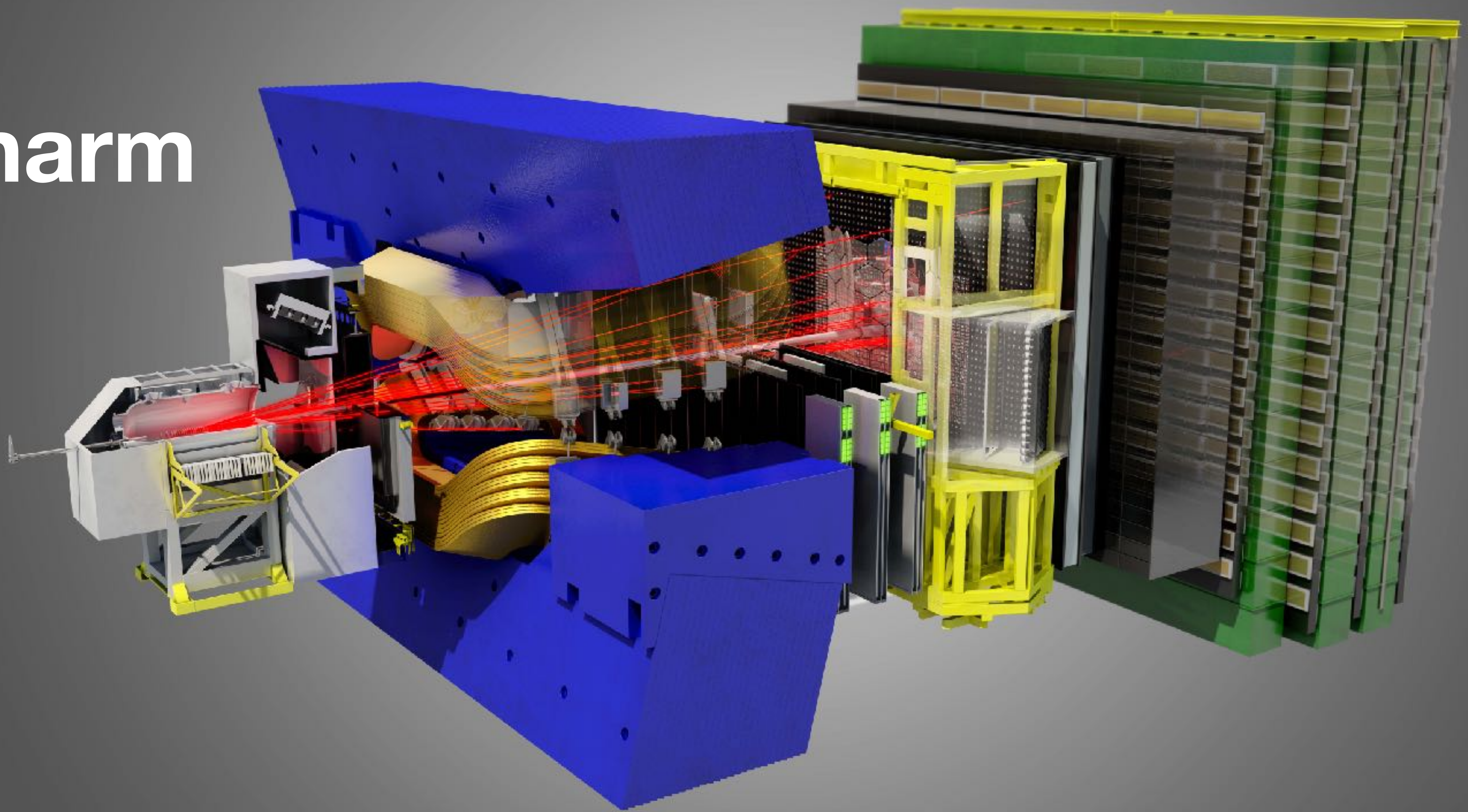
CP violation in beauty and charm quarks at LHCb

D. Manuzzi on behalf of
the LHCb collaboration
La Thuile, 27th March 2023

57th Rencontres de Moriond
QCD & High Energy Interactions



News from LHCb

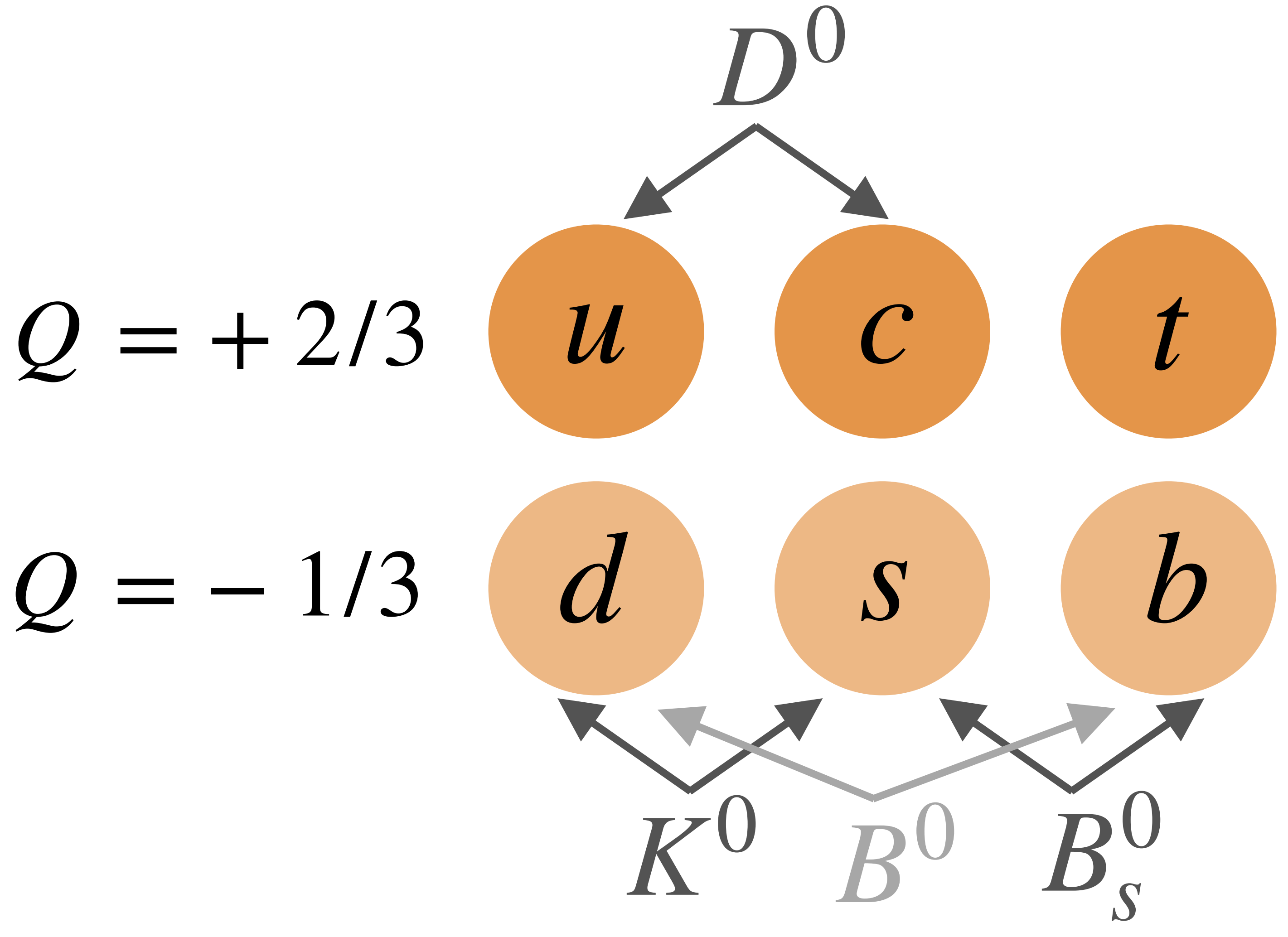
- CP violation (CPV) in **charm**:
  - $A_{CP}(D^0 \to K^+K^-)$, *September 2022* [arXiv:2209.03179]
  - Local CPV search in $D^+_{(s)} \to K^-K^+K^+$, *March 2023* [arXiv:2303.04062]

- Direct measurements of the **CKM parameter** γ:
  - with $B^\pm \to [K^\mp\pi^\pm\pi^\pm\pi^\mp]_D h^\pm$, *September 2022* [arXiv:2209.03692]
  - with $B^\pm \to [h^+h^-\pi^+\pi^-]_D h'^\mp$, *January 2023* [arXiv:2301.10328]
    - $h = K, \pi$

- CPV in **penguin-mediated decays**
  - Time- and polarisation-dependent analysis of $B^0_s \to \phi\phi$ decays, *NEW!!!* [LHCb-PAPER-2023-001-002]

Charm CP violation

- **Unique** laboratory to study **CPV in up-type** quarks



- **Predicted to be small** in the Standard Model (SM)
  - smallness of involved CKM elements
  - SM predictions have to face non-perturbative strong interactions
    - $A_{CP} \sim 10^{-4} - 10^{-3}$ [PRD 85 (2012) 034036] [PRD 86 (2012) 036012] [JHEP 05 (2012) 140] [PLB 774 (2017) 235-242] [PRD 75 (2007) 036008]

- **Direct CPV observed in March 2019** by LHCb
  - Measured value challenges first-principles QCD calculations
    ⇒ enhancement of QCD rescattering or new physics
    [PRD 99 (2019) 11, 113001] [JHEP 07 (2019) 020] [JHEP 12 (2019) 104] [JHEP 09 (2021) 126] [JHEP 05 (2021) 179] [arXiv:2203.04056]
    - **For review see: [arXiv:2011.04443v1], [arXiv:2208.05769v2]**

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$
$$= (-1.54 \pm 0.29) \times 10^{-3}$$

[PRL 122 (2019) 211803]

- **Further measurements are needed in the charm sector**

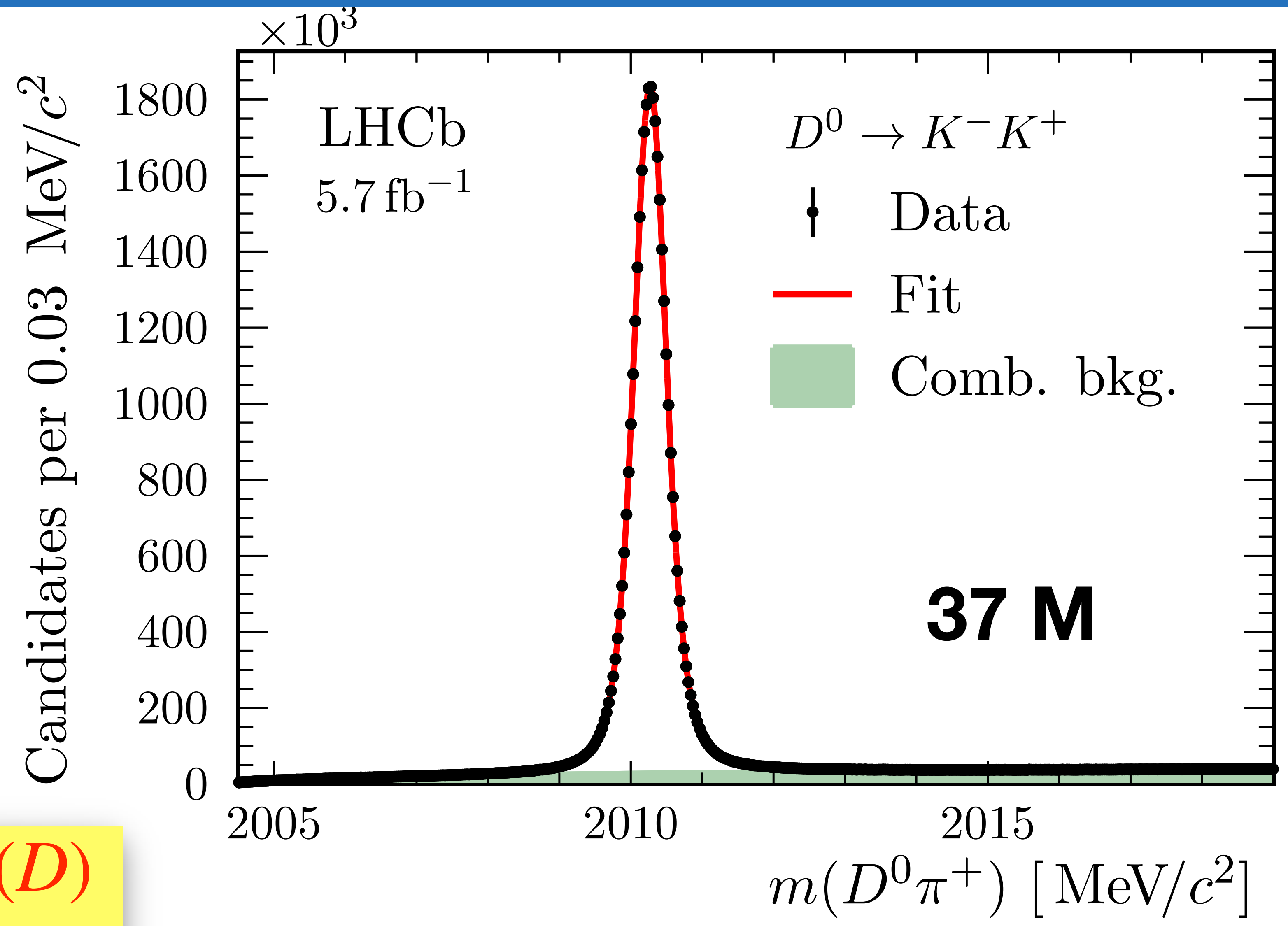
Measurement of $A_{CP}(D^0 \to K^+K^-)$

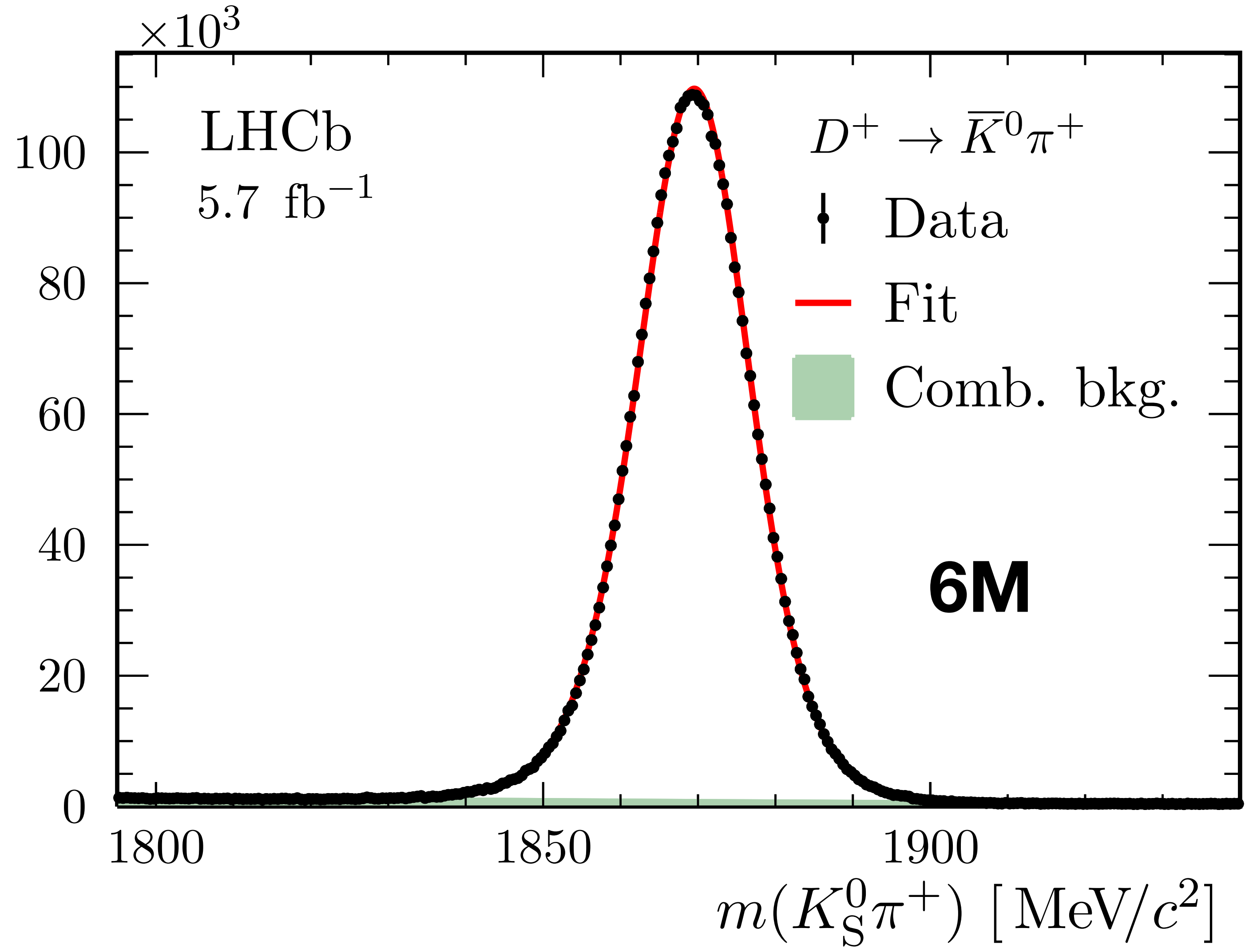
[arXiv:2209.03179]

- New measurement with **Run2 data**
- $D^{*+} \to D^0\pi^+_{\rm soft}$ to **tag** the D^0 flavour
- Raw asymmetries with **invariant-mass fits**

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

- $A(D\to f)$: Raw asym. $\frac{N-\bar{N}}{N+\bar{N}}$
- $A_{CP}(D\to f)$: **Physical *CP* asym.** $\frac{\Gamma(D\to f)-\Gamma(\bar{D}\to f)}{\Gamma(D\to f)-\Gamma(\bar{D}\to f)}$
- $A_{\rm det}(f)$: Final state detection asym.
- $A_{\rm det}(\text{tag})$: Tagging particle detection asym.
- $A_{\rm prod}(D)$: Production asym.





[arXiv:2209.03179]

- Nuisance asymmetries subtracted using raw asym. of Cabibbo-favoured decays
  - Two procedures almost statistically independent
    - Accurate **kinematic reweighting** of all channels
    - $D^+_{(s)} \to K^0_S h^+$ is bottleneck to final precision

Run1 method [PLB767 (2017) 177]

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

Additional, new method

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

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

Result of this analysis:

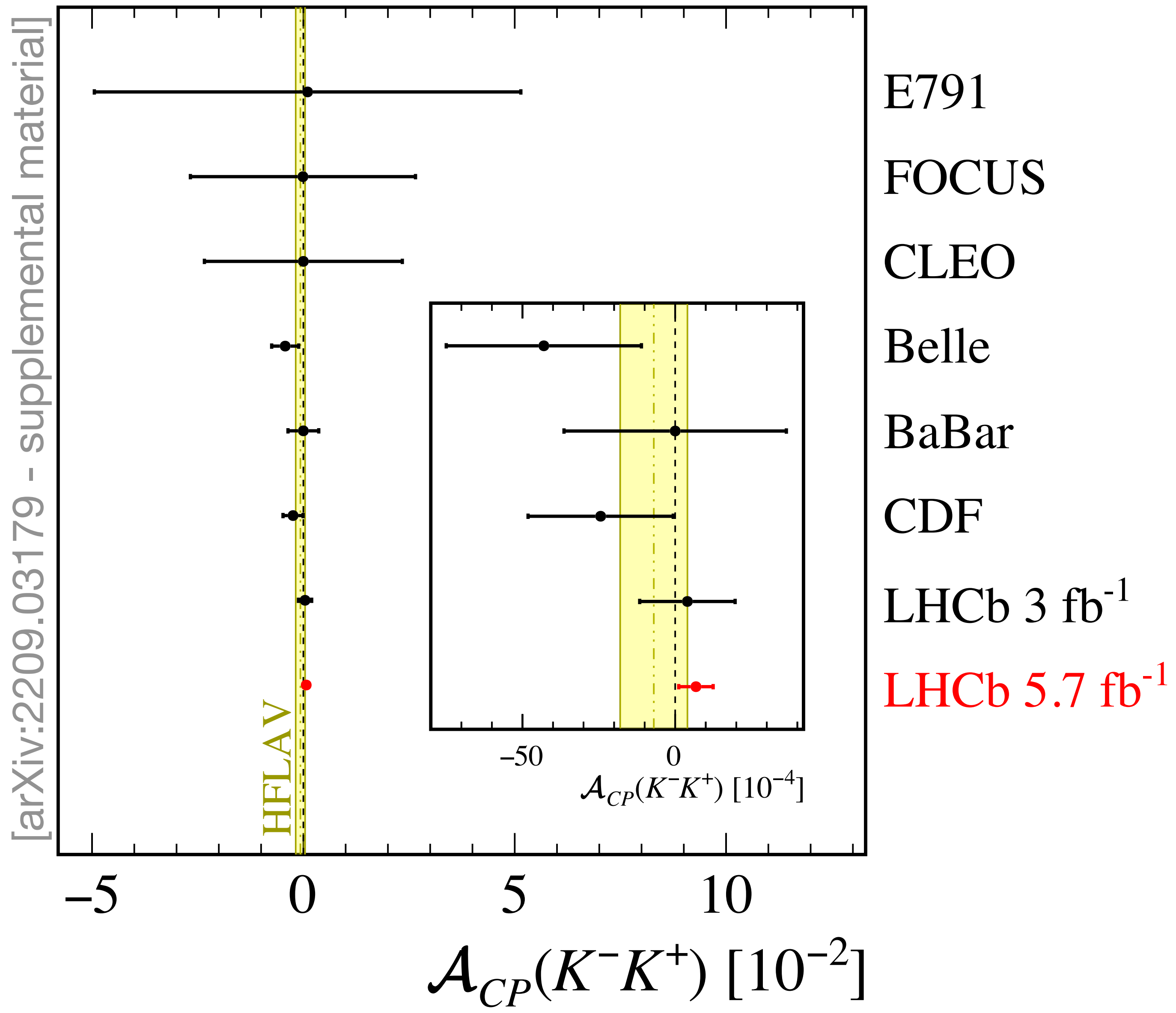
[arXiv:2209.03179]

$$A_{CP}(D^0 \to K^+K^-) = \left(6.8 \pm 5.4 \pm 1.6\right) \times 10^{-4}$$

stat. syst.

Uncertainty about half of the previous world average

[HFLAV]



[PRL 105 (2010) 081803]

$$A_{CP}(D \to f) \simeq a_f^d + \frac{\langle t \rangle_f}{\tau_D} \Delta Y_f$$

$a_f^d \to$ CPV in decay

$\Delta Y_f \to$ CPV in mixing and interf. mixing/decay

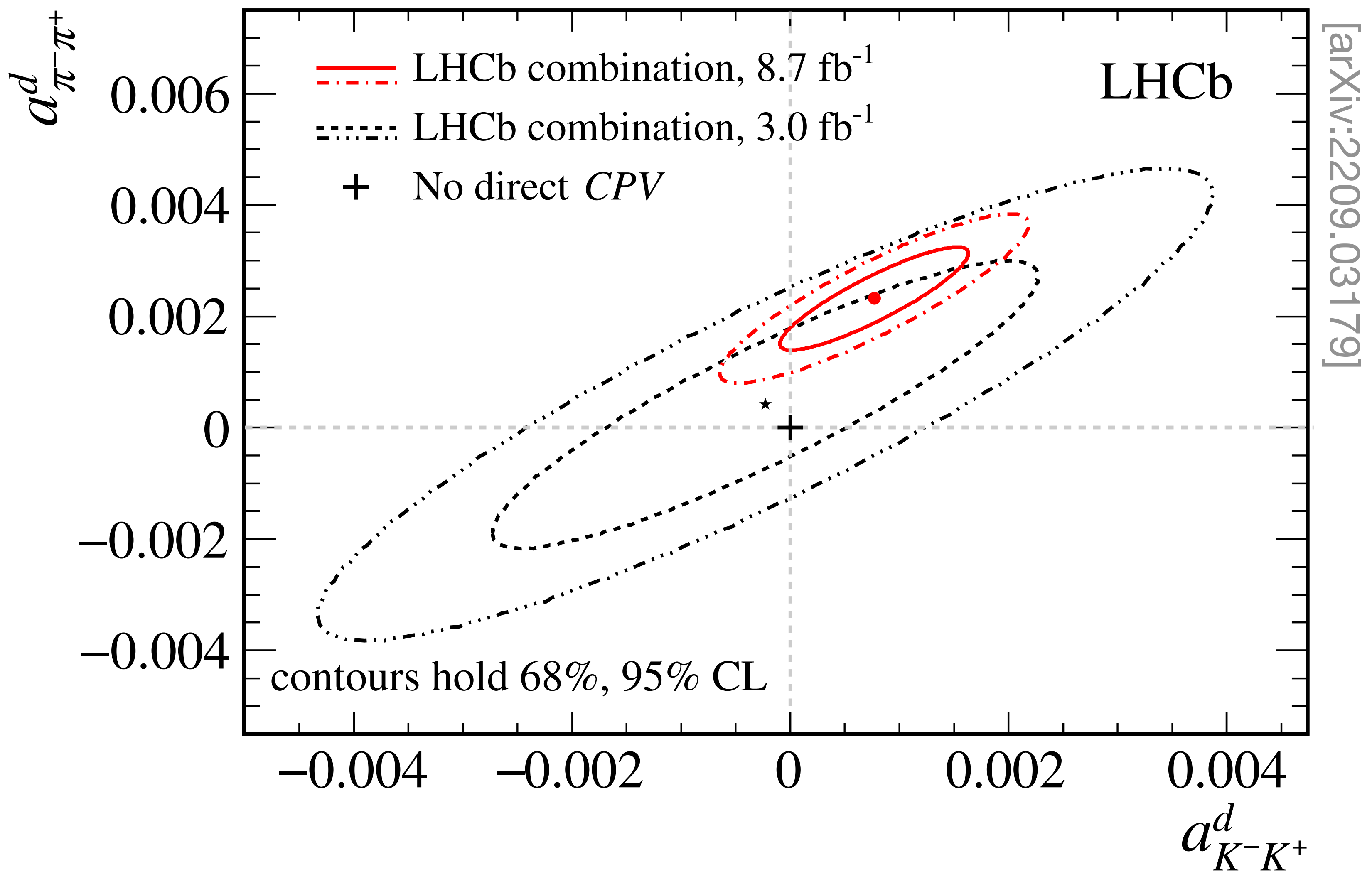
A_{CP} depends on all the CPV categories.
Hence, **using all LHCb measurements** of $\Delta Y_{h^+h^-}$, $\langle t \rangle_{h^+h^-}$, $A_{CP}(D^0 \to K^+K^-)$, and ΔA_{CP}:

[PRL 122 (2019) 211803, PRD 104 (2021) 072010]

[arXiv:2209.03179]

$$a^d_{K^+K^-} = (7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi^+\pi^-} = (23.2 \pm 6.1) \times 10^{-4}$$
$$\rho(a^d_{KK}, a^d_{\pi\pi}) = 0.88$$

1st evidence of CPV for a single charm decay channel (3.8σ)

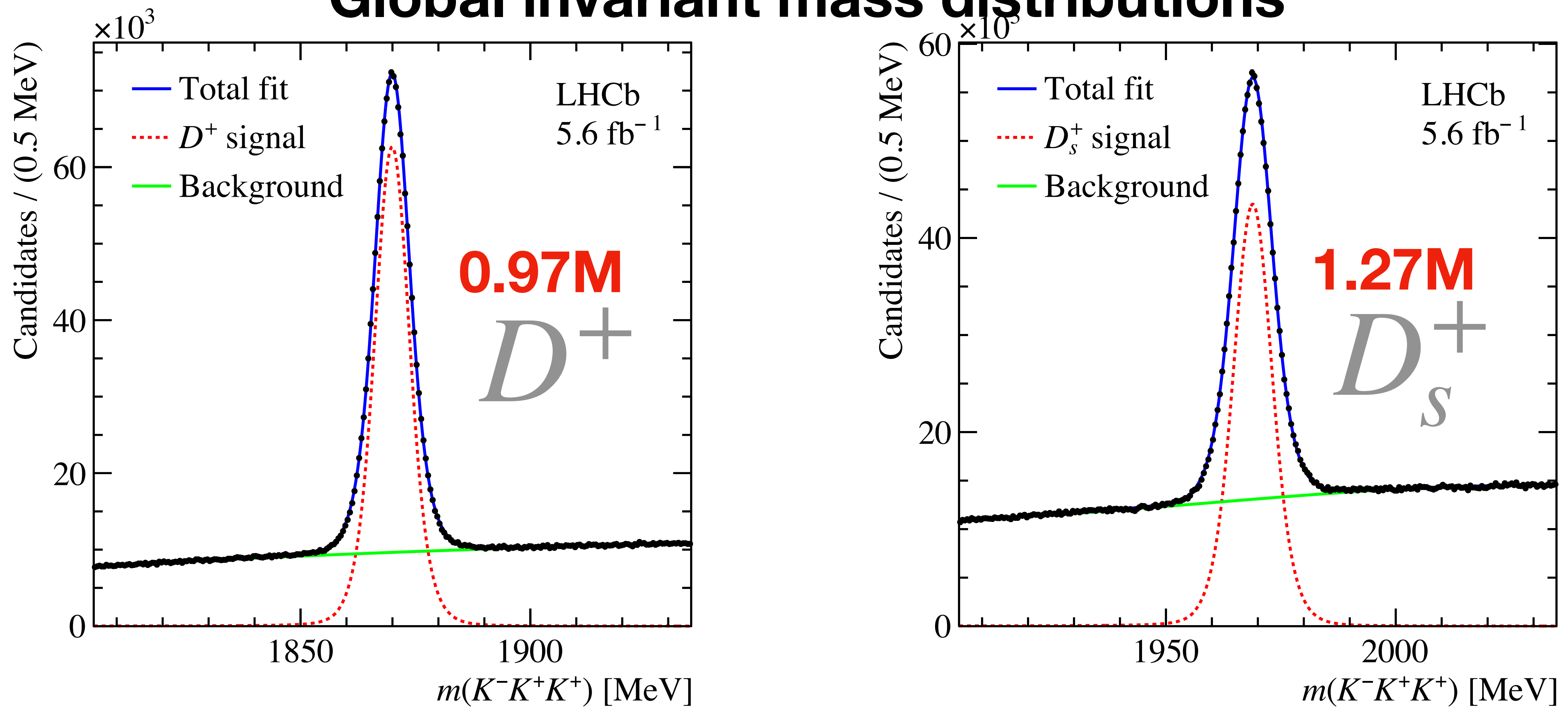


Local CPV in $D^+_{(s)} \to K^-K^+K^+$

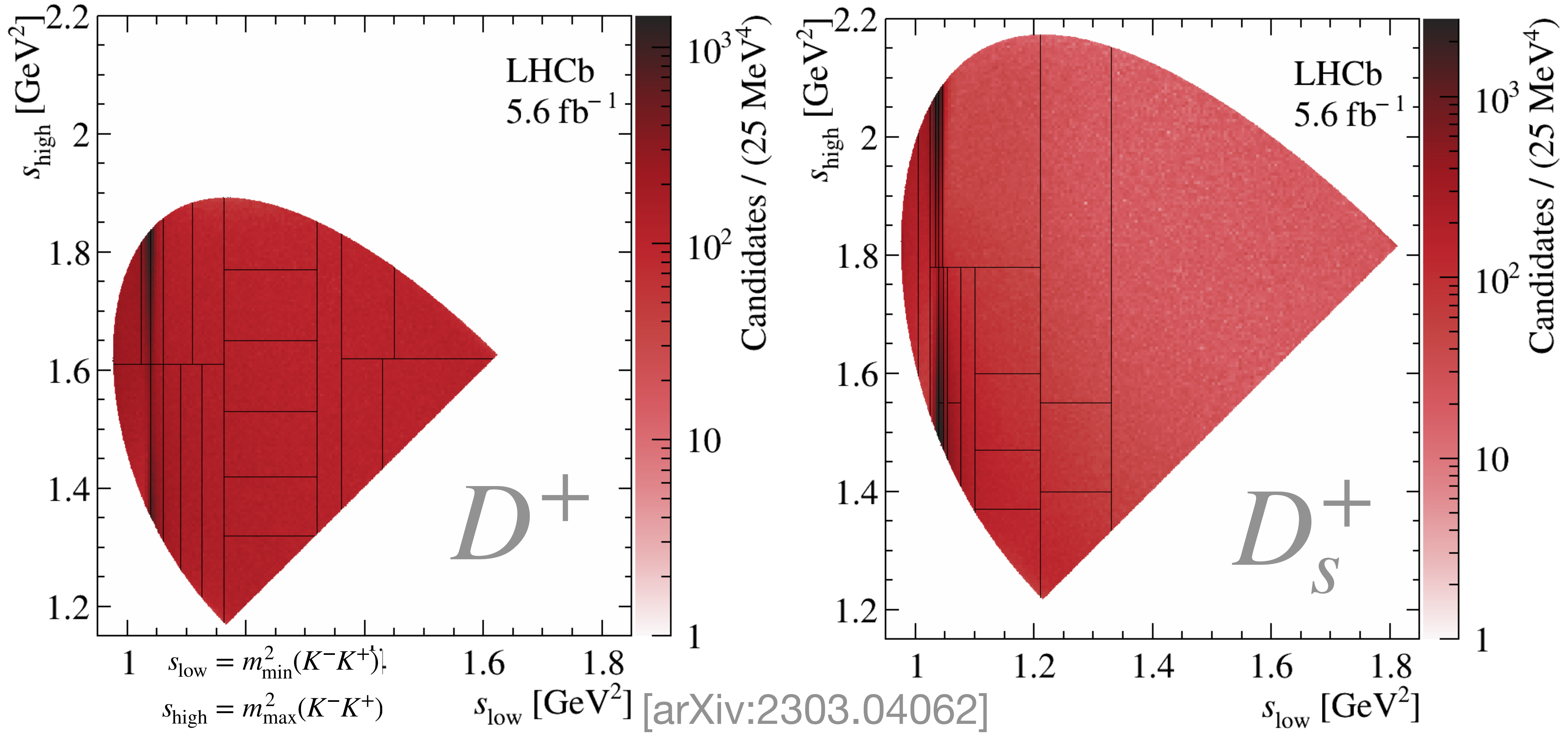
[arXiv:2303.04062]

- **Multibody decays**
  - local CP asymmetries possibly larger than the integrated ones
- $D^+_s \to K^-K^+K^+$
  - Cabibbo suppressed
  - might show CPV
- $D^+ \to K^-K^+K^+$
  - Doubly-Cabibbo Suppressed
  - CPV essentially forbidden in the SM

Global invariant mass distributions



Dalitz plot distributions



[arXiv:2303.04062]

Local CPV in $D^+_{(s)} \to K^- K^+ K^+$

- **Run2 data sample**
- Dalitz plot divided in **21 bins** to enhance sensitivity
  - pattern of the main resonances is reproduced
    - $\approx$ const. strong phase

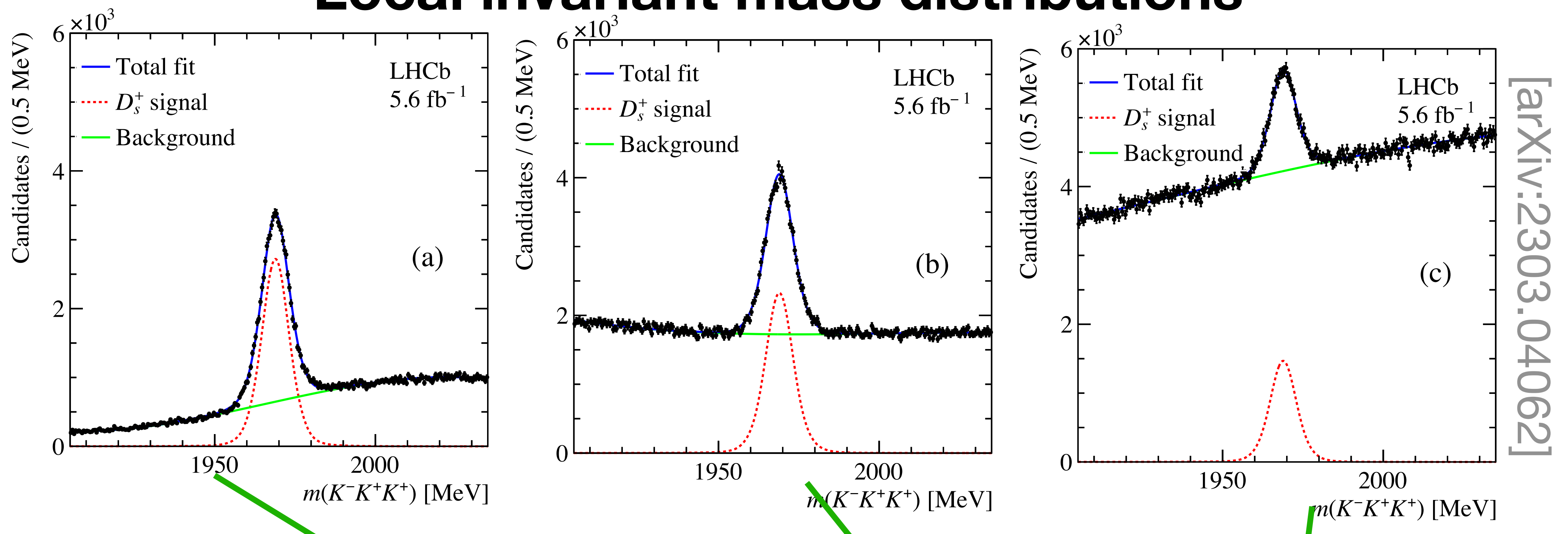
- χ^2 test to compare Dalitz distribution of yields obtained by mass fit in each bin

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

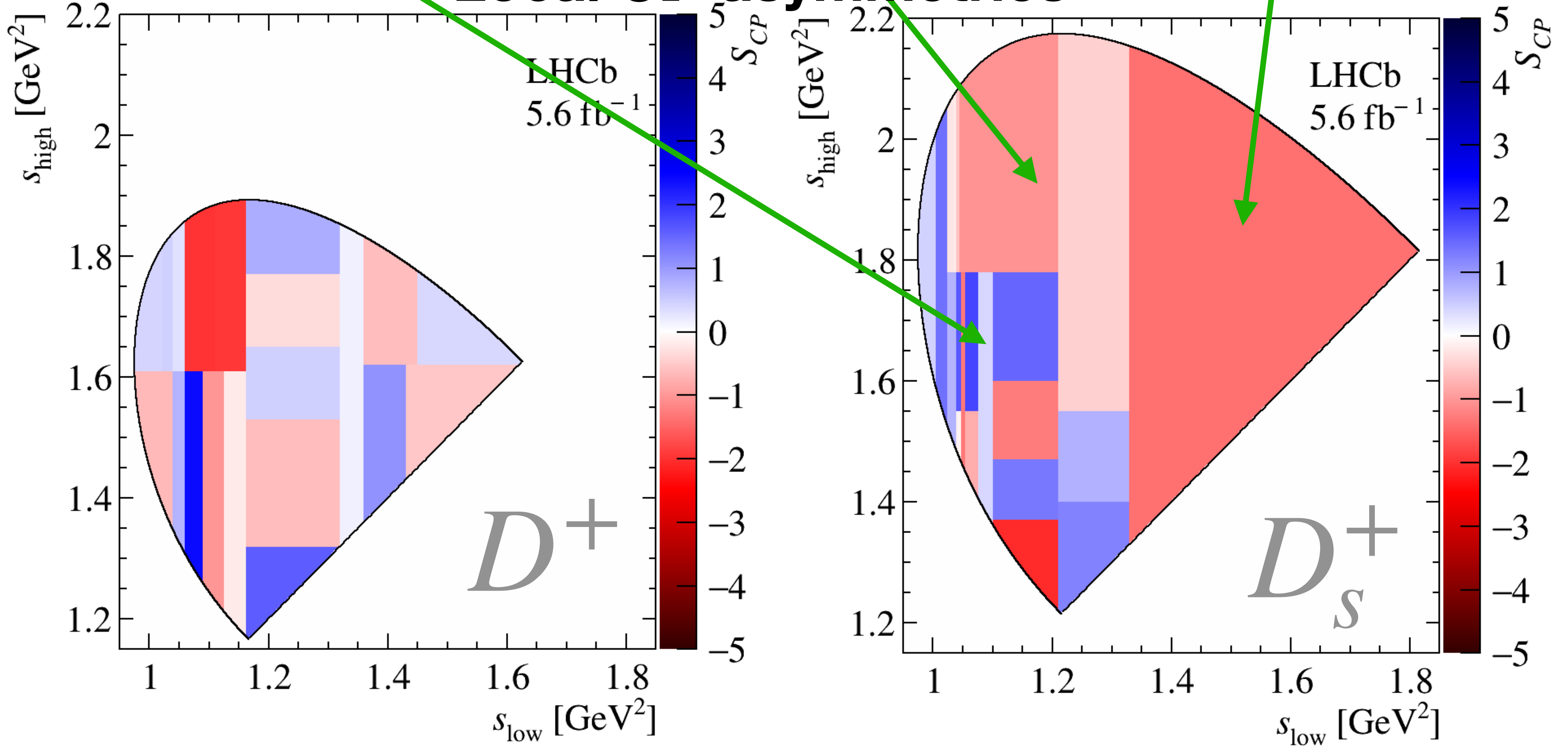
- Variation of the *Miranda* method:
  - Not affected by *global* nuisance asym.
  - *Local* nuisance asym. are negligible
    - Checked with **simulation and control samples** (Cabibbo-favoured $D^+ \to K^-\pi^+\pi^+$, $D^+_s \to K^-K^+\pi^+$ decays)

[PRD 78 (2008) 051102]
[PRD 80 (2009) 096006]

Local invariant mass distributions



Local CP asymmetries



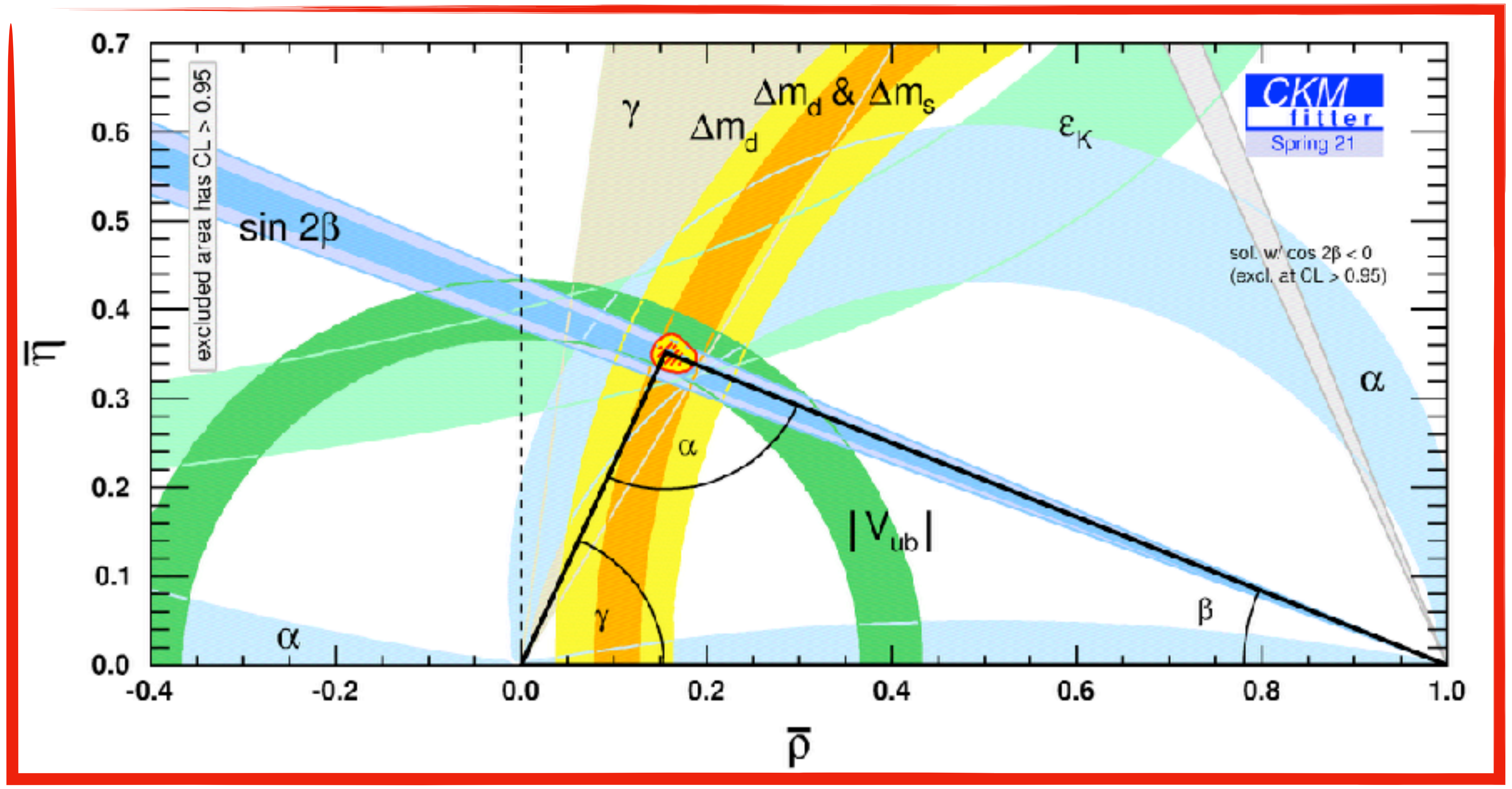
$p-$value $= 31.6\,\%$ [arXiv:2303.04062] $p-$value $= 13.3\,\%$

NO CPV is observed

First CPV search in $D^+_{(s)} \to K^-K^+K^+$ decays

The angle γ of the UT

- **The Unitarity Triangle** (UT):
  - Geometrical representation of a requirement due to the unitarity of the CKM matrix
  - **stringent tests of the SM**



$$V_{ub}^{*}V_{ud} + V_{cb}^{*}V_{cd} + V_{tb}^{*}V_{td} = 0$$

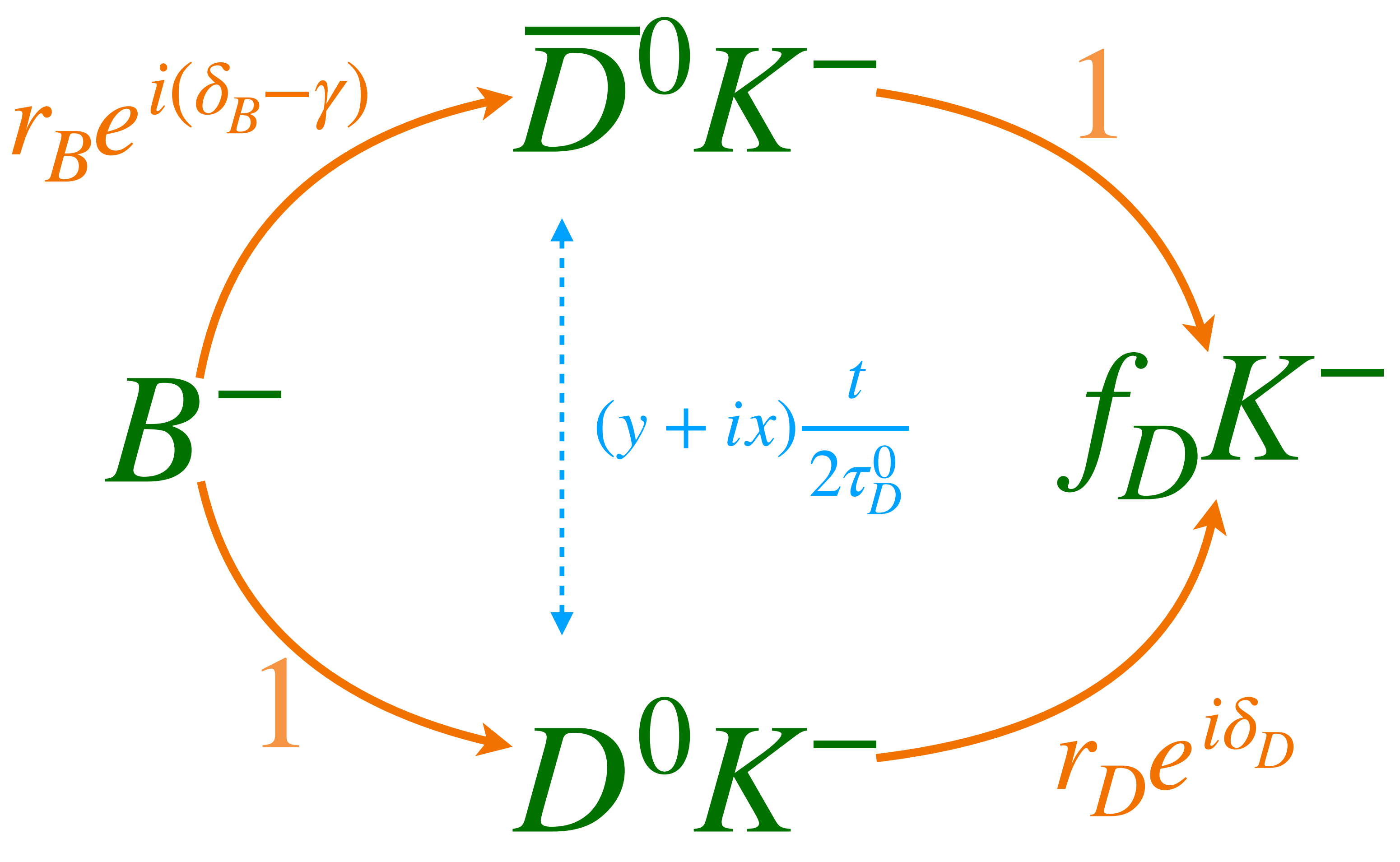
- **The angle γ** of the UT
  - directly measurable in tree-level decays with **interference** between $b \to cW$ and $b \to uW$ transitions
    - Today: Several **time-independent** methods: $B^{\pm} \to D^{(*)}h^{(*)}$ with D mixture of D^0 and $\overline{D}^0$ decaying to the same final state (f_D)
    - **Time-dependent** methods: $B^0 \to D^{\mp}\pi^{\pm}$, $B_s^0 \to D_s^{\mp}K^{\pm}$ exploiting interference between mixing and decay
    - **Combination** of measurements from many channels
  - **Remarkable SM benchmark** to be compared with indirect measurements involving loop-level transitions

$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right) \equiv \phi_3$$

The angle γ of the UT: generalities

- The γ parameter is obtained combining CP **asymmetries** and **decay rates**
  - Various methods depending on f_D
  - Charm decay parameters as **external inputs**

Golden mode: $B^{\pm} \to f_D K^{\pm}$



$$\Gamma(B^{\pm} \to f_D h^{\pm}) \propto r_D^2 + r_B^2 + 2 r_D r_B R_{f_D} \cos(\delta_B + \delta_d \pm \gamma)$$

Charm mixing

$$-r_D R_{f_D}(y \cos\delta_D - x \sin\delta_D) + (x^2 + y^2)/2$$
$$-r_B[y \cos(\delta_B \pm \gamma) + x \sin(\delta_B \pm \gamma)]$$

Charm mixing parameters

$$x \equiv \frac{\Delta m}{\Gamma}, \quad y \equiv \frac{\Delta\Gamma}{2\Gamma} \quad < 1\,\%$$

Coherence factor, $0 < R_{f_D} < 1$, suppresses interference and reduces sensitivity

γ with $B^\pm \to [K^\mp\pi^\pm\pi^\pm\pi^\mp]_D h^\pm$

[arXiv:2209.03692]

$h = K, \pi$

- Superposition of Cabibbo-Favoured and Doubly-Cabibbo-Suppressed D decays
  - $B^\pm \to [K^\mp\pi^\pm\pi^\pm\pi^\mp]_D h^\pm$, $B^\pm \to [K^\pm\pi^\mp\pi^\mp\pi^\pm]_D h^\pm$, $X_b \to D^{*+}[D^0\pi]\mu^-\overline{\nu}_\mu X$

Bin	$R^i_{K3\pi}$
1	$0.66\,^{+0.18}_{-0.21}$
2	$0.85\,^{+0.14}_{-0.21}$
3	$0.78\,^{+0.12}_{-0.12}$
4	$0.25\,^{+0.16}_{-0.25}$

JHEP 05 (2021) 164

- **Global $R_{K3\pi} \approx 0.4$, but in phase-space bins it is larger**
  - 4 bins chosen according to LHCb amplitude analysis
  - **increased sensitivity with binned measurement**

[PRD68 (2003) 033003]
[PLB802 (2020) 135188]

[arXiv:2209.03692]

Results of this analysis (LHCb Run1+Run2):

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

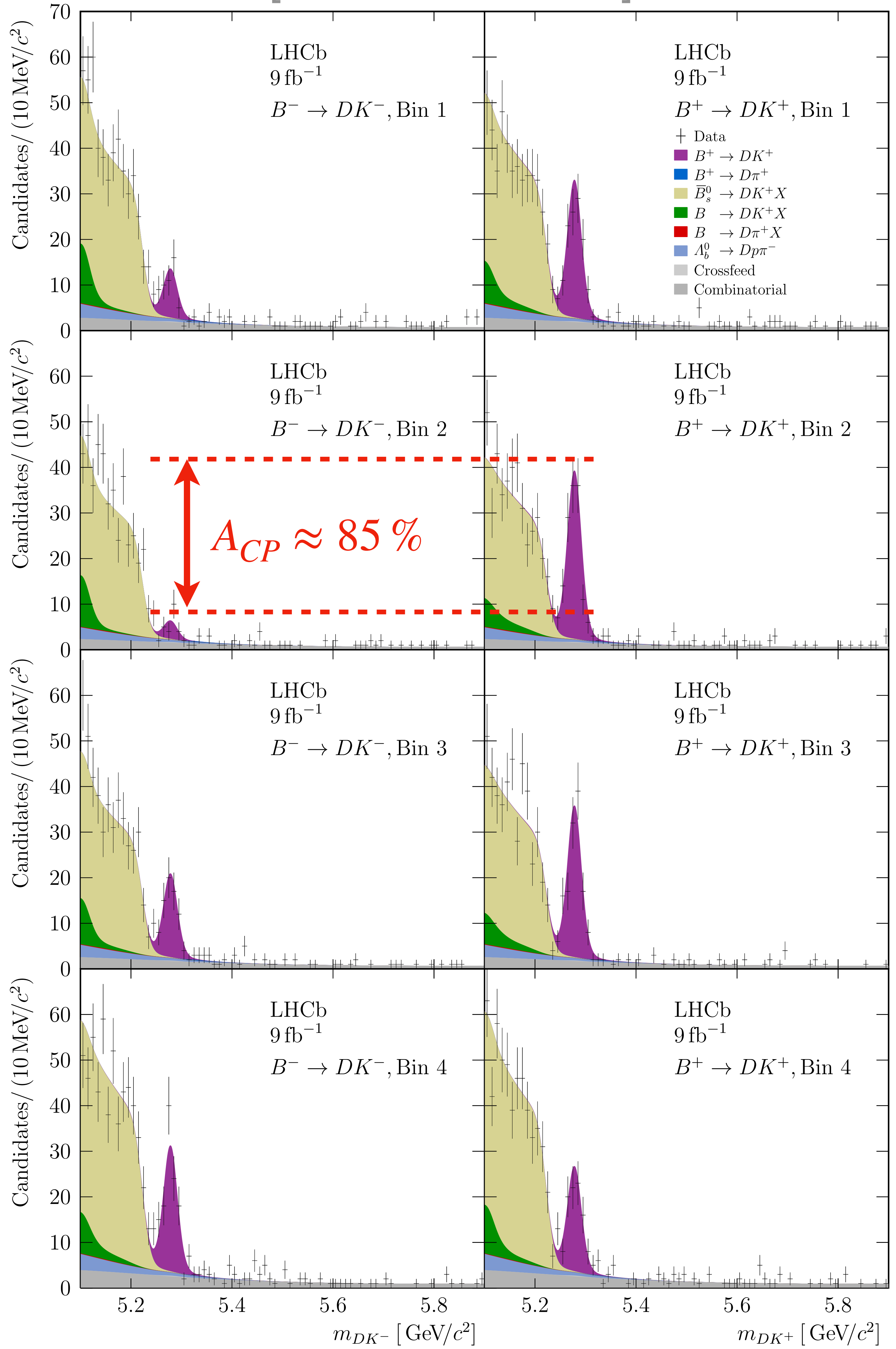
stat. syst. ext.

2nd most precise determination of γ

- External inputs:
  - Hadronic D decay parameters from model-independent determinations by CLEO-c, BES-III, and LHCb
  - Charm mixing parameters by LHCb
  - First source of uncertainty now, but **improvements are expected**
    - incoming $20\ \text{fb}^{-1}$ of BES$-$III data
    - LHCb measurement of charm mixing

[PLB802 (2020) 135188]
[JHEP 05 (2021) 164]
[PRL 116 (2016) 241801]

[arXiv:2209.03692]



LHCb combination for γ

[LHCb-CONF-2022-003]

- Combination of results from beauty and charm sectors
- Frequentist approach
  - 52 parameters
  - 173 observables
  - Fit probability 80%
- Includes updated and new measurements
  - $B^{\pm} \to [h^{\pm}h'^{\mp}\pi^0]_D h^{\pm}$ 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 $\overline{B} \to D^0(\to K^0_s\pi^+\pi^-)\mu^-\overline{\nu}_\mu X$ arXiv:2208.06512
  - $A_{CP}(D^0 \to K^-K^+)$ arXiv:2209.03179

[LHCb-CONF-2022-003]

$x = \left(0.398^{+0.050}_{-0.049}\right)\%$

$y = \left(0.636^{+0.020}_{-0.019}\right)\%$

D^0 mixing

$|q/p| = \left(0.995^{+0.015}_{-0.016}\right)$

$\phi = (2.5 \pm 1.2)^\circ$

CPV in D^0mixing

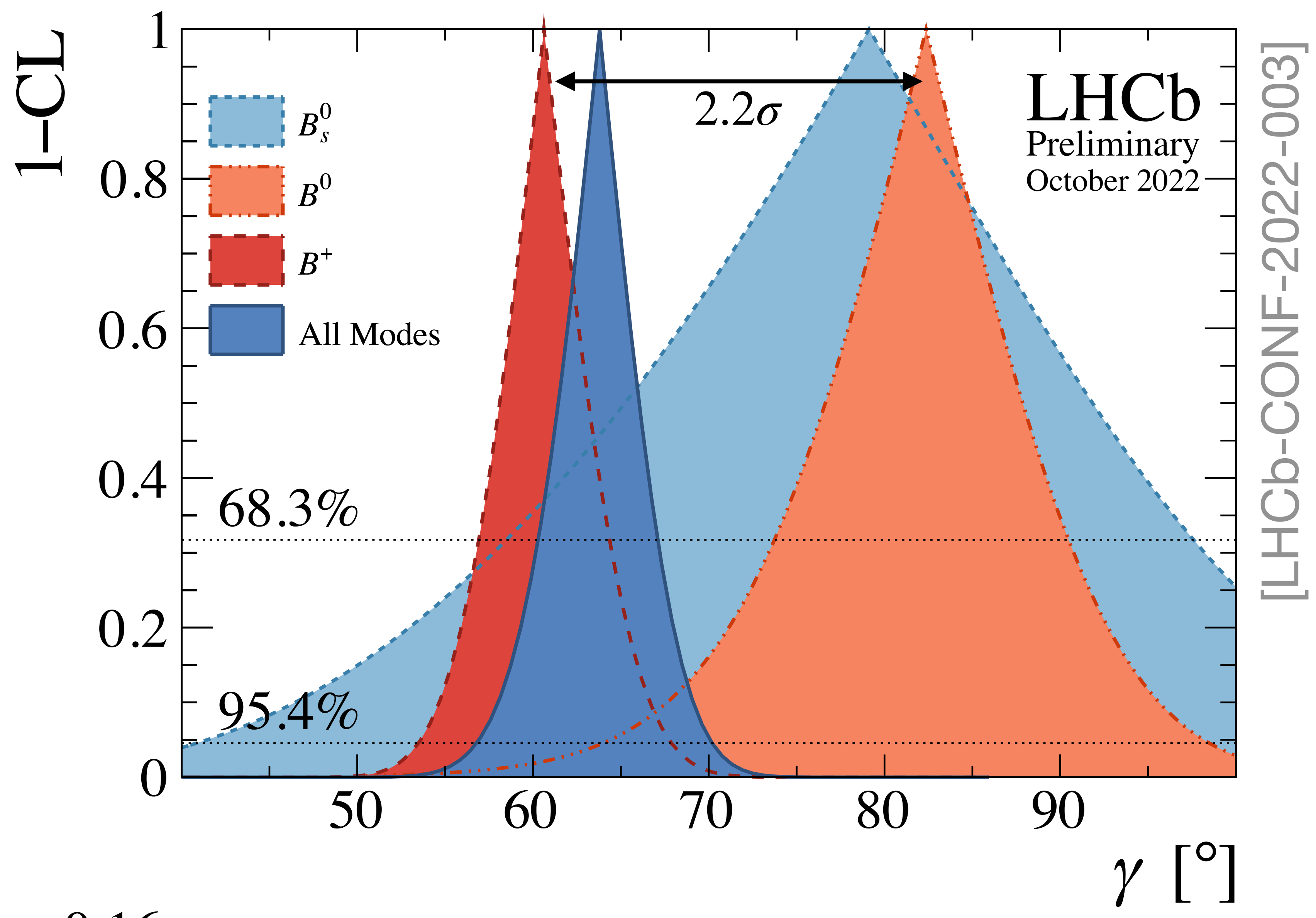
$$\gamma = \left(63.8^{+3.5}_{-3.7}\right)^\circ$$

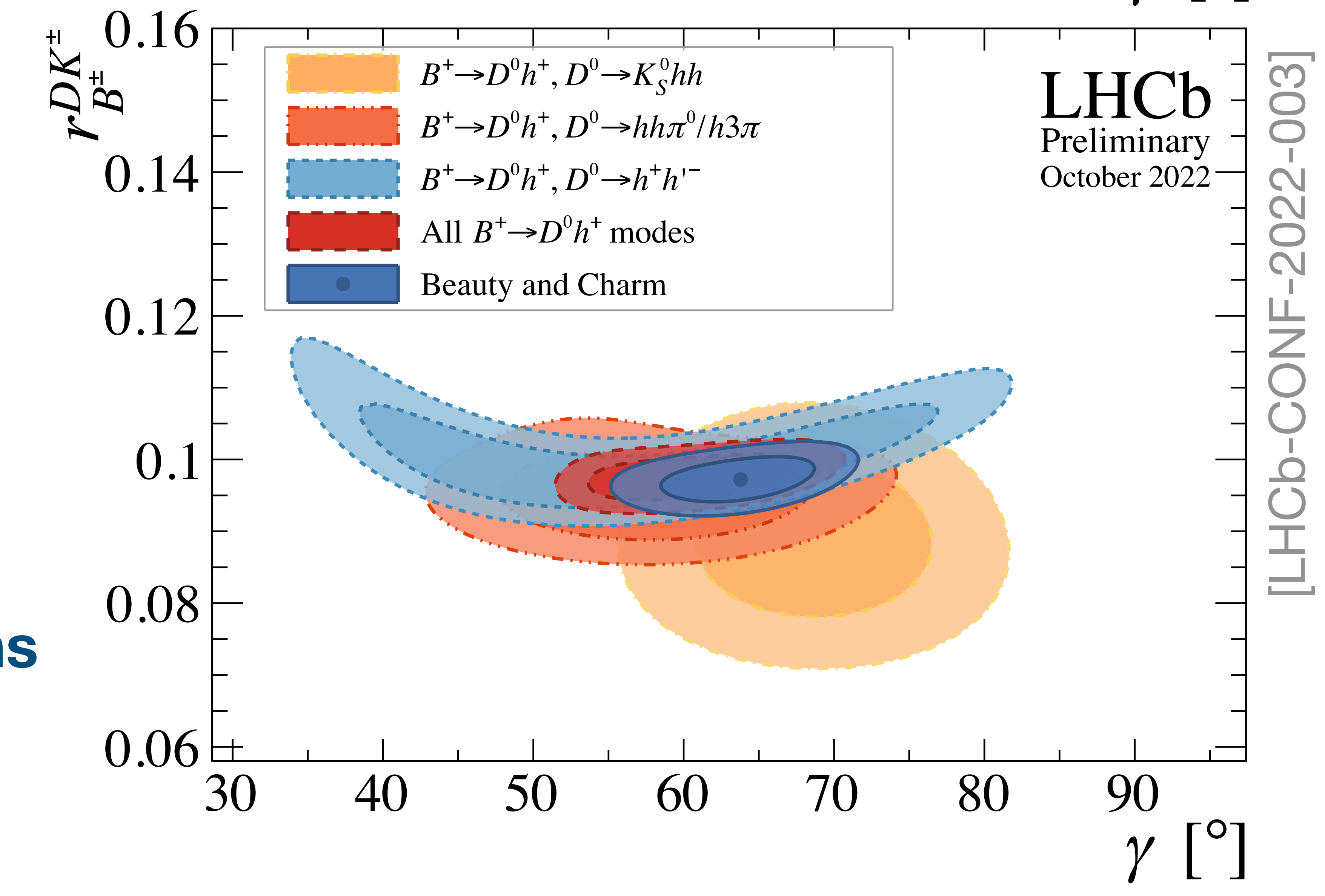
Syst. Uncertainty ~ 1%

Compatibile with indirect determinations

$\gamma = \left(65.7^{+0.9}_{-2.7}\right)^\circ$ CKMfitter

$\gamma = \left(65.8 \pm 2.2\right)^\circ$ UTFit



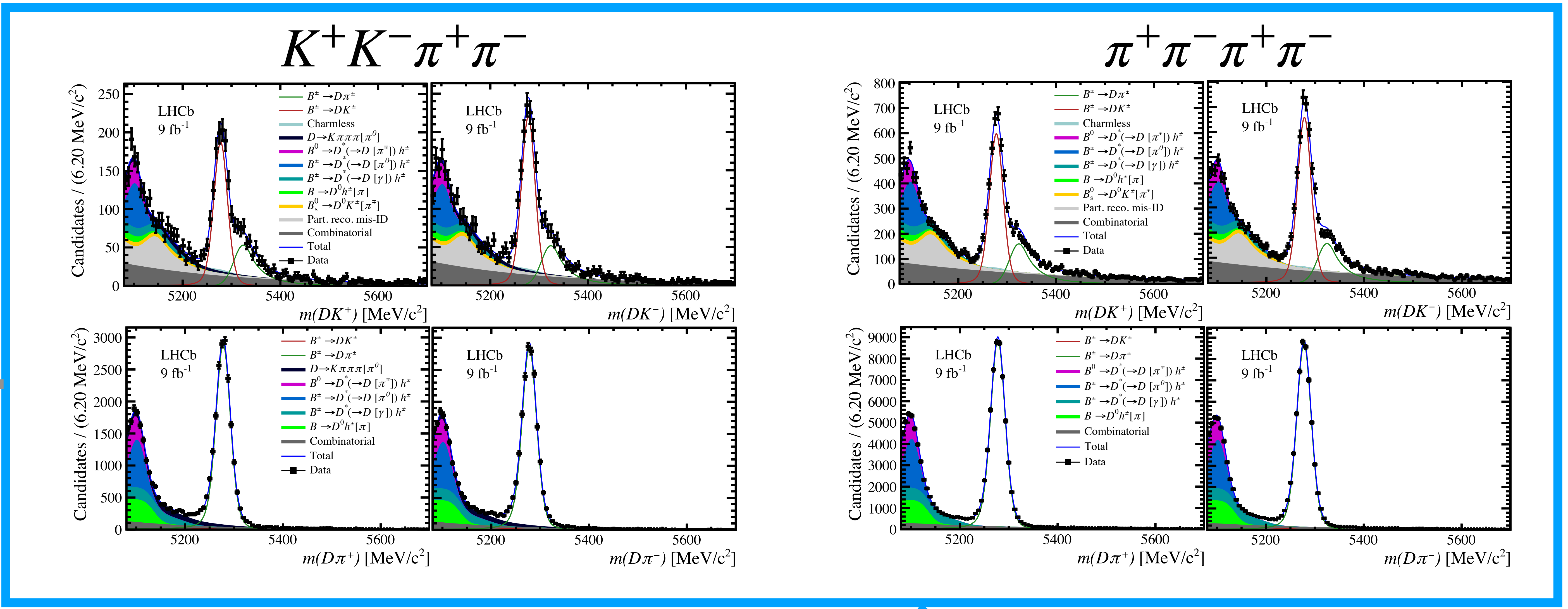


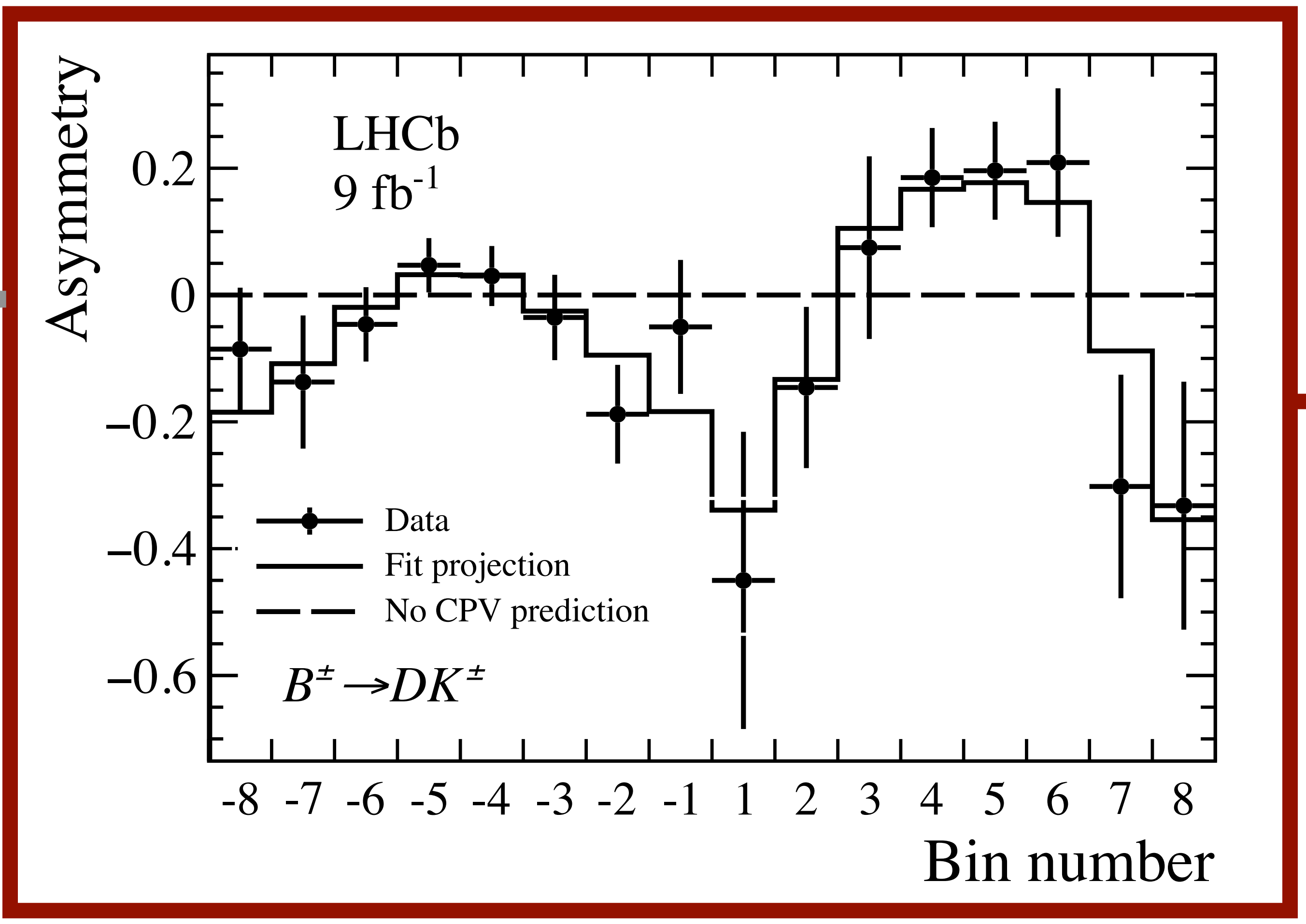
γ with $B^{\pm} \to [h^+h^-\pi^+\pi^-]_D h'^{\mp}$

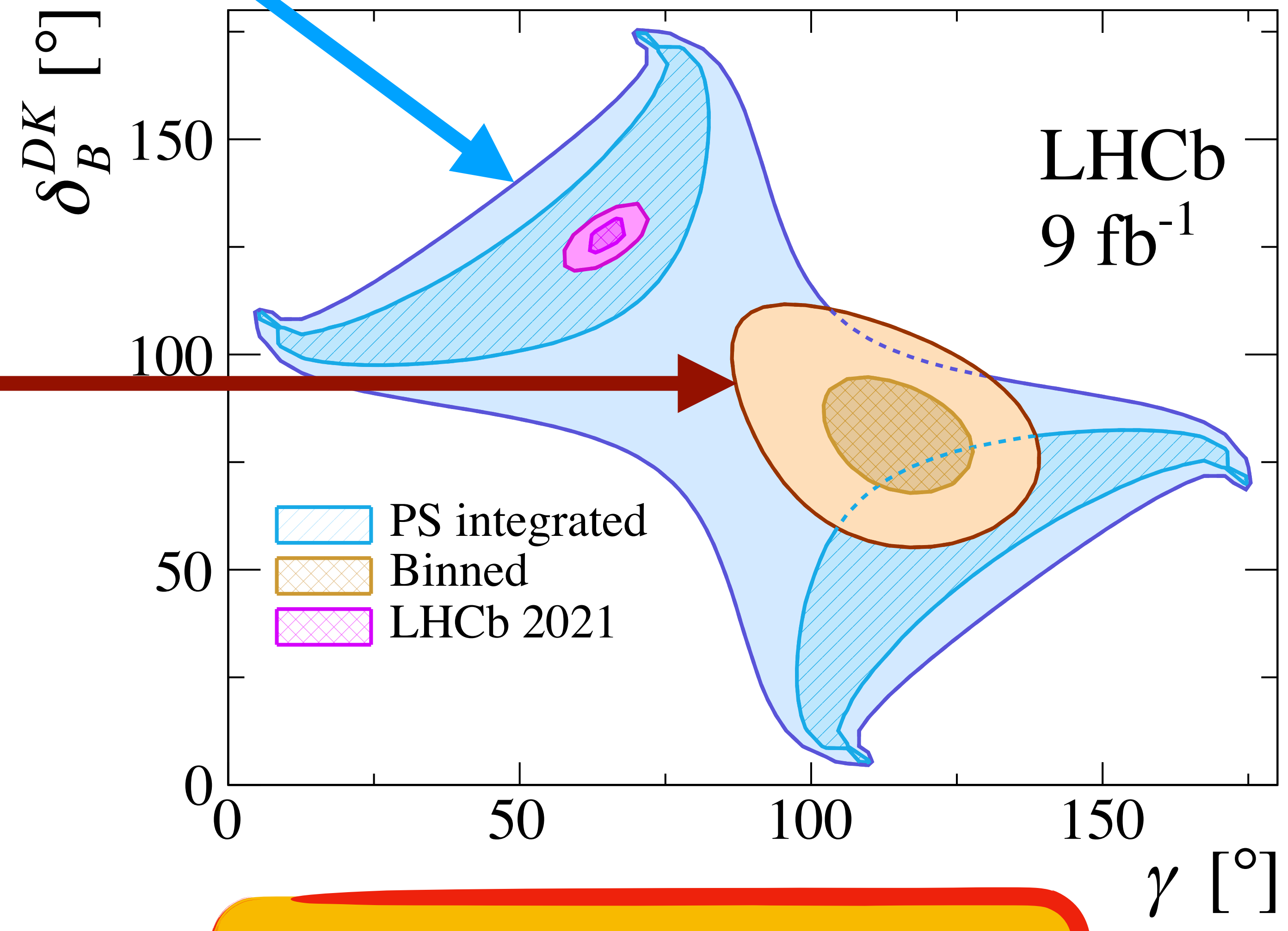
[arXiv:2301.10328]

- First study of CPV in $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$
- LHCb **Run1+Run2** data
  - Not included in LHCb combination yet
- Integrated analysis for both $K^+K^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$ final states
- Also binned analysis for $K^+K^-\pi^+\pi^-$
  - Charm decay parameters from LHCb amplitude analysis [JHEP 02 (2019) 126]
  - **Precision will improve** and value may change after charm model-independent measurements

[arXiv:2301.10328]



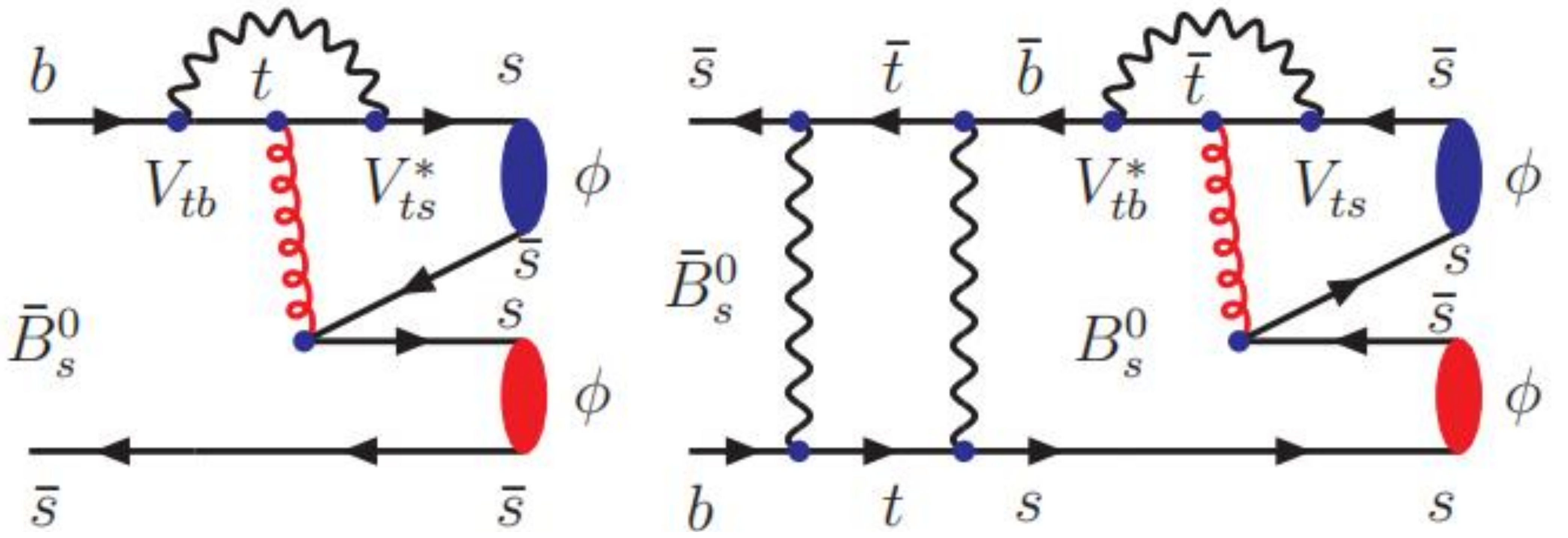




$$\gamma = \left(116^{+12}_{-14}\right)^{\circ}$$

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

- **Motivations:**
  - The SM predicts CPV to be suppressed in this channel
  - Any CPV enhancement would point to new physics in the B_s^0 mixing or in the **penguin-mediated** $b \to s$ decay



- **Caveat:** angular analysis needed to disentangle the three polarisation states of the $B \to VV$ decays
  - (0, CP even), (||, CP even), (⊥, CP odd)

$A_i = \langle f_i | H_W | B_s^0 \rangle$

$\bar{A}_i = \langle f_i | H_W | \bar{B}_s^0 \rangle$

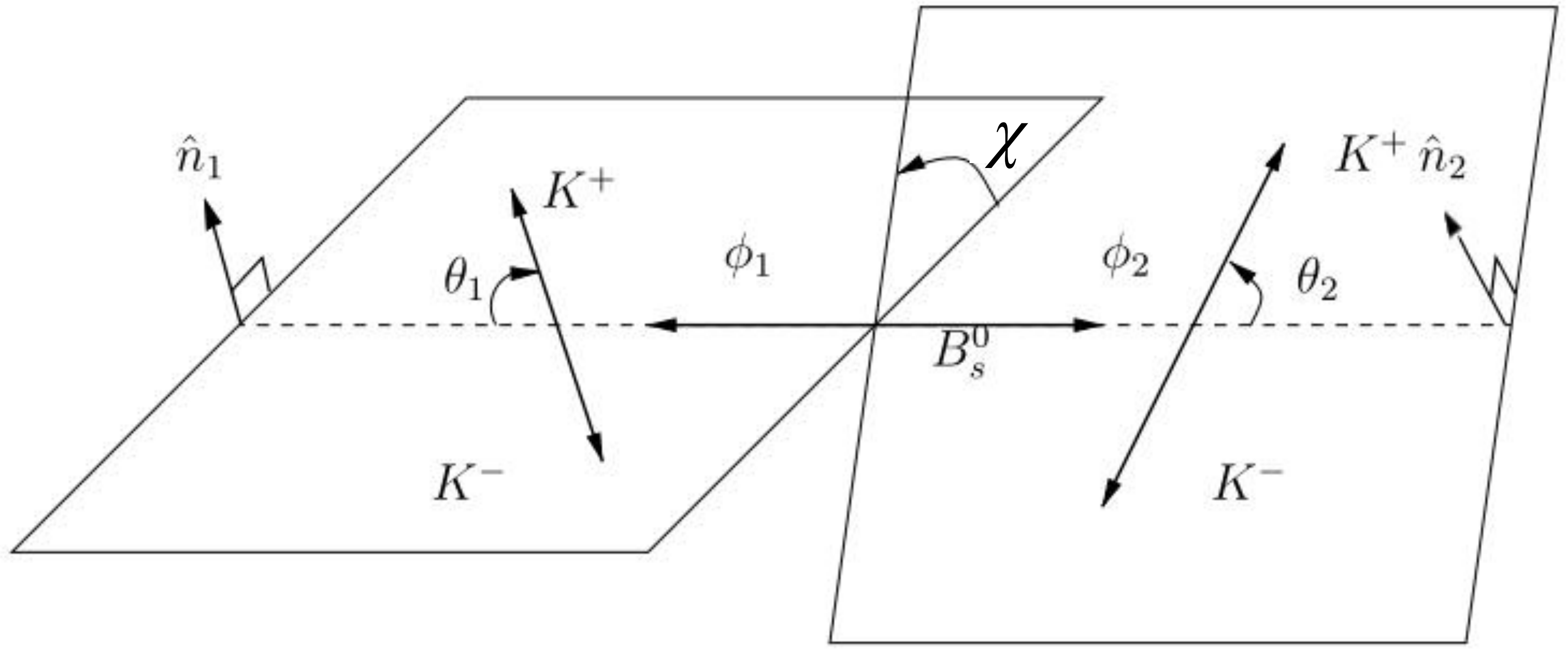
$i \in \{0, \parallel, \perp\}$

$\eta_{0,\parallel(\perp)} = \pm 1$

$|B_{s,H(L)}^0\rangle = |B_s^0\rangle p \pm |\bar{B}_s^0\rangle q$

$$\lambda_i \equiv \eta_i \frac{q}{p} \frac{\bar{A}_i}{A_i} = |\lambda_i| e^{-i\phi_{s,i}}$$

- **Target CP observables:** $\phi_{s,i}$, $|\lambda_i|$
  - The SM predicts no dependance of the CP observables on the polarisation
    - CP phase: $\phi_i = \phi_s^{s\bar{s}s} \approx 0$
    - Direct CP violation parameter: $|\lambda_i| = |\bar{A}_i / A_i| = |\lambda| \approx 1$ (No CPV in mixing)



[Nucl. Phys. B 774 (2007) 64] [PRL 89 (2002) 231803][arXiv:0810.0249]
[PRD 80 (2009) 114026] [Nucl. Phys. B 935 (2018) 17][PRD 96 (2017) 073004]

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

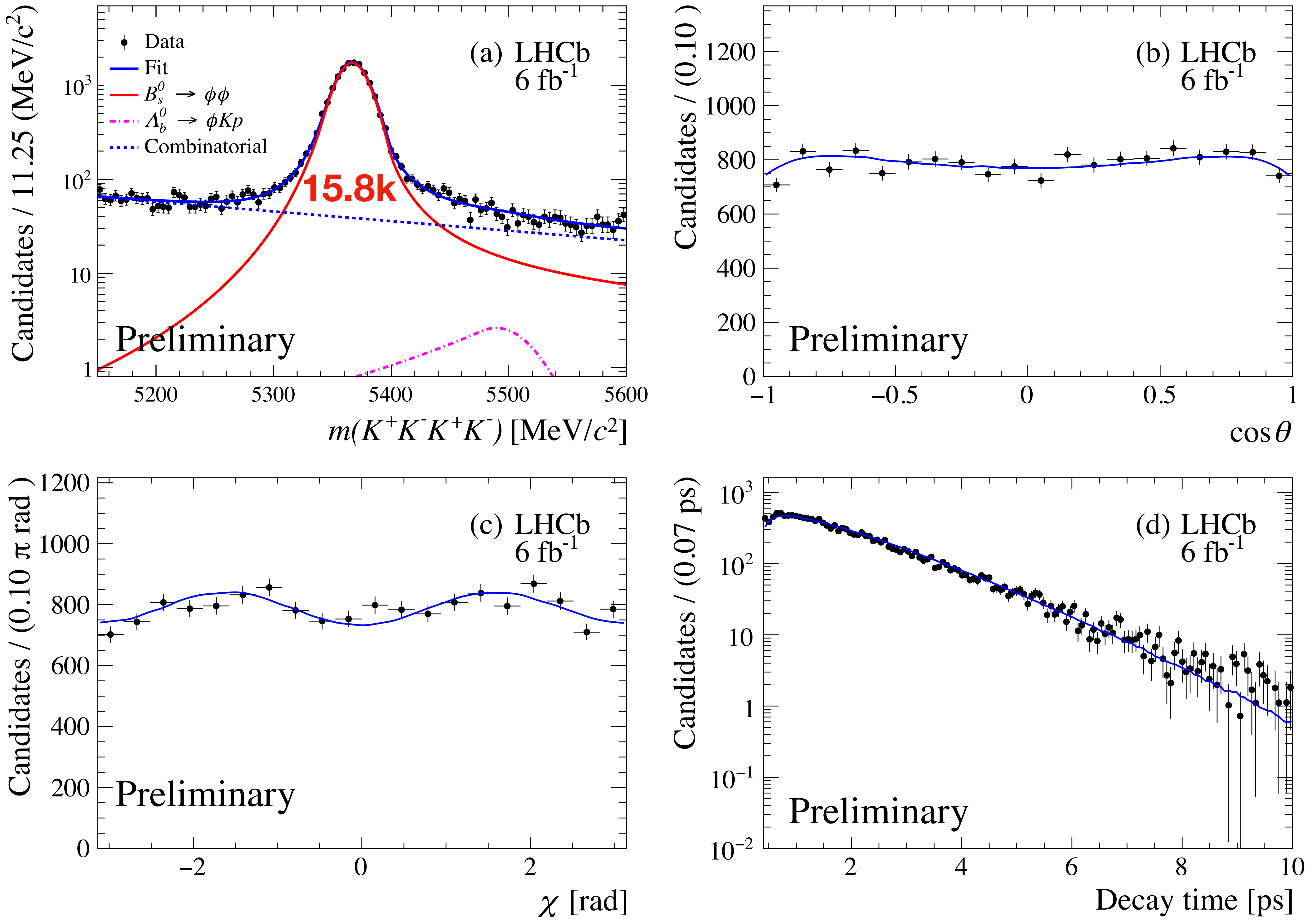
[LHCb-PAPER-2023-001-002]

- **Data:**
  - **Run2** data ($6\ \text{fb}^{-1}$)
  - Results are then **combined with Run1** measurements (additional $3\ \text{fb}^{-1}$)

- **Strategy:**
  1. Invariant-mass fit to subtract the background
  2. Flavour-tagged fit to decay time and helicity angles to get the CP observables

     [details in the backup]

- **Main experimental challenges:**
  - Decay-time resolution (≈ 40 fs)
  - Flavour-tagging power ($\approx 6\,\%$)
  - Their calibration



Helicity angles (χ, θ) defined in the previous slide

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

[LHCb-PAPER-2023-001-002]

This analysis, **Run2 only**

polarisation-independent fit

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

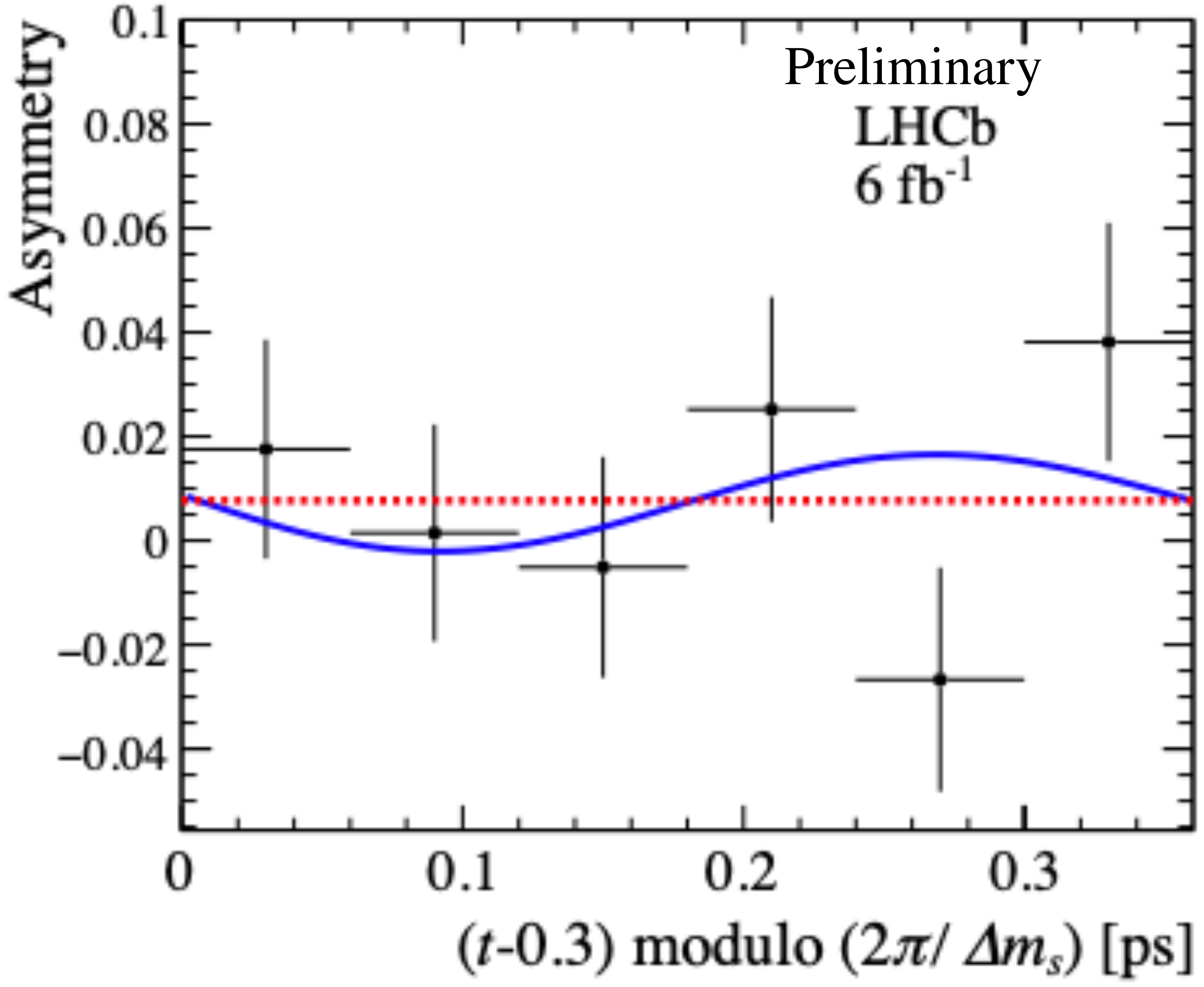
stat. syst.

polarisation-dependent fit

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

stat. only   stat. only

First measurement



[LHCb-PAPER-2023-001-002 - Supp. material]

[LHCb-PAPER-2023-001-002]

Run1+Run2

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

Most precise measurement of time-dependent CPV in penguin-dominated decays of neutral B mesons

No evidence of CPV
in both the polarisation-independent and the polarisation-dependent analyses

Conclusions

- **LHCb Run2 data have been providing remarkable insights** in both the charm and beauty CPV sectors
  - First evidence of CPV in charm in a single decay channel (3.8σ)
  - New search for local CPV in charm multi-body decays
  - Uncertainty on γ already below 4°
    - Further improvements are expected with other decay modes and better knowledge of charm hadronic parameters
  - Precise CPV measurements in penguin-dominated B_s^0 decays

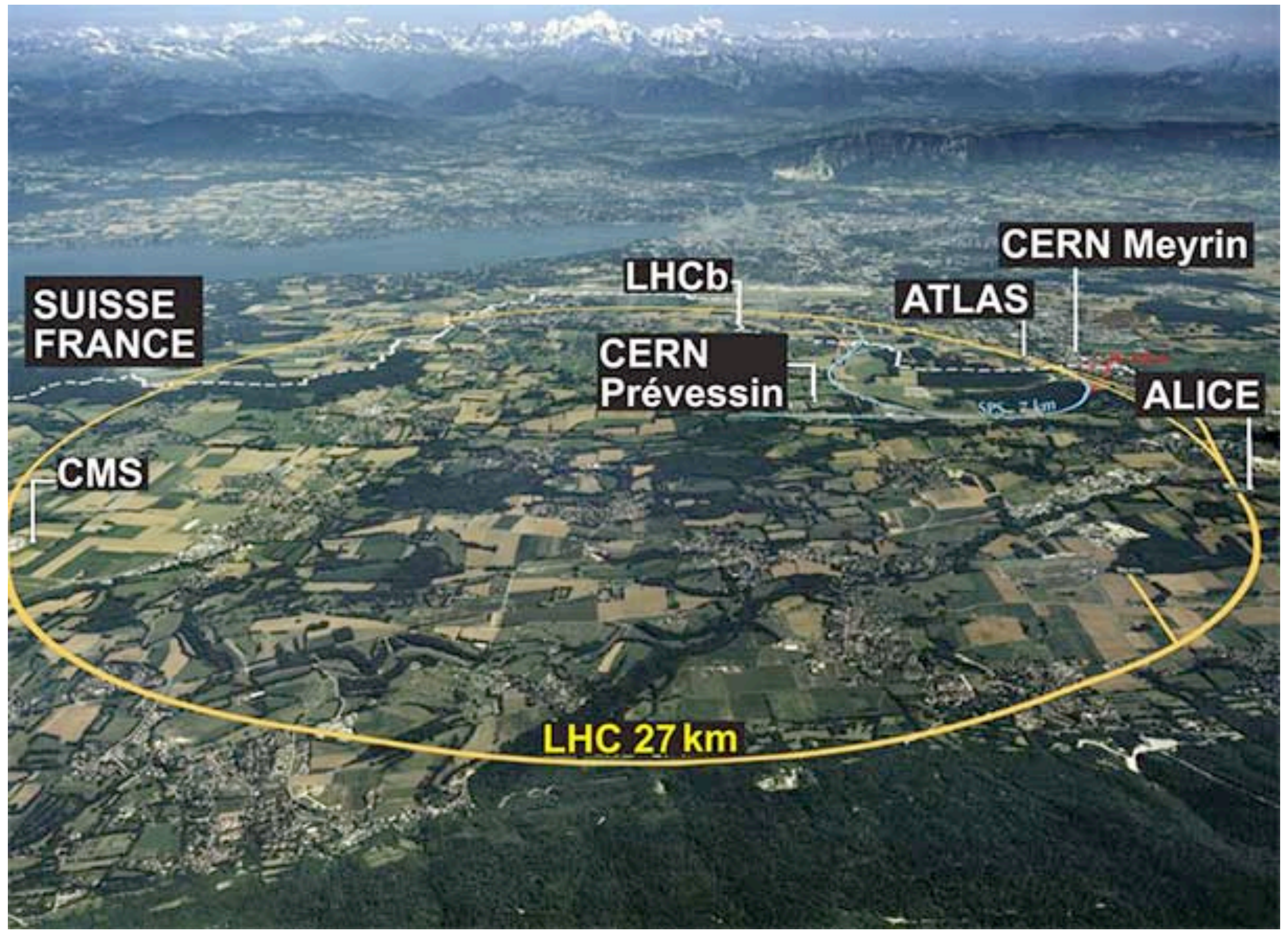
News of the last 6 months

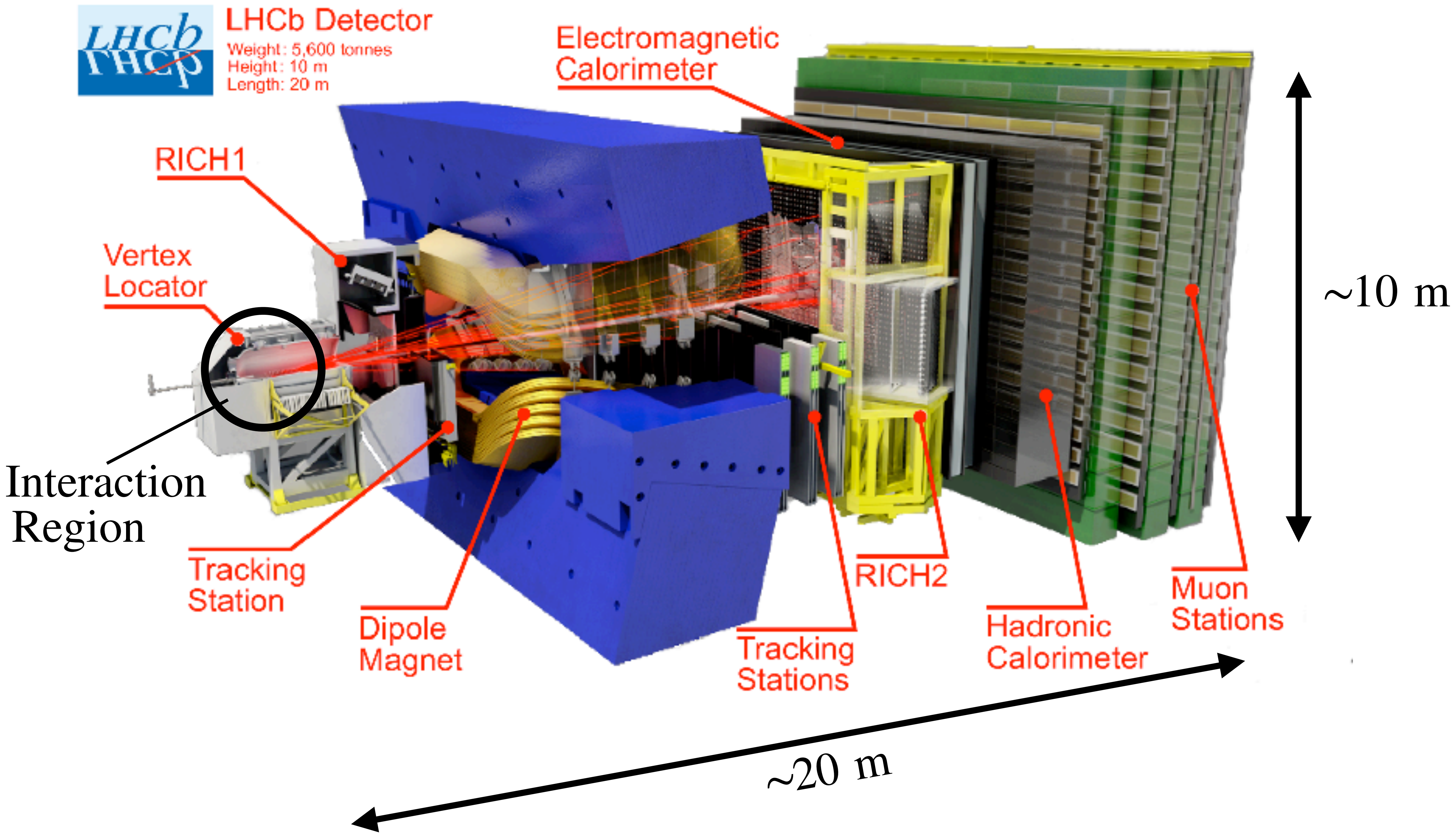
- LHCb Upgrade I is expected to improve the measurements in Run3
  - Higher integrated luminosity
  - Removal of hardware trigger
    - Higher trigger efficiency, smaller detection asymmetries

Backup slides

The LHCb experiment

- LHCb is a forward spectrometer, operating at LHC $(\sqrt{s} = 13\ \text{TeV})$
  - High geometrical in collecting $b\bar{b}$ and $c\bar{c}$ quark pairs
  - Excellent decay-time resolution, momentum resolution, PID performances





[JINST 3 S08005]
[Int. J. Mod. Phys. A 30 (2015)1530022]

$A_{CP}(D^0 \to K^+K^-)$: yields and systematics

Table 2: Systematic uncertainties on $\mathcal{A}_{CP}(K^-K^+)$ for the two calibration procedures C_{D^+} and $C_{D_s^+}$. The total uncertainties are obtained as the sums in quadrature of the individual contributions. Correlations between the systematic uncertainties of the two calibration procedures are also reported.

Source	C_{D^+} $[10^{-4}]$	$C_{D_s^+}$ $[10^{-4}]$	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

$$C_{D^+}: \ \mathcal{A}_{CP}(K^-K^+) = [13.6 \pm 8.8\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4},$$

$$C_{D_s^+}: \ \mathcal{A}_{CP}(K^-K^+) = [\ 2.8 \pm 6.7\,(\text{stat}) \pm 2.0\,(\text{syst})] \times 10^{-4},$$

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

Table 1: Signal yields and statistical reduction factors arising from the kinematic weighting of the sample for the various decay modes and both calibration procedures.

Decay mode	Signal yield $[10^6]$		Red. factor	
	C_{D^+}	$\mathrm{C}_{D_s^+}$	C_{D^+}	$\mathrm{C}_{D_s^+}$
$D^0 \to K^-K^+$	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

γ with $B^\pm \to [h^+h^-\pi^+\pi^-]_D h'^\mp$: yields

D decay	Component	Reconstructed as: $B^\pm \to DK^\pm$	$B^\pm \to D\pi^\pm$
$D \to K^+K^-\pi^+\pi^-$	$B^\pm \to DK^\pm$	3026 ± 38	142 ± 2
	$B^\pm \to D\pi^\pm$	240 ± 1	44349 ± 218
	Partially reconstructed bkg	87 ± 1	27 ± 1
	$D \to K^\mp\pi^\pm\pi^-\pi^+\pi^0$	44 ± 13	580 ± 168
	Combinatorial bkg	460 ± 23	1820 ± 193
	Charmless bkg	189 (fixed)	N/A
$D \to \pi^+\pi^-\pi^+\pi^-$	$B^\pm \to DK^\pm$	8676 ± 105	386 ± 5
	$B^\pm \to D\pi^\pm$	676 ± 2	126322 ± 386
	Partially reconstructed bkg	256 ± 2	81 ± 4
	Combinatorial bkg	1344 ± 27	4172 ± 90
	Charmless bkg	688 (fixed)	N/A

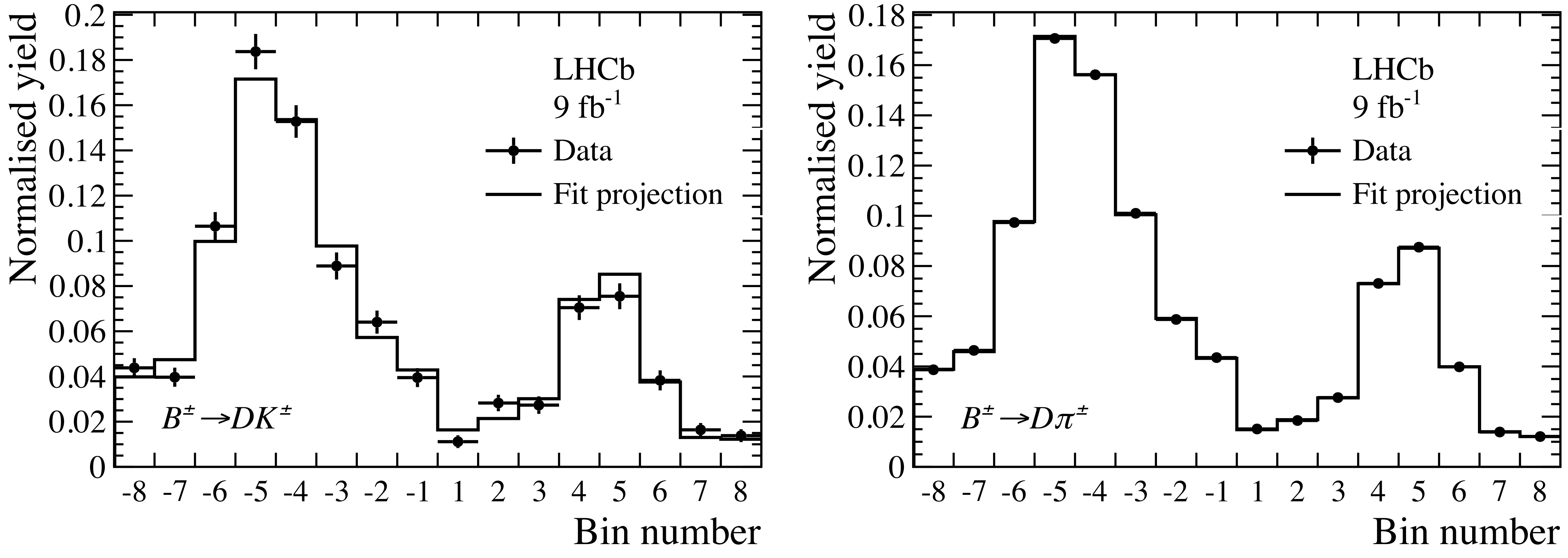


Figure 5: Total bin yields for the (left) $B^\pm \to DK^\pm$ and (right) $B^\pm \to D\pi^\pm$ decays. The data are overlaid with the fit projections.

γ with $B^\pm \to [h^+h^-\pi^+\pi^-]_D h'^\mp$: systematics

Table 5: Uncertainties on the results of the binned analysis.

	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

Table 6: Uncertainties on the results of the phase-space integrated analysis.

	Uncertainty ($\times 10^3$)					
Source	$A_K^{KK\pi\pi}$	$A_\pi^{KK\pi\pi}$	$A_K^{\pi\pi\pi\pi}$	$A_\pi^{\pi\pi\pi\pi}$	$R_{CP}^{KK\pi\pi}$	$R_{CP}^{\pi\pi\pi\pi}$
Charmless background	1.2	< 0.1	0.4	< 0.1	13.9	8.5
External parameters	1.0	0.7	1.0	0.7	4.0	4.0
Fixed yield fractions	0.1	< 0.1	0.1	< 0.1	1.3	1.4
Mass shape	0.3	< 0.1	0.2	< 0.1	3.1	3.1
PID efficiency	0.1	< 0.1	0.1	< 0.1	2.5	1.6
Total systematic	1.6	0.7	1.1	0.7	15.1	10.1
Statistical	23.5	5.5	13.3	3.1	24.2	14.3

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

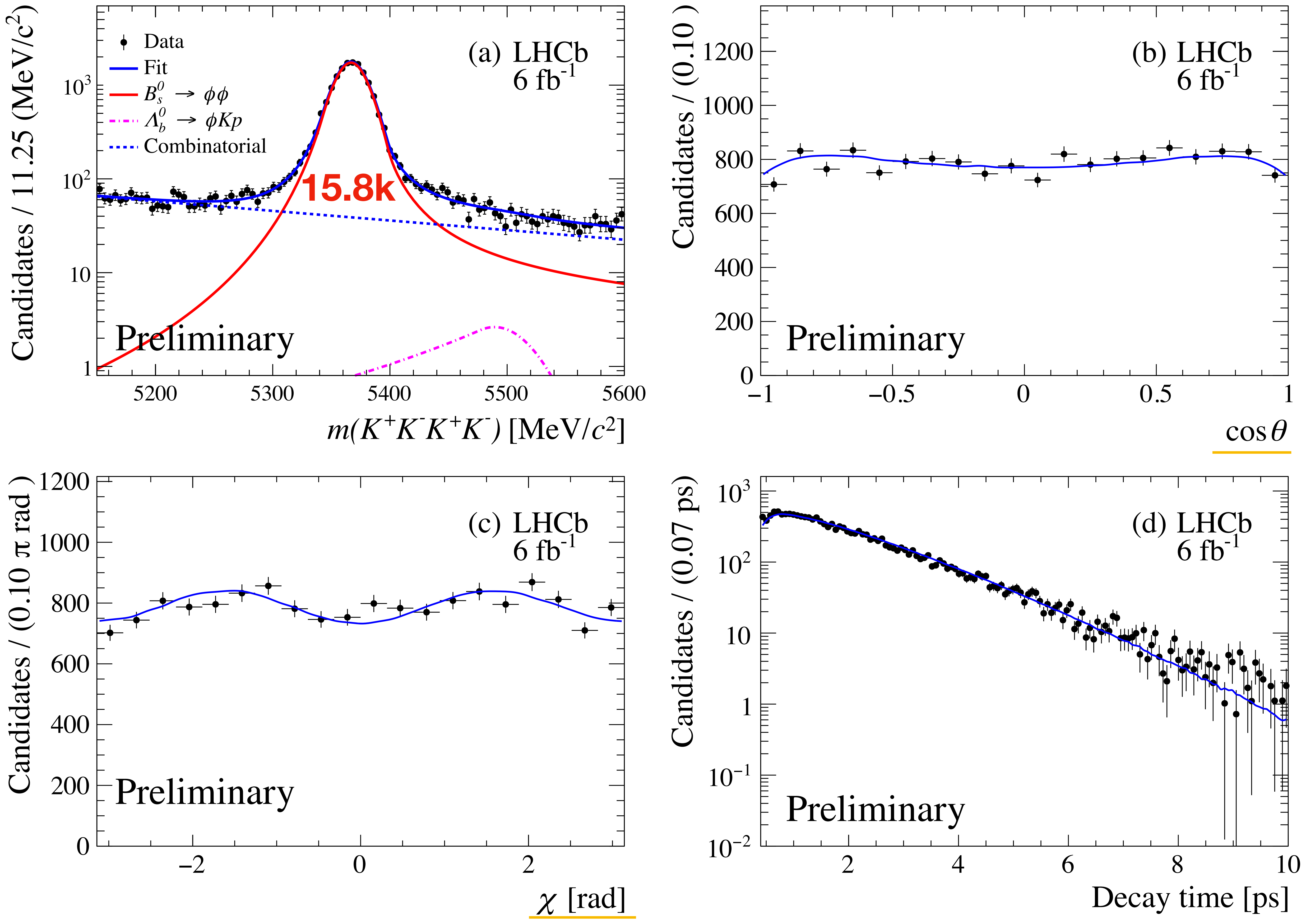
- **Strategy:**
  1. Invariant-mass fit
     to subtract the background
  2. Flavour-tagged fit to
     decay time and helicity angles
     to get the CP observables

$$\frac{d^4\Gamma(t,\vec{\Omega})}{dt d\vec{\Omega}} \propto \sum_{k=1}^{6} h_k(t) f_k(\vec{\Omega})$$ ← Functions of the helicity angles [JHEP 12 (2019) 155]

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

N_k, a_k, b_k, c_k, d_k are functions of $\phi_{s,i}$ and $|\lambda_i|$

$Q = \pm 1$ depending on initial B_s^0 flavour



[LHCb-PAPER-2023-001-002]

- **Main experimental challenges:**
  - Decay-time resolution (≈ 40 fs)
  - Flavour-tagging power ($\approx 6\,\%$)
  - Their calibration

CP violation in $B_s^0 \to \phi\phi$ decays: systematics

Table 2: Systematic uncertainties (in units of 10^{-3}) for physics parameters in the polarization-independent fit.

Source	$\phi_s^{s\bar{s}s}$ [rad]	$\|\lambda\|$	$\|A_0\|^2$	$\|A_\perp\|^2$	$\delta_\parallel - \delta_0$ [rad]	$\delta_\perp - \delta_0$ [rad]
Time resolution	4.9	2.6	0.8	0.8	0.1	3.4
Flavor tagging	4.8	4.7	0.9	1.3	1.2	9.7
Angular acceptance	3.9	4.9	1.4	1.7	4.7	1.2
Time acceptance	2.3	1.7	0.1	0.1	5.6	0.7
Mass fit & factorization	2.2	4.4	1.9	2.3	2.3	2.5
MC truth match	1.1	0.2	0.1	0.1	0.2	0.3
Fit bias	0.8	0.7	0.9	0.3	3.6	0.7
Candidate multiplicity	0.3	0.2	0.1	0.8	0.2	0.1
Total	8.8	8.6	2.7	3.3	8.5	10.7

Flavour Tagging at LHCb