurement of γ with $B^{\pm} \to [h^+h^-\pi^{\pm}\pi^{\mp}]_D h^{\pm}$

- First study of CP violation in $B^{\pm} \to [K^+K^-\pi^{\pm}\pi^{\mp}]_D h^{\pm}$
- LHCb Run 1 + Run 2 data sample
- Integrated analysis for $K^+K^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$
- Also binned analysis for $K^+K^-\pi^+\pi^- \to$ charm-decay parameters taken from LHCb amplitude analysis JHEP 02 (2019) 126

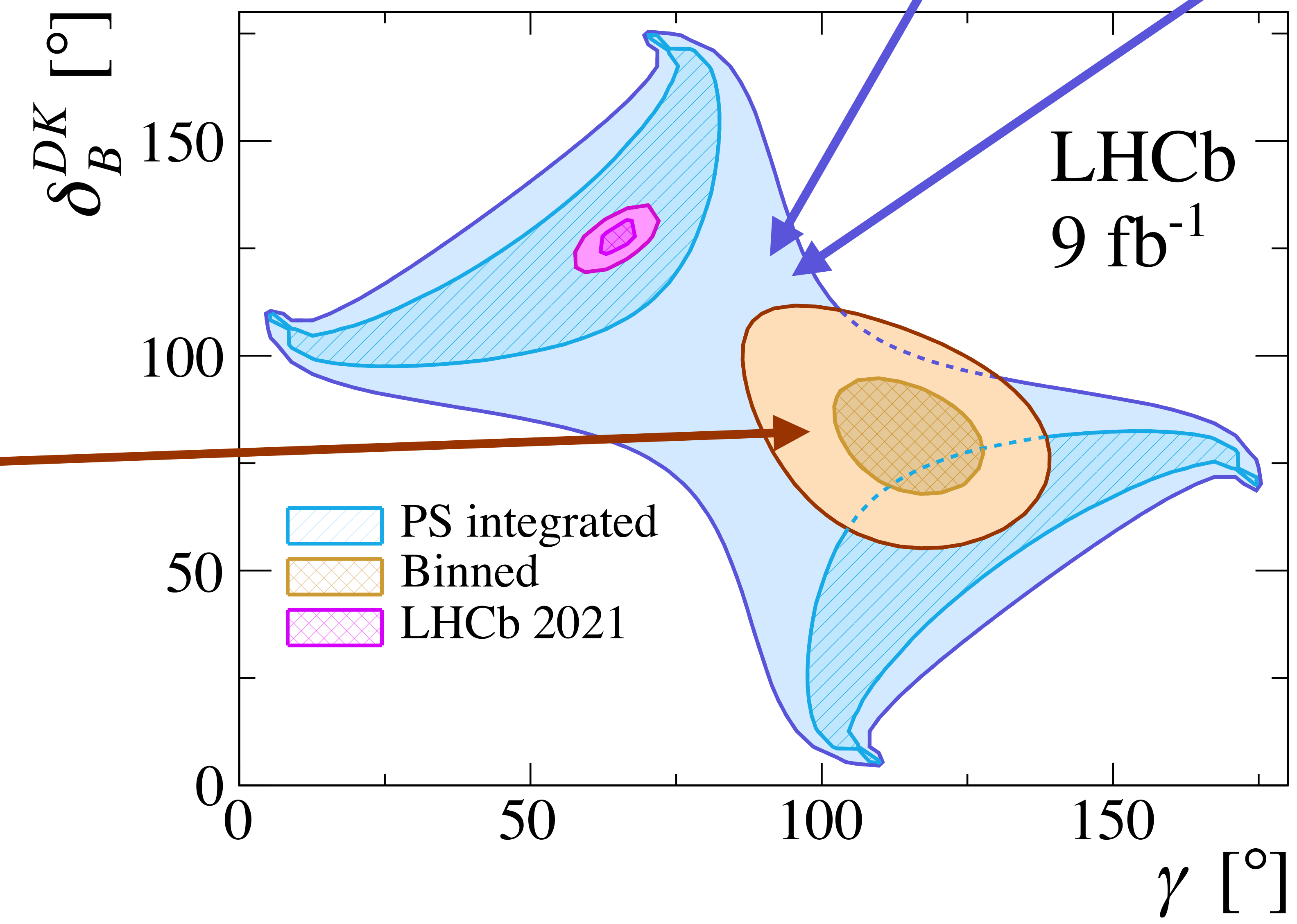




$K^+K^-\pi^+\pi^-$



$\pi^+\pi^-\pi^+\pi^-$



arXiv:2301.10328

$$\gamma = \left(116^{+12}_{-14}\right)^{\circ}$$

Precision will improve after charm model-independent measurements

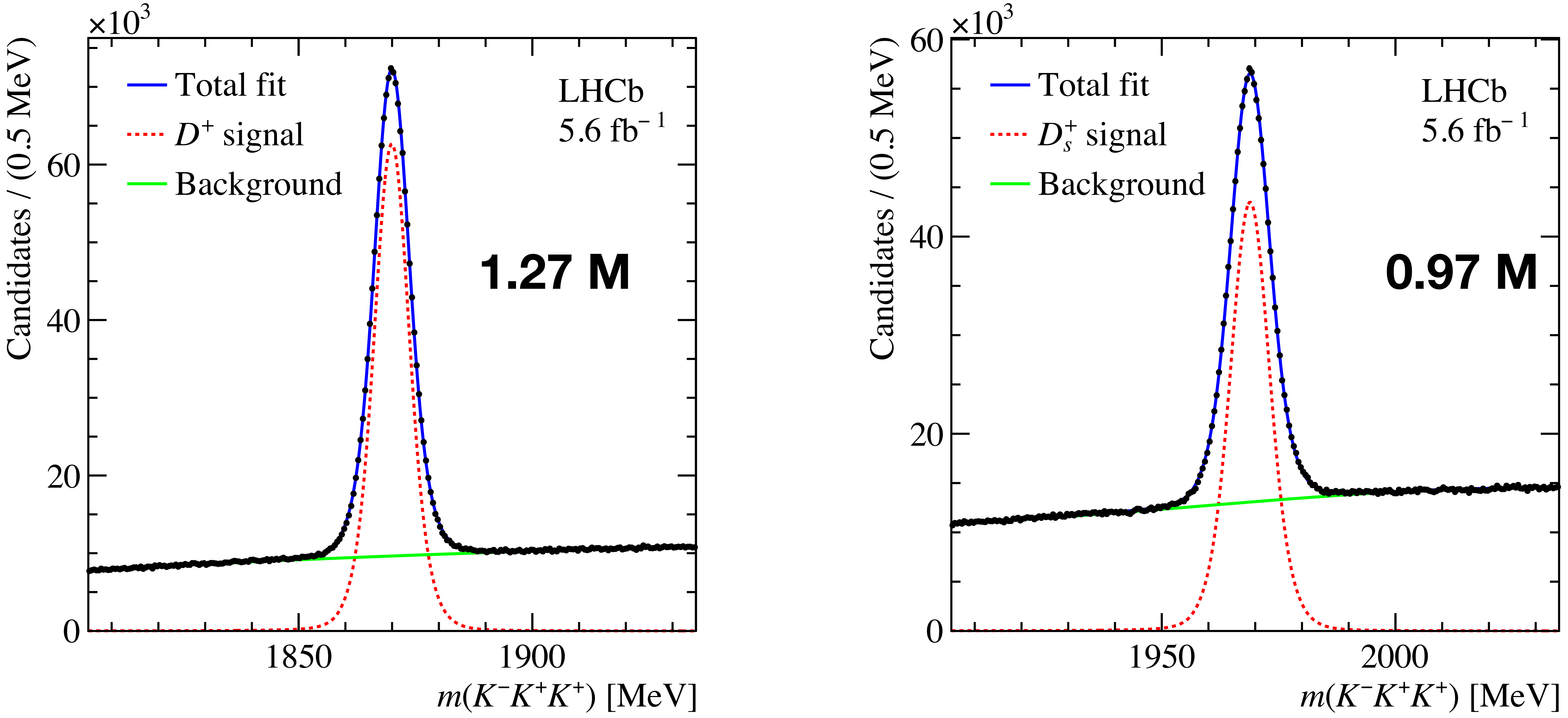
$\mathcal{CP}$ violation in charm

- 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

Search for local *CP* violation in $D^+_{(s)} \to K^- K^+ K^+$

[arXiv:2303.04062](https://arxiv.org/abs/2303.04062)

- Multibody decays: local *CP* asymmetries possibly larger than integrated ones
- $D_s^+ \to K^- K^+ K^+$: Cabibbo-suppressed → might show *CP* violation
- $D^+ \to K^- K^+ K^+$: Doubly-Cabibbo-suppressed → no *CP* violation in SM



LHCb 2016-2018 data sample

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

- Dalitz plot divided in 21 bins that reproduce the pattern of the main resonances ($\simeq$ constant strong phase)

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

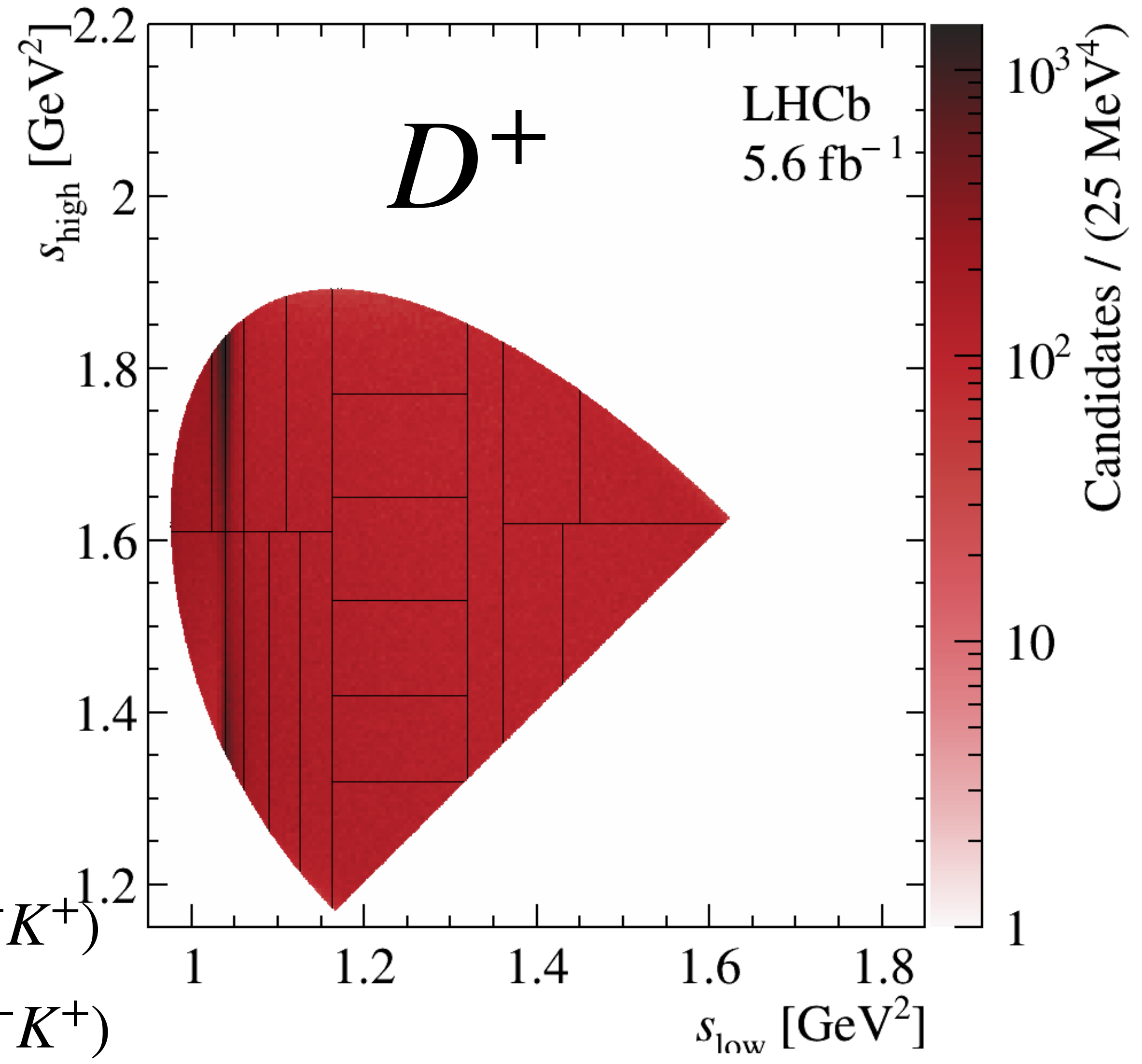
arXiv:2303.04062

α takes into account global nuisance asymmetries

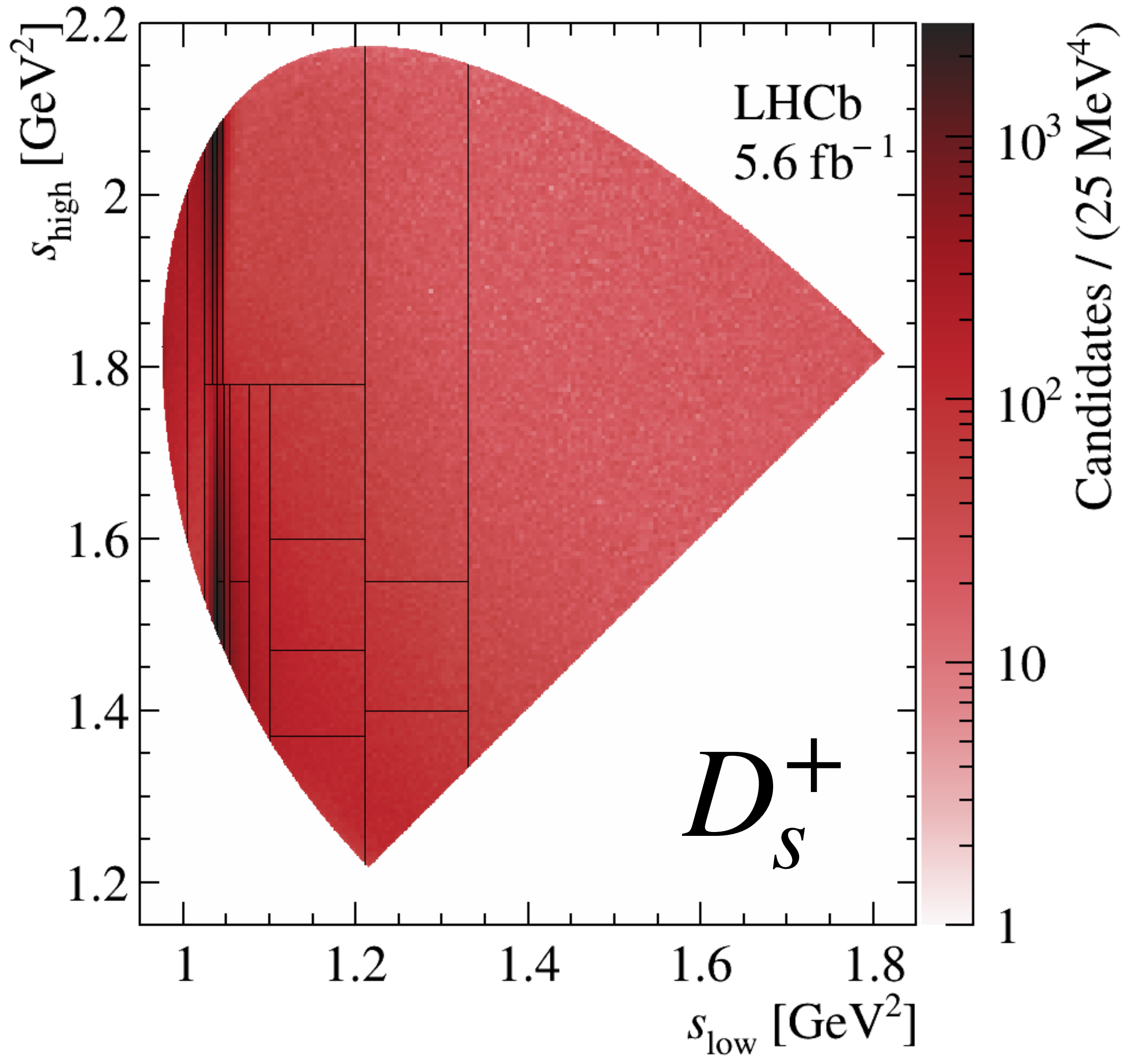
$$S^i_{C\!P} = \frac{N^i(D^+_{(s)}) - \alpha N^i(D^-_{(s)})}{\sqrt{\alpha\left(\delta^2_{N^i(D^+_{(s)})} + \delta^2_{N^i(D^-_{(s)})}\right)}}, \quad \alpha = \frac{\sum_i N^i(D^+_{(s)})}{\sum_i N^i(D^-_{(s)})}, \quad \chi^2 = \sum_i \left(S^i_{C\!P}\right)^2$$

- Control samples: Cabibbo-favoured $D^+ \to K^-\pi^+\pi^+$ and $D^+_s \to K^-K^+\pi^+$

- Sensitivity studies: possible observation of $C\!P$ violation if relative magnitude of amplitudes for ϕK^+ or $f_0 K^+$ differs from 3% to 7% (or phase differs from 3° to 7°) between $D^+_{(s)}$ and $D^-_{(s)}$



$s_{\rm low} = m^2_{\rm min}(K^-K^+)$
$s_{\rm high} = m^2_{\rm max}(K^-K^+)$

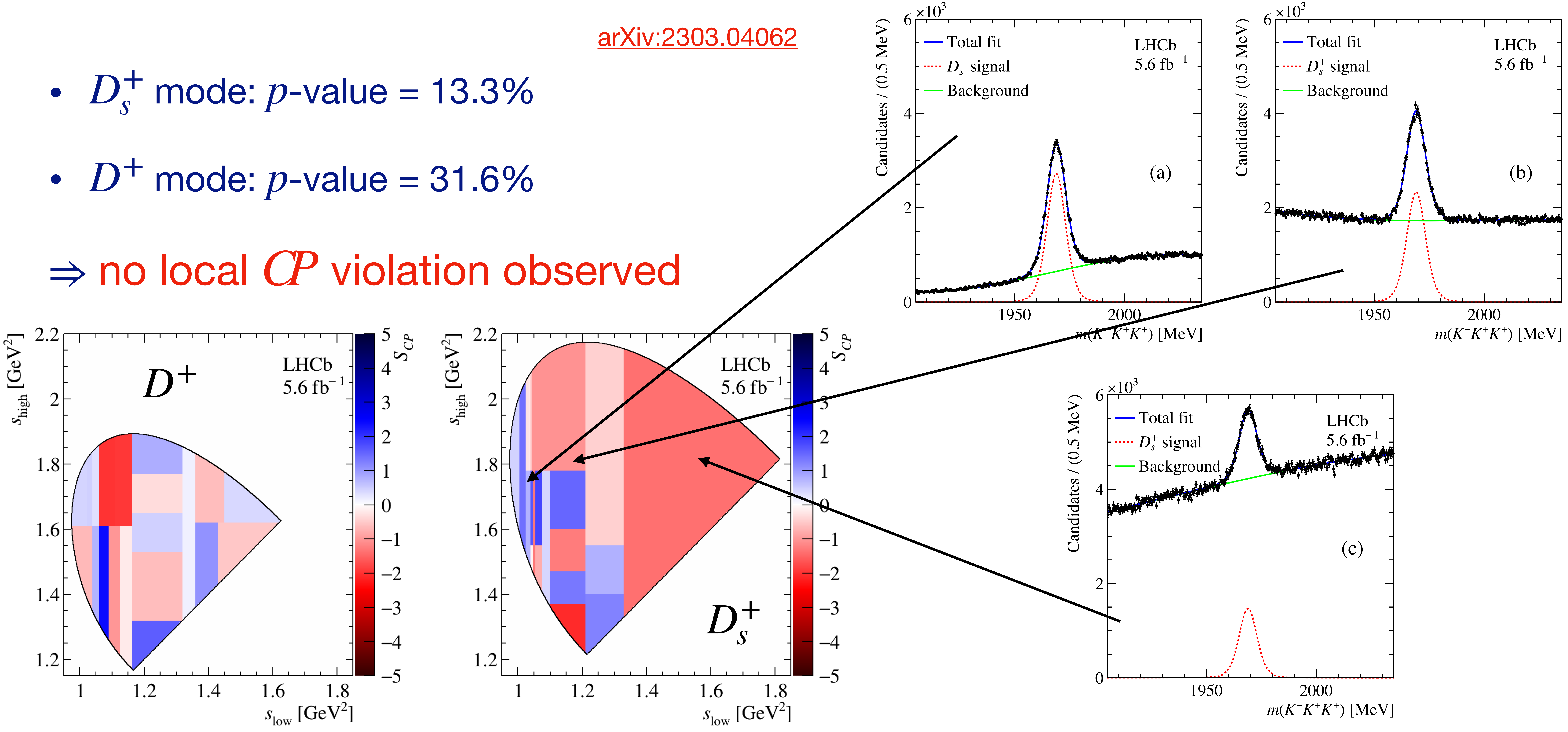


Search for local CP violation in $D^+_{(s)} \to K^- K^+ K^+$

arXiv:2303.04062

- D_s^+ mode: p-value = 13.3%
- D^+ mode: p-value = 31.6%

$\Rightarrow$ no local CP violation observed



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

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

Physical CP asymmetry — Final state detection asymmetry — Tagging particle detection asymmetry — Production asymmetry

- Run 2 data sample
- Nuisance asymmetries corrected with Cabibbo-favoured decays → two calibration procedures almost statistically independent

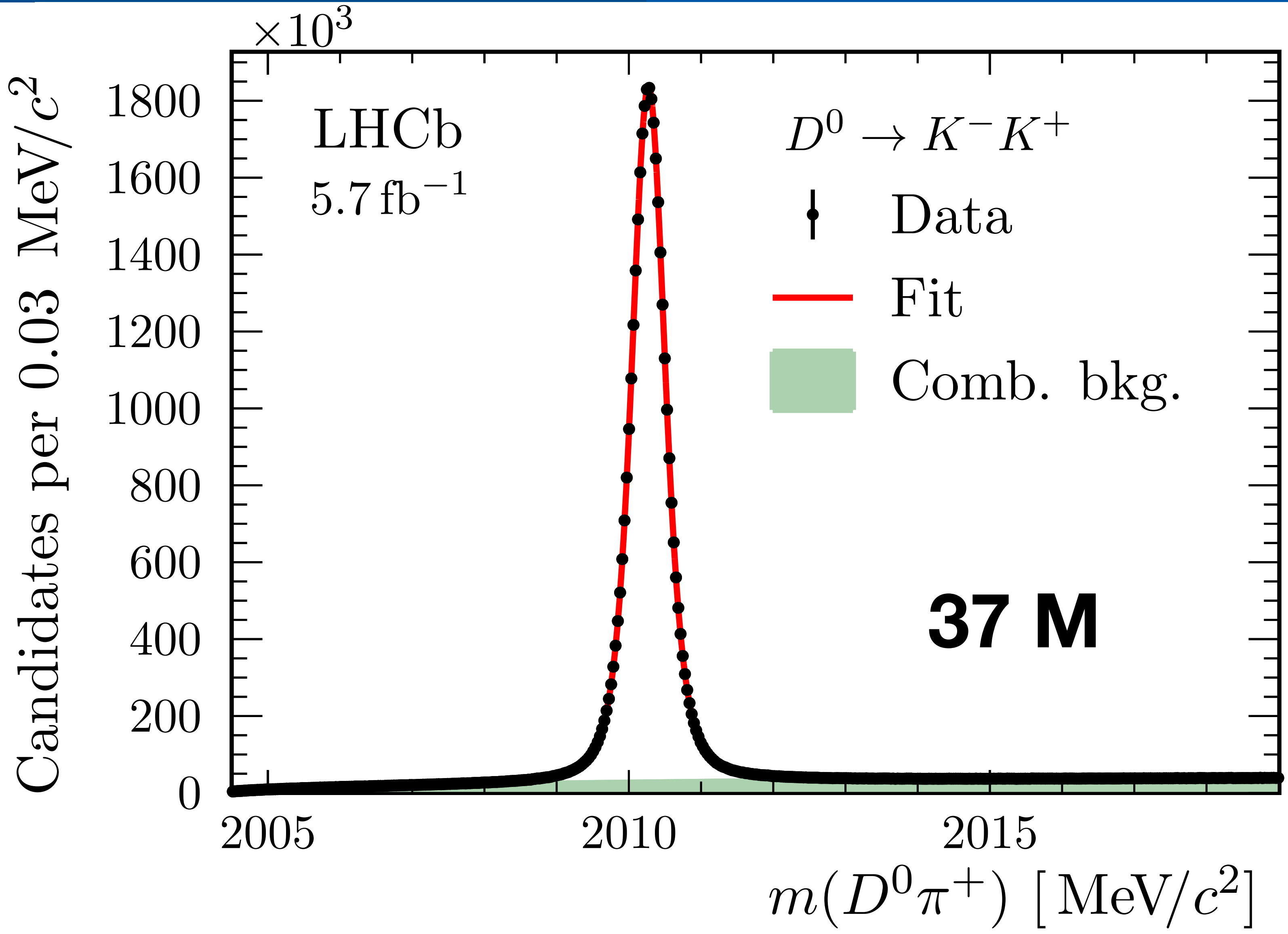
$$A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\pi^+_{soft}) + A(D^+ \to K^-\pi^+\pi^+) - [A(D^+ \to \overline{K}^0\pi^+) - A(\overline{K}^0)]$$

Original method (used also in Run 1)

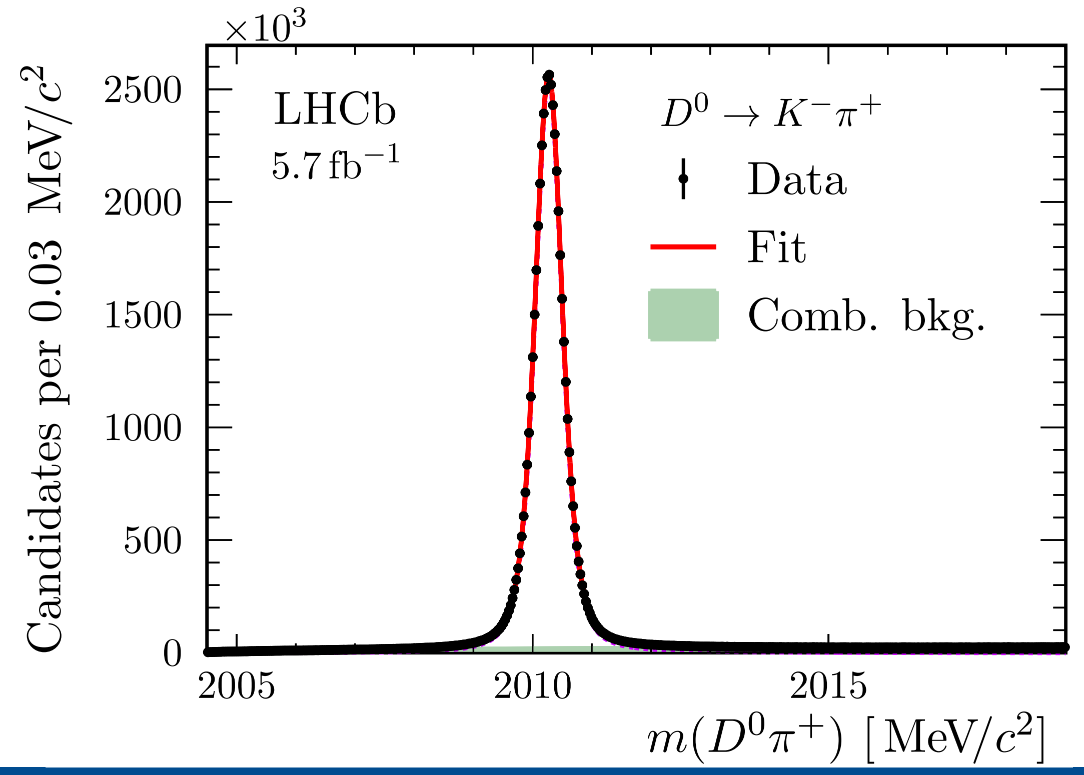
$$A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\pi^+_{soft}) + A(D_s^+ \to \phi\pi^+) - [A(D_s^+ \to \overline{K}^0 K^+) - A(\overline{K}^0)]$$

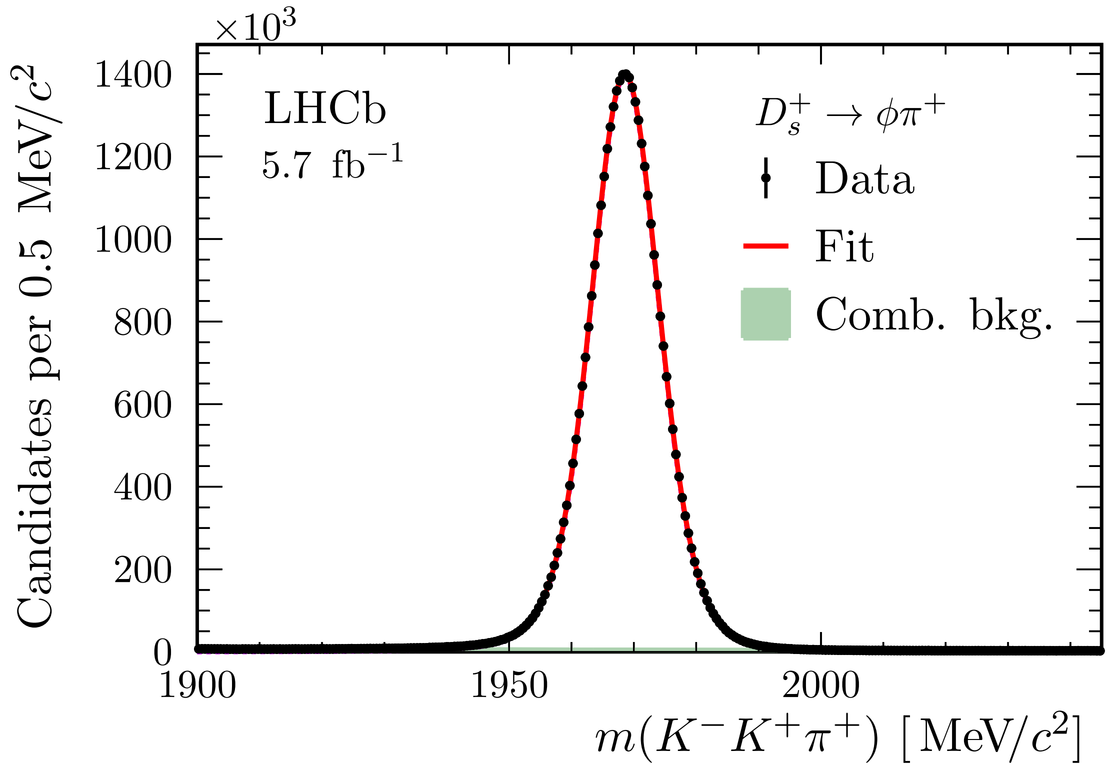
New method

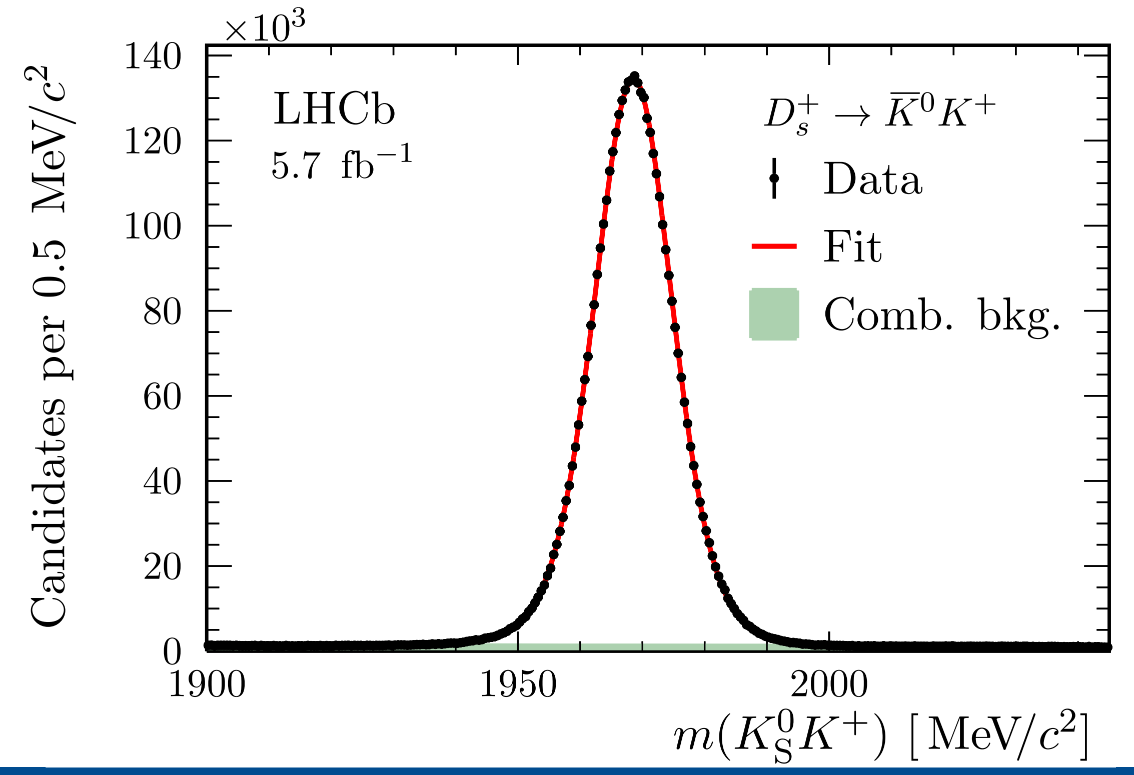
$$A_{CP}(D \to f) = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \bar{f})}$$



arXiv:2209.03179







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

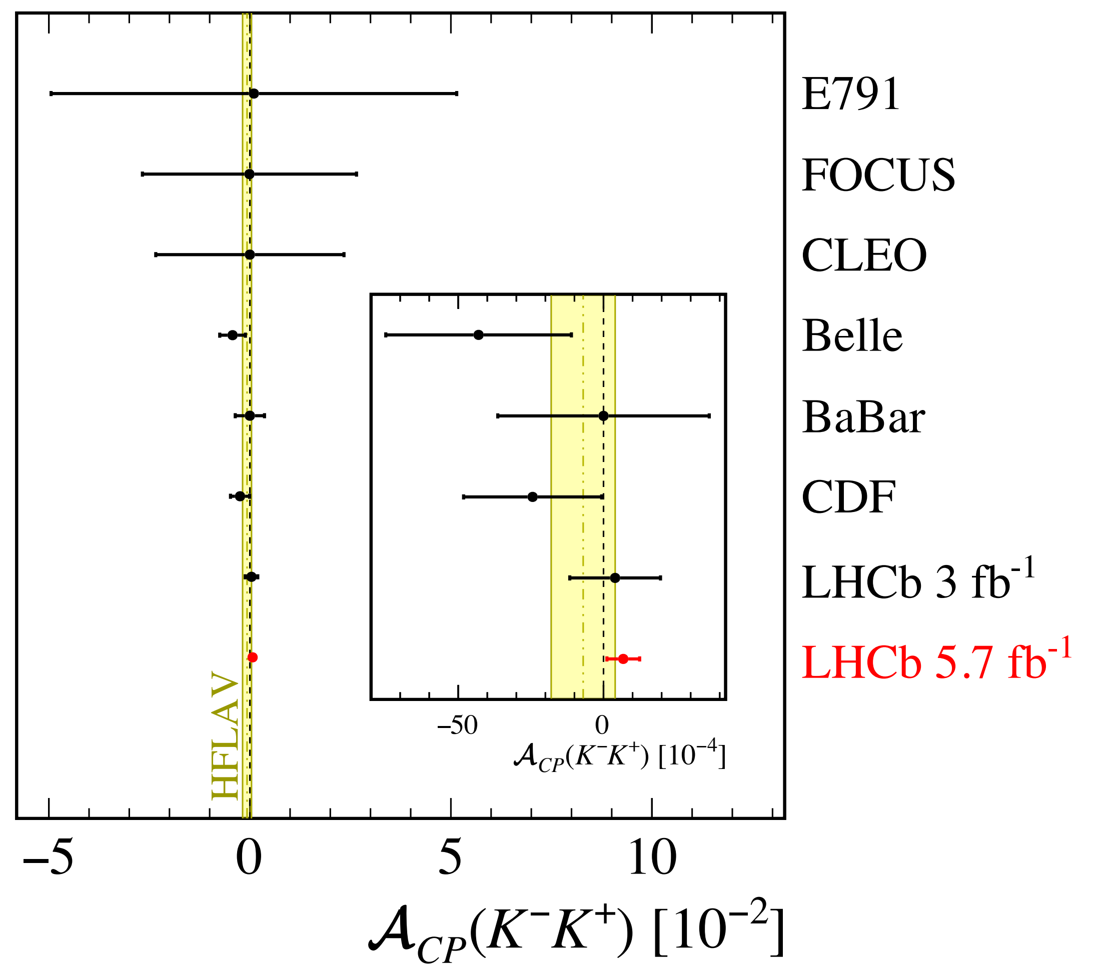
$A_{CP}(K^-K^+)\,|\,D^+ = (13.6 \pm 8.8 \pm 1.6) \times 10^{-4}$

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

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

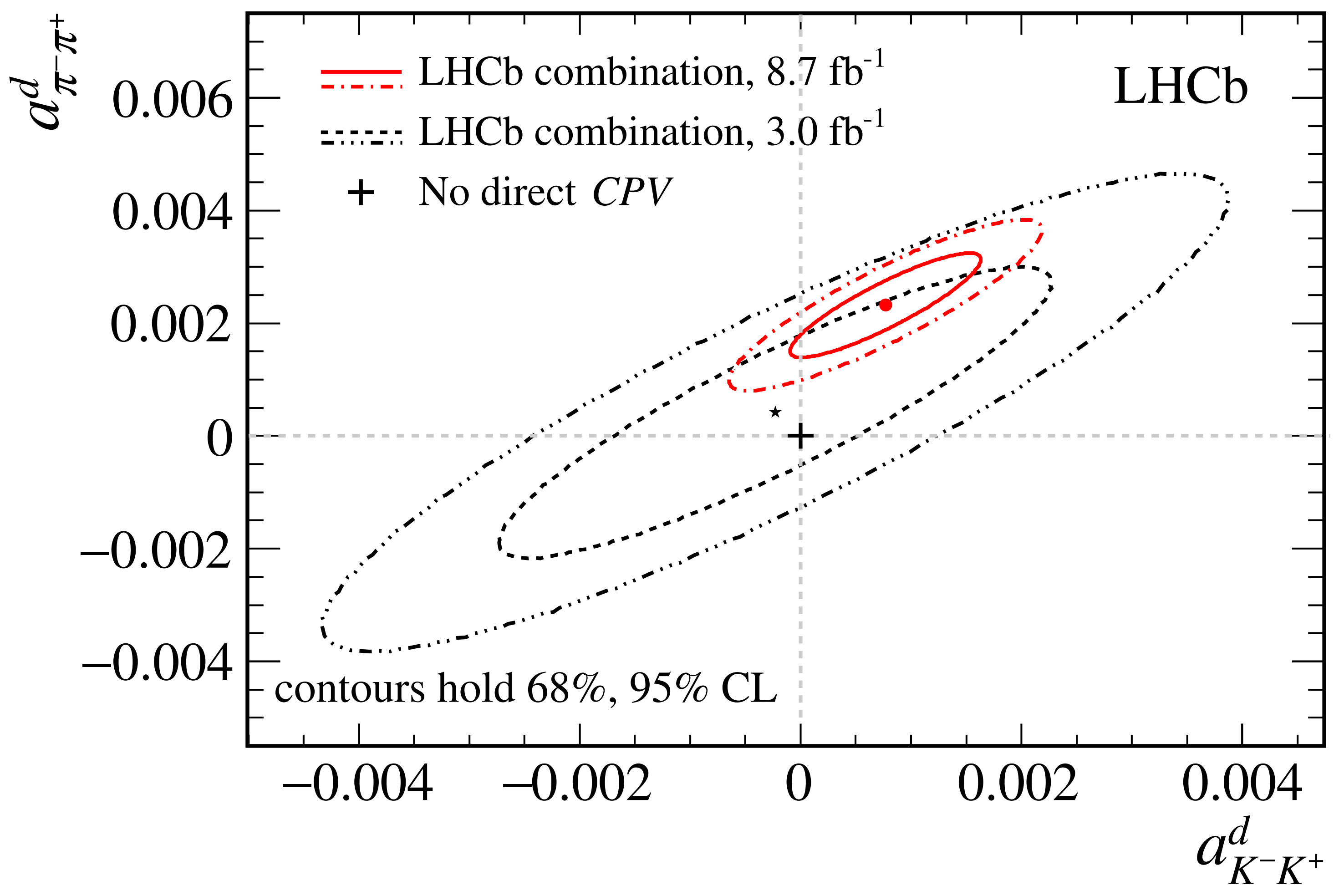
$\rho_{\text{syst}} = 0.28$

arXiv:2209.03179



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

Conclusions

- New precise tests of SM in B_s^0 mixing

- γ now known with an uncertainty $< 4^\circ$
  $\Rightarrow$ further improvements expected with other decay modes and also better knowledge of charm hadronic parameters

- First evidence of $C\!P$ violation in charm in single decay channel at 3.8σ

- New search of local $C\!P$ violation in charm multi-body decays

- The LHCb Upgrade I will improve the measurements in Run 3
  - higher integrated luminosity
  - removal of hardware trigger $\rightarrow$ higher trigger efficiency, smaller detection asymmetries

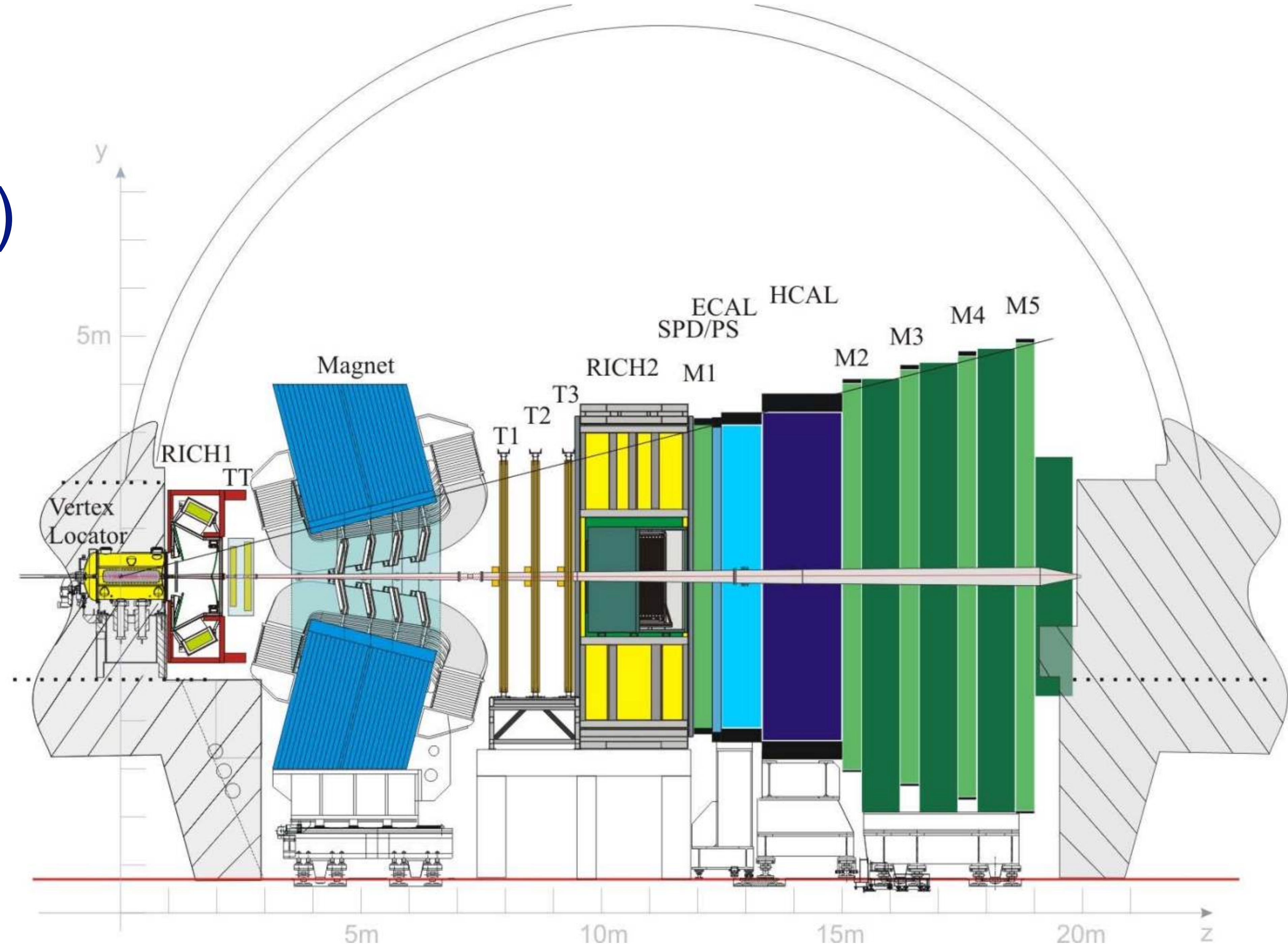
Backup

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

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



τ_L of $B_s^0 \to J/\psi\eta$

arXiv:2206.03088

Source	Uncertainty [fs]
Simulated sample sizes	5.2
A_{VELO}	1.1
A_{DLS}	–
$A_{\mathrm{IP}\chi^2}$	0.4
A_{MVA}	1.7
B^+ lifetime	4.0
Time resolution model	0.3
VELO half alignment	3.8
τ for $B_s^0 \to \chi_c\eta$ component	0.7
Mass model	0.8
B^0 component	0.4
Momentum scale	–
z-scale	0.3
Data-simulation χ^2_{IP} differences	0.1
Mass-time correlation	0.5
B_c^+ component	1.0
Quadrature sum	8.0

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**
$B^\pm \to Dh^\pm$	$D \to K_S^0h^+h^-$	[31]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K_S^0K^\pm\pi^\mp$	[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
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	[36]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B_s^0 \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[38]	Run 1	As before
$B_s^0 \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[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
$D^0 \to K_S^0\pi^+\pi^-$	x, y	[50]	Run 1	As before
$D^0 \to K_S^0\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[51]	Run 1	As before
$D^0 \to K_S^0\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[52]	Run 2	As before
$D^0 \to K_S^0\pi^+\pi^-$ (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]
$a_{K^+K^-}^{d}[\%]$	0.090	$^{+0.057}_{-0.057}$	[0.033, 0.147]	$^{+0.11}_{-0.12}$	[−0.03, 0.20]
$a_{\pi^+\pi^-}^{d}[\%]$	0.240	$^{+0.061}_{-0.062}$	[0.178, 0.301]	$^{+0.12}_{-0.12}$	[0.12, 0.36]

γ + charm combination

LHCb-CONF-2022-003

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

Measurement of γ with $B^{\pm} \to [h^{+}h^{-}\pi^{\pm}\pi^{\mp}]_{D}h^{\pm}$

CP -violating observable	Fit result $(\times 10^2)$
x_{-}^{DK}	$7.9 \pm 2.9 \pm 0.4 \pm 0.4$
y_{-}^{DK}	$-3.3 \pm 3.4 \pm 0.4 \pm 3.6$
x_{+}^{DK}	$-12.5 \pm 2.5 \pm 0.3 \pm 1.7$
y_{+}^{DK}	$-4.2 \pm 3.1 \pm 0.3 \pm 1.3$
$x_{\xi}^{D\pi}$	$-3.1 \pm 3.5 \pm 0.7 \pm 0.1$
$y_{\xi}^{D\pi}$	$-1.7 \pm 4.7 \pm 0.6 \pm 1.1$

arXiv:2301.10328

Bin	$B^- \to DK^-$	$B^+ \to DK^+$	$B^- \to D\pi^-$	$B^+ \to D\pi^+$
8	17 ± 6	74 ± 10	312 ± 21	920 ± 34
7	21 ± 7	71 ± 10	309 ± 21	1160 ± 37
6	81 ± 12	173 ± 15	1025 ± 36	2422 ± 53
5	157 ± 15	271 ± 19	2103 ± 50	4226 ± 68
4	146 ± 15	230 ± 17	1750 ± 46	3899 ± 66
3	52 ± 9	143 ± 14	671 ± 30	2554 ± 54
2	43 ± 9	120 ± 13	468 ± 25	1417 ± 41
1	11 ± 6	65 ± 10	369 ± 22	1137 ± 37
-1	66 ± 10	26 ± 7	1009 ± 35	376 ± 23
-2	93 ± 12	51 ± 9	1477 ± 41	442 ± 25
-3	152 ± 15	39 ± 9	2424 ± 53	690 ± 30
-4	277 ± 19	88 ± 12	3800 ± 65	1851 ± 47
-5	339 ± 21	93 ± 13	4185 ± 68	2210 ± 50
-6	180 ± 15	46 ± 9	2375 ± 52	939 ± 34
-7	61 ± 10	34 ± 8	1127 ± 36	376 ± 23
-8	71 ± 10	29 ± 7	987 ± 34	283 ± 20

	Uncertainty $(\times 10^2)$					
Source	x_{-}^{DK}	y_{-}^{DK}	x_{+}^{DK}	y_{+}^{DK}	$x_{\xi}^{D\pi}$	$y_{\xi}^{D\pi}$
Mass shape	0.02	0.02	0.03	0.06	0.02	0.04
Bin-dependent mass shape	0.11	0.05	0.10	0.19	0.68	0.16
PID efficiency	0.02	0.02	0.03	0.06	0.02	0.04
Low-mass background model	0.02	0.02	0.03	0.04	0.02	0.02
Charmless background	0.14	0.15	0.12	0.14	0.01	0.02
CP violation in low-mass background	0.01	0.10	0.08	0.12	0.07	0.26
Semi-leptonic b-hadron decays	0.05	0.27	0.06	0.01	0.07	0.19
Semi-leptonic charm decays	0.02	0.07	0.03	0.15	0.06	0.24
$D \to K^{\mp}\pi^{\pm}\pi^{+}\pi^{-}$ background	0.11	0.05	0.07	0.04	0.09	0.05
$\Lambda_b^0 \to pD\pi^-$ background	0.01	0.25	0.14	0.04	0.06	0.34
$D \to K^{\mp}\pi^{\pm}\pi^{+}\pi^{-}\pi^{0}$ background	0.30	0.05	0.19	0.07	0.05	0.01
Fit bias	0.06	0.05	0.13	0.02	0.06	0.13
Total LHCb systematic	0.37	0.43	0.34	0.32	0.70	0.57
c_i, s_i	0.35	3.64	1.74	1.29	0.14	1.10
Total systematic	0.51	3.67	1.78	1.33	0.72	1.24
Statistical	2.87	3.40	2.51	3.05	4.24	5.17

Measurement of γ with $B^{\pm} \to [h^+h^-\pi^{\pm}\pi^{\mp}]_D h^{\pm}$

arXiv:2301.10328

CP -violating observable	Fit results
$A_K^{KK\pi\pi}$	$0.093 \pm 0.023 \pm 0.002$
$A_\pi^{KK\pi\pi}$	$-0.009 \pm 0.006 \pm 0.001$
$A_K^{\pi\pi\pi\pi}$	$0.060 \pm 0.013 \pm 0.001$
$A_\pi^{\pi\pi\pi\pi}$	$-0.0082 \pm 0.0031 \pm 0.0007$
$R_{CP}^{KK\pi\pi}$	$0.974 \pm 0.024 \pm 0.015$
$R_{CP}^{\pi\pi\pi\pi}$	$0.978 \pm 0.014 \pm 0.010$

Charm formalism

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

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

- Direct CP violation when $|A_f|^2 \neq |\overline{A}_{\bar{f}}|^2$
- 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 $\phi_f \equiv \arg[(q\overline{A}_f)/(pA_f)] \neq 0$

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

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

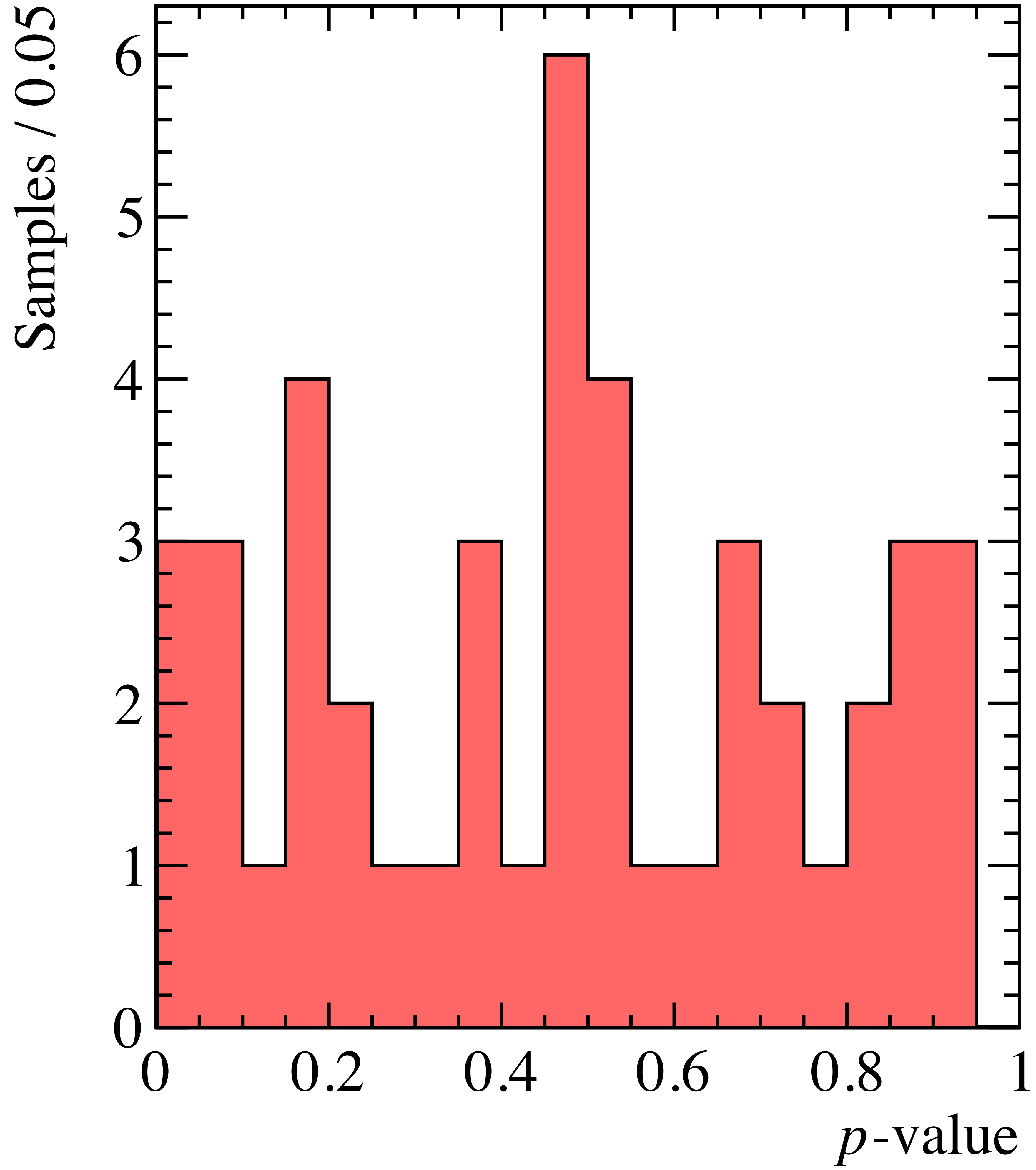
PRL 103 (2009) 071602
PRD 80 (2009) 076008
PRD 103 (2021) 053008

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

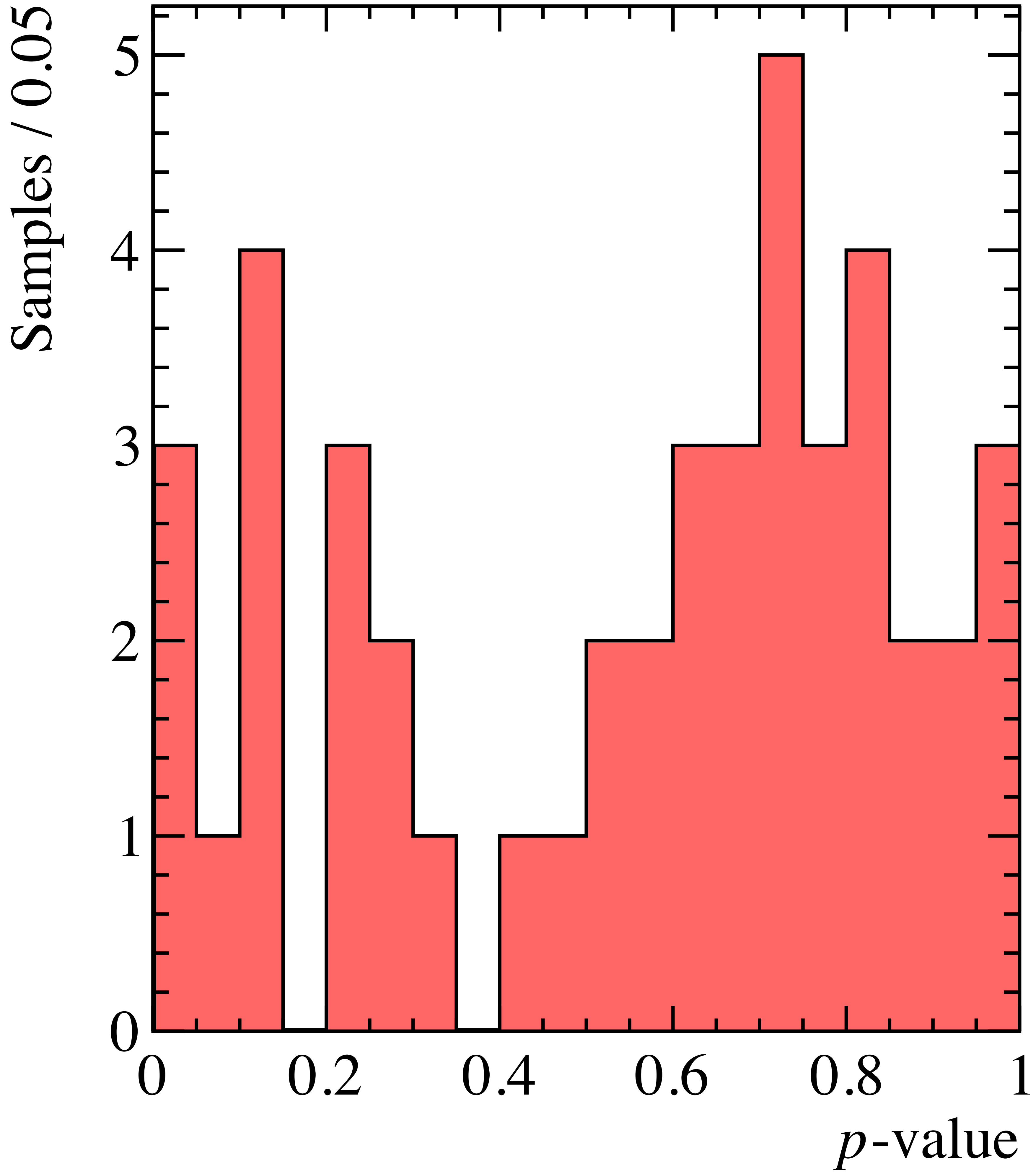
Search for local *CP* violation in $D^+_{(s)} \to K^- K^+ K^+$

[arXiv:2303.04062](https://arxiv.org/abs/2303.04062)

$D_s^+ \to K^- K^+ \pi^+$



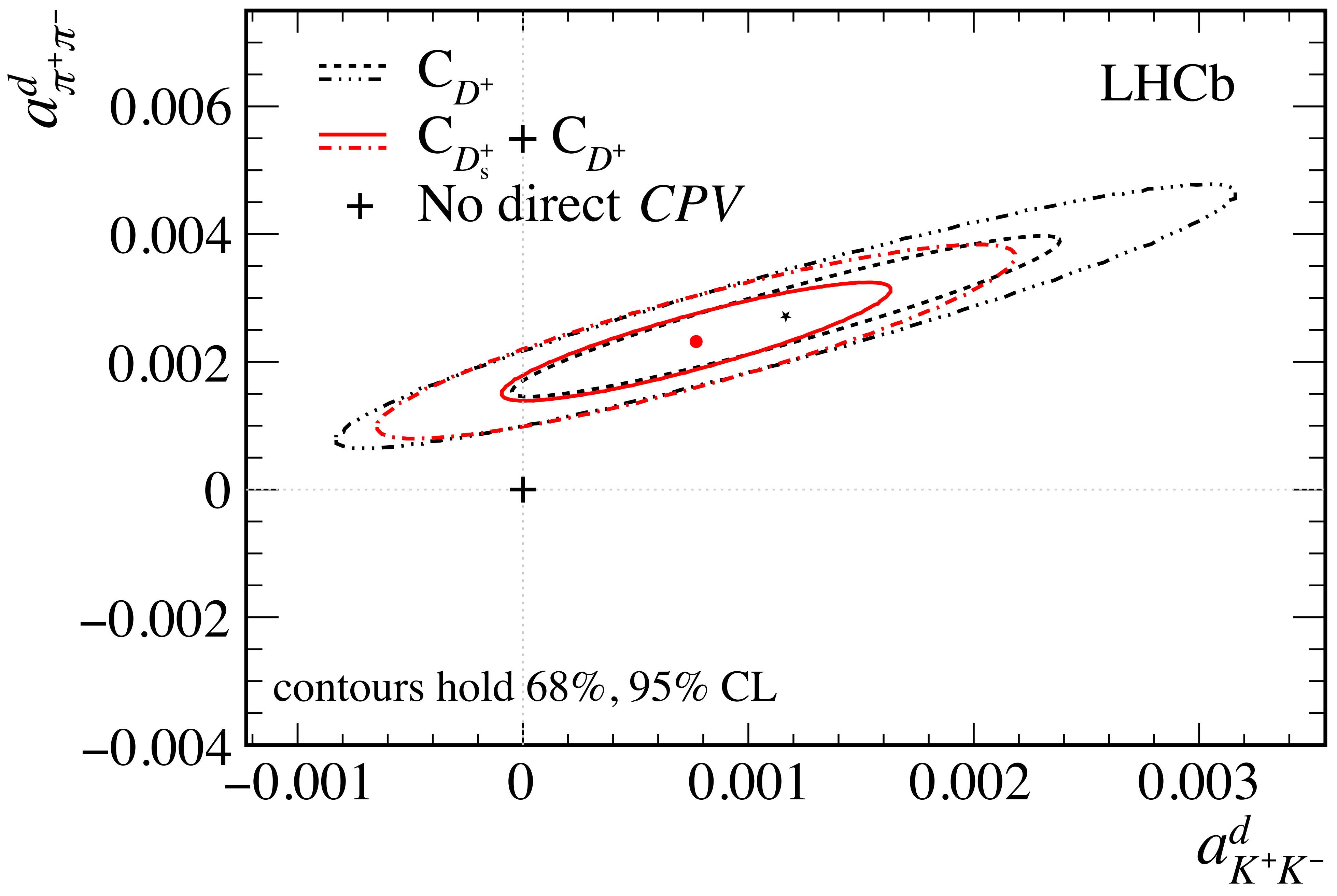
$D^+ \to K^- \pi^+ \pi^+$



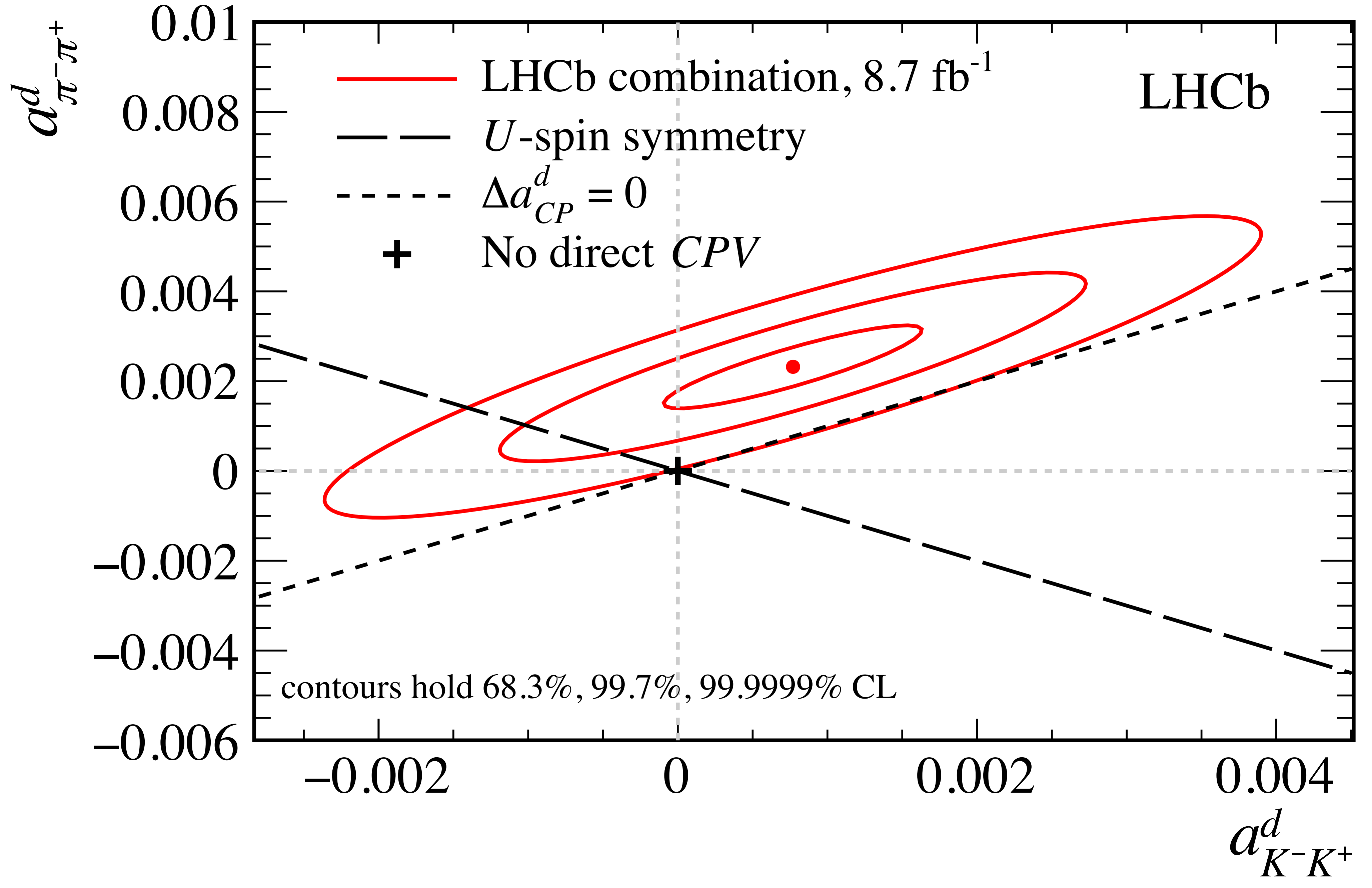
Measurement of $A_{CP}(D^0 \to K^-K^+)$

Decay mode	Signal yield $[10^6]$		Red. factor	
	C_D^+	C_{Ds}^+	C_D^+	C_{Ds}^+
$D^0 \to K^-K^+$	37	37	0.75	0.75
$D^0 \to K^-\pi^+$	58	56	0.35	0.75
$D^+ \to K^-\pi^+\pi^+$	188	–	0.25	–
$D^+ \to \overline{K}^0\pi^+$	6	–	0.25	–
$D_s^+ \to \phi\pi^+$	–	43	–	0.55
$D_s^+ \to \overline{K}^0K^+$	–	5	–	0.70

Source	C_D^+ $[10^{-4}]$	C_{Ds}^+ $[10^{-4}]$	Corr.
Fit model	1.1	1.0	0.05
Peaking backgrounds	0.3	0.4	0.74
Secondary decays	0.6	0.3	–
Kinematic weighting	0.8	0.4	–
Neutral kaon asymmetry	0.6	1.3	1.00
Charged kaon asymmetry	–	1.0	–
Total	1.6	2.0	0.28



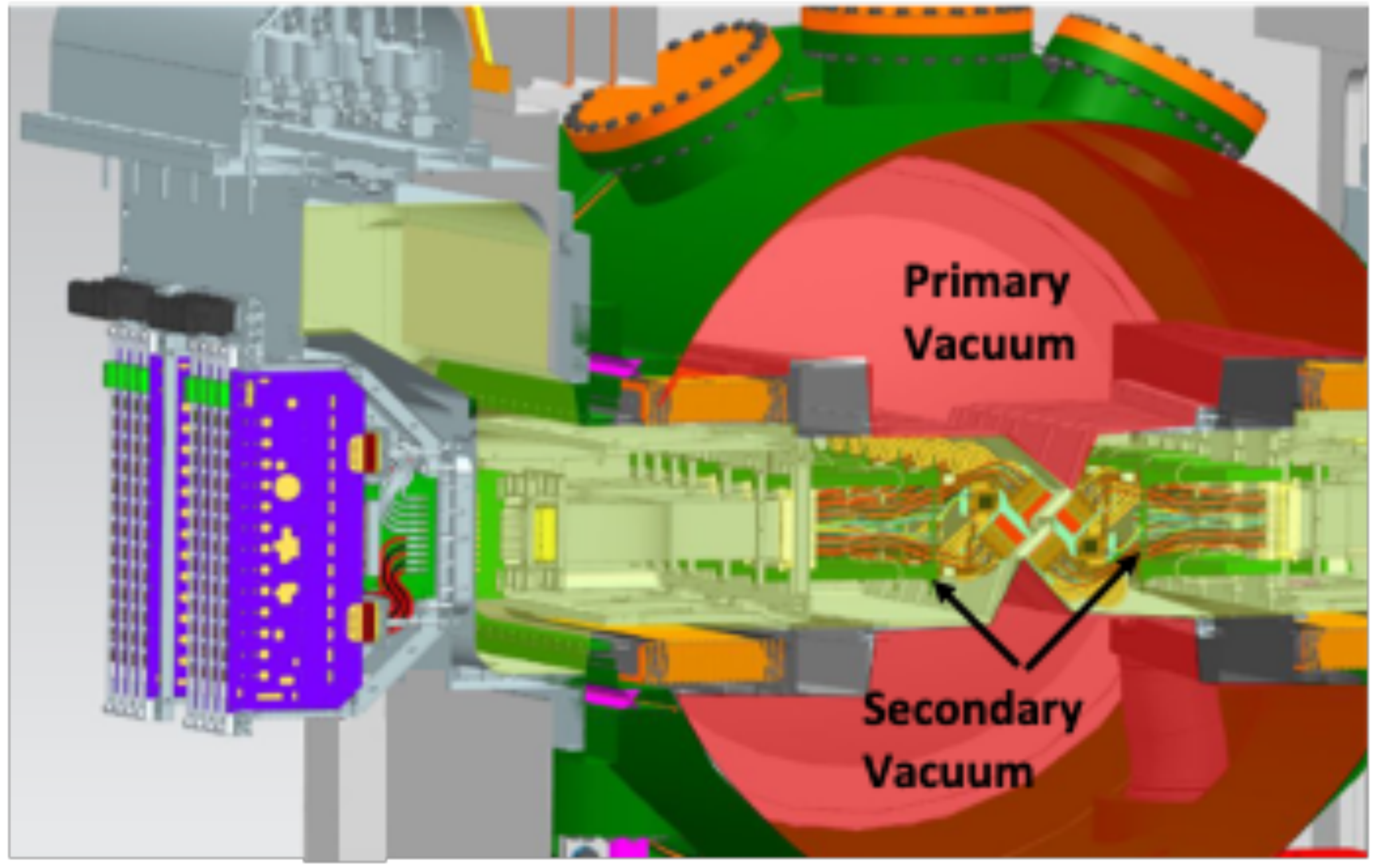
arXiv:2209.03179



VELO vacuum incident

The VELO detector is installed in a secondary vacuum inside the LHC primary vacuum.

The primary and secondary volumes are separated by two thin walled Aluminium boxes, the RF foils



On 10th January 2023, during a VELO warm up in neon, there was a loss of control of the protection system

A pressure differential of 200 mbar built up between the two volumes, whereas the foils are designed to withstand 10 mbar only

Initial investigations show no damage to the VELO modules; sensors show correct leakage currents, microchannels show no leaks

RF foils have suffered plastic deformation up to 14 mm and have to be replaced. Major intervention, planning under study

- Replace now (delay), or replace at the end of the year (run in 2023 with VELO partially open)
- Physics programme of 2023 is significantly affected, commissioning of Upgrade I systems can proceed as planned