University of Chinese Academy of Sciences

Latest measurements of CP violation at LHCb

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第二十一届全国重味物理和CP破坏研讨会

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Outline

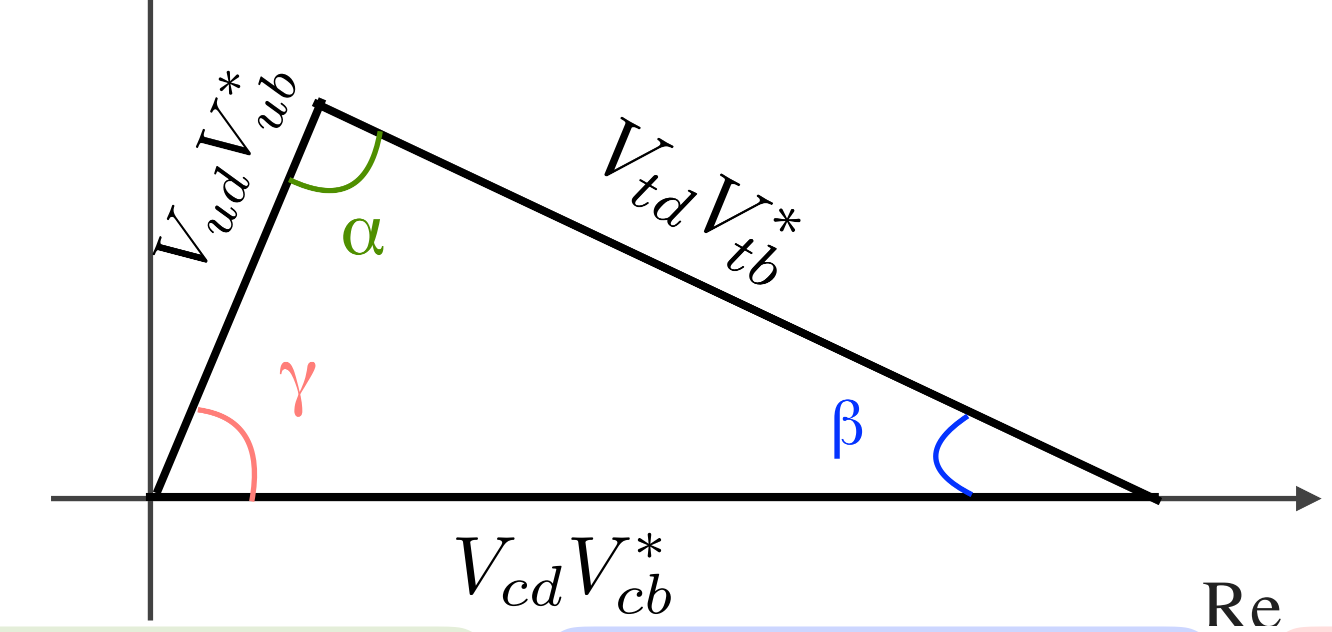
- Introduction
- CKM angle γ
- CKM angle $\beta_{(s)}$
- Direct CPV in Beauty
- CPV in charm
- CPV in Baryons *See in the next talk by Xinchen Dai*

CKM matrix

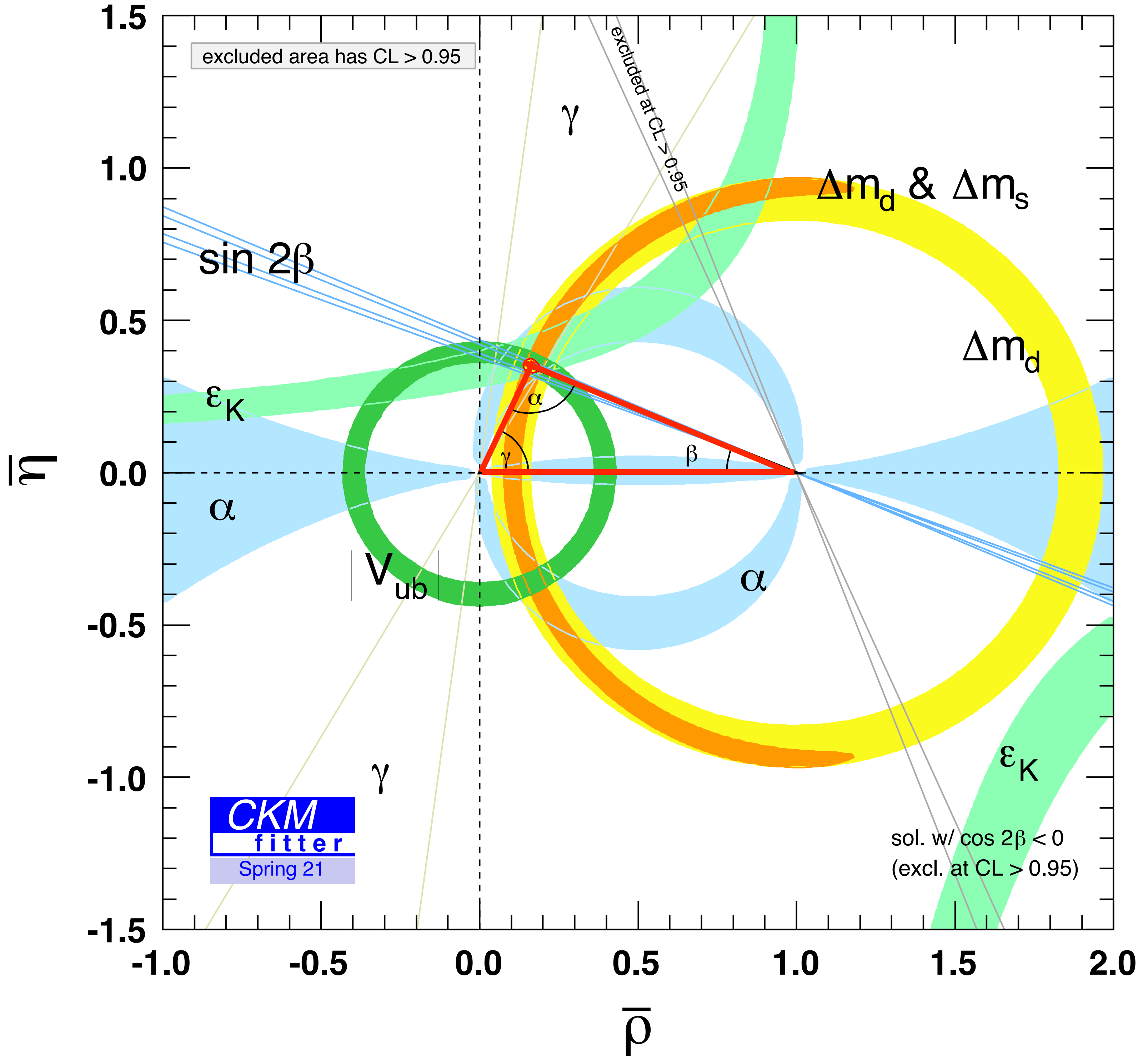
$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5) \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

- Key test of the SM: Verify unitarity of CKM matrix
  - Magnitudes: branching fractions or mixing frequencies
  - Phases: CP violation measurement
- Sensitive probe for new physics

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



$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



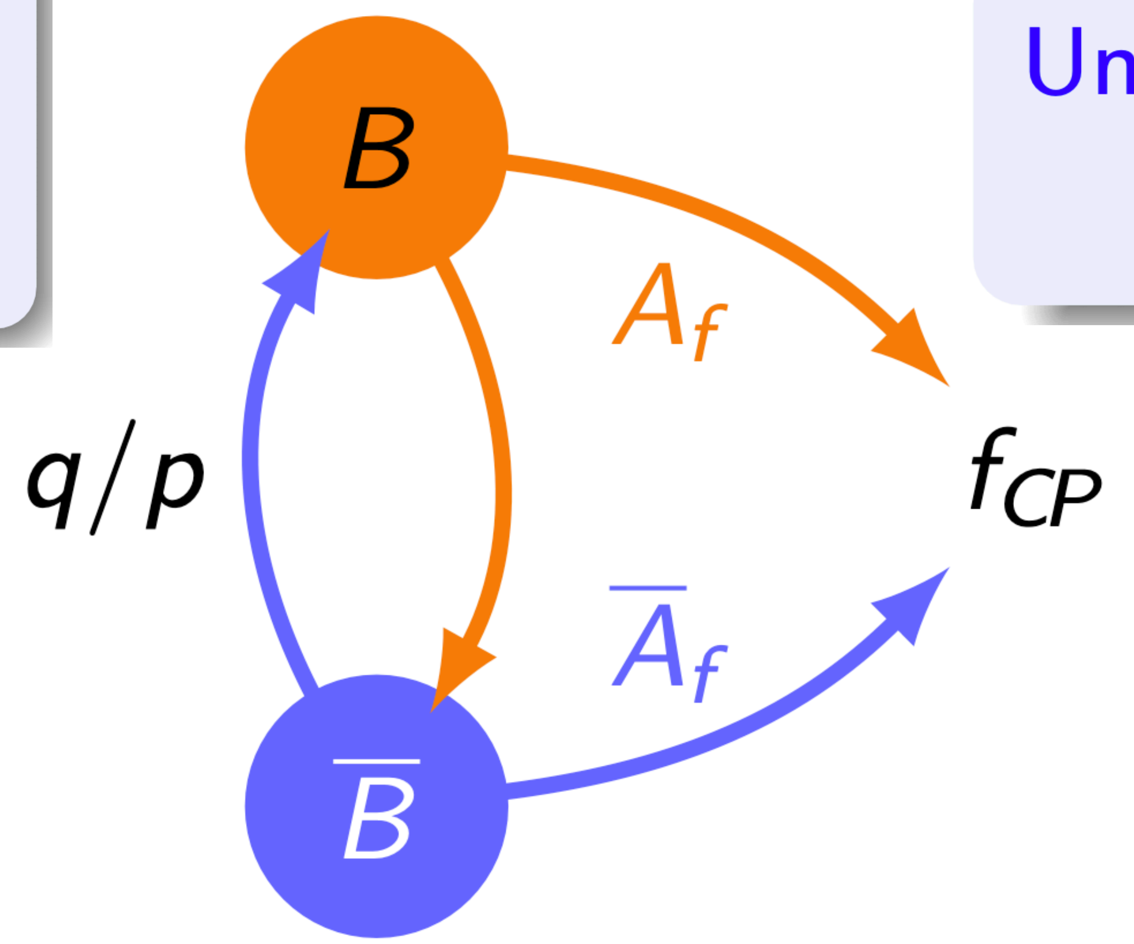
Three types of CP Violation

- CP-violating nature of weak interaction has multiple manifestations
- Requires two interfering amplitudes with different strong and weak phases

CP violation in mixing

Unequal transition probabilities between flavour eigenstates

$$P(B \to \overline{B}) \neq P(\overline{B} \to B)$$



CP violation in decay

Unequal CP-conjugated decay rates

$$\Gamma(B \to f) \neq \Gamma(\overline{B} \to \overline{f})$$

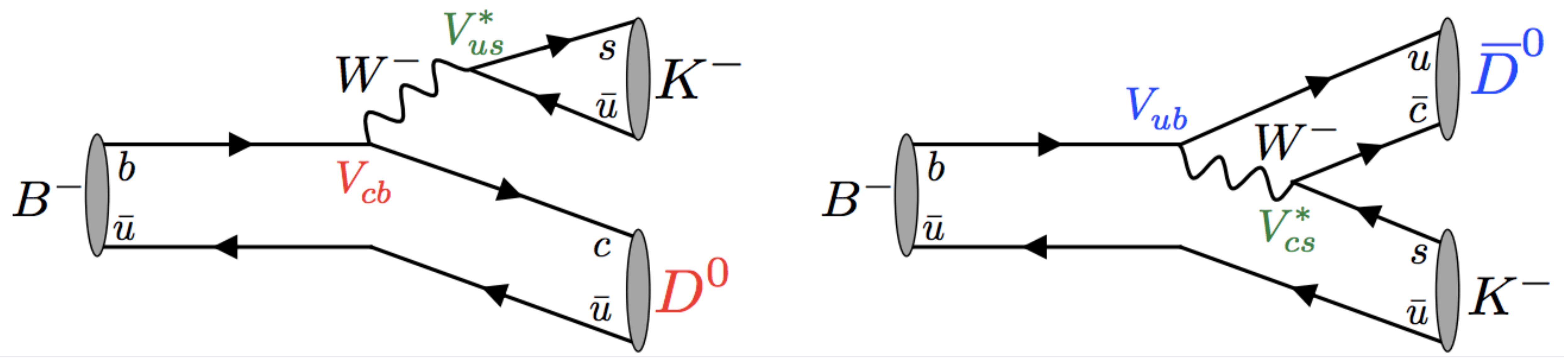
CP violation in interference of decays with/without mixing

Time-dependent or time-integrated difference of decay rates of initial flavour eigenstates

$$\Gamma(B_{(\rightsquigarrow \overline{B})} \to f_{CP})(t) \neq \Gamma(\overline{B}_{(\rightsquigarrow B)} \to f_{CP})(t)$$

γ measurements

- Relative weak phase γ in interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transition
- Measured with tree-level decays, theoretically clean observable ($\delta\gamma \sim 10^{-7}$)



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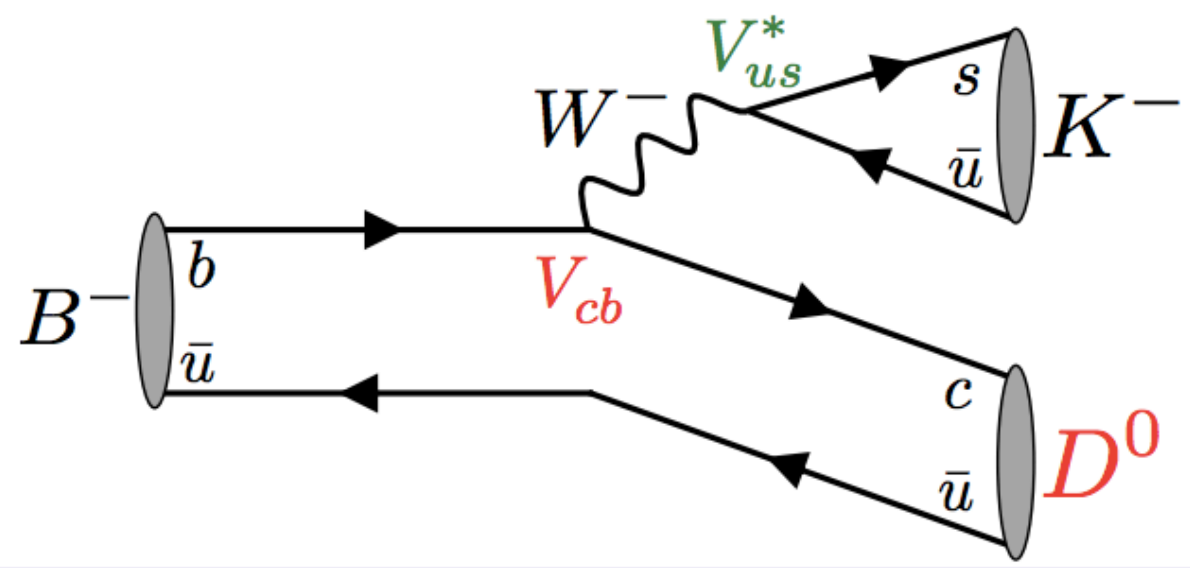
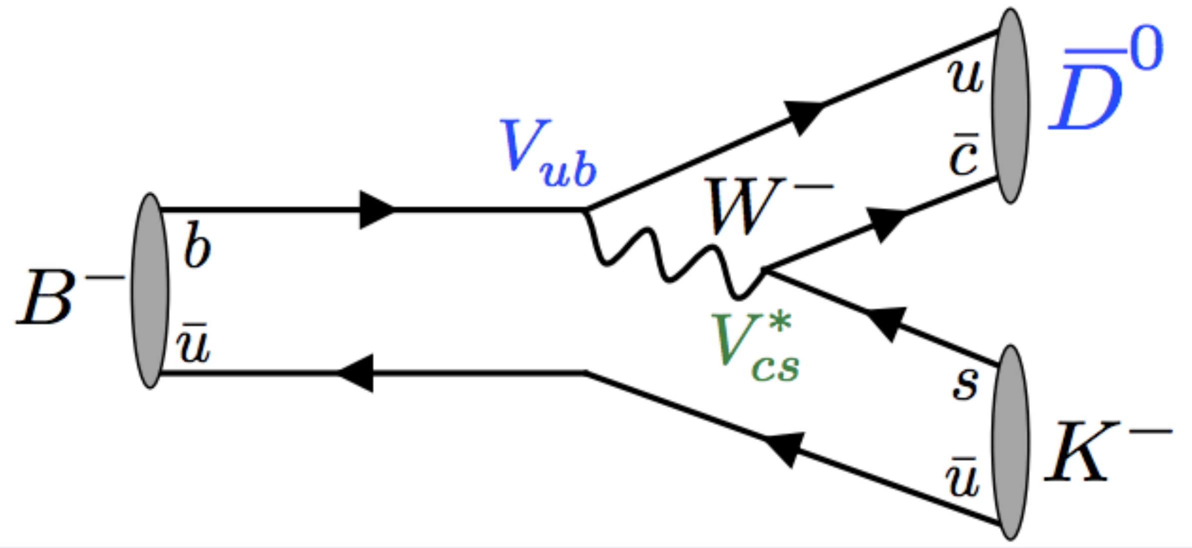
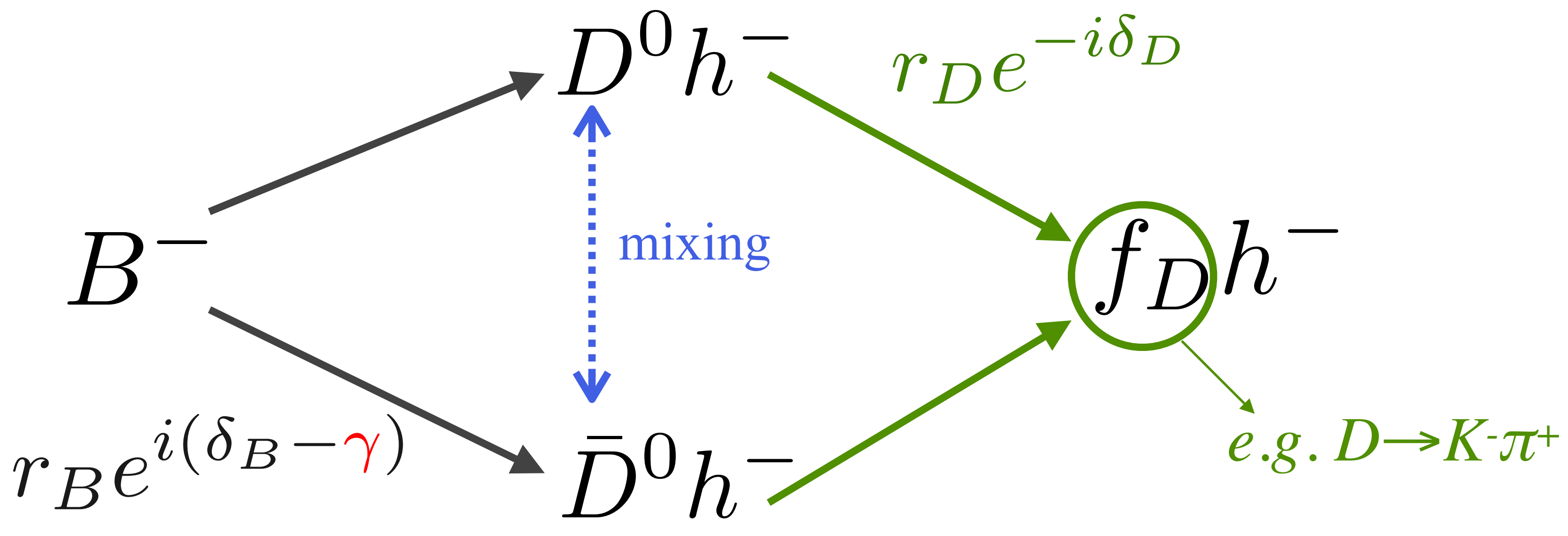






$$\Gamma(B^\pm \to Dh^\pm) \propto |r_D e^{-i\delta_D} + r_B e^{i(\delta_B \pm \gamma)}|^2 \Rightarrow r_D^2 + r_B^2 + 2\kappa_D \kappa_B r_D r_B cos(\delta_B + \delta_D \pm \gamma)$$

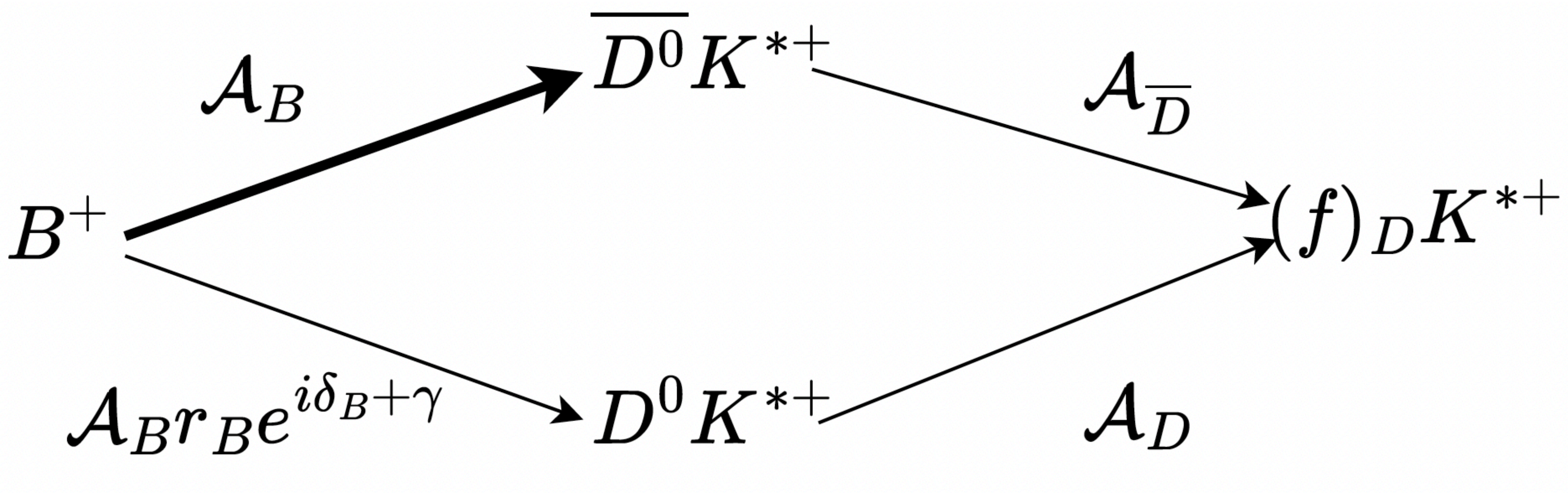
- Interference occurs when D^0 and $\bar{D}^0$ decay to the same final state f
  - ◇ GLW: CP eigenstates, e.g. $D \to KK$, $D \to \pi\pi$
  - ◇ ADS: CF or DCS decays, e.g. $D \to K\pi$
  - ◇ BPGGSZ: self-conjugated 3-body final states, GLW/ADS analysis across the D decay phase space, e.g. $D \to K_s^0 \pi\pi$
  - ◇ Time-dependent: $B_s^0 \to D_s^- K^+$ & Dalitz: $B^0 \to \bar{D}^0 K^+ \pi^-$

γ measurement in $B^+ \to DK^{*+}(\to K_S^0\pi^+)$

LHCb-PAPER-2024-023
in preparation

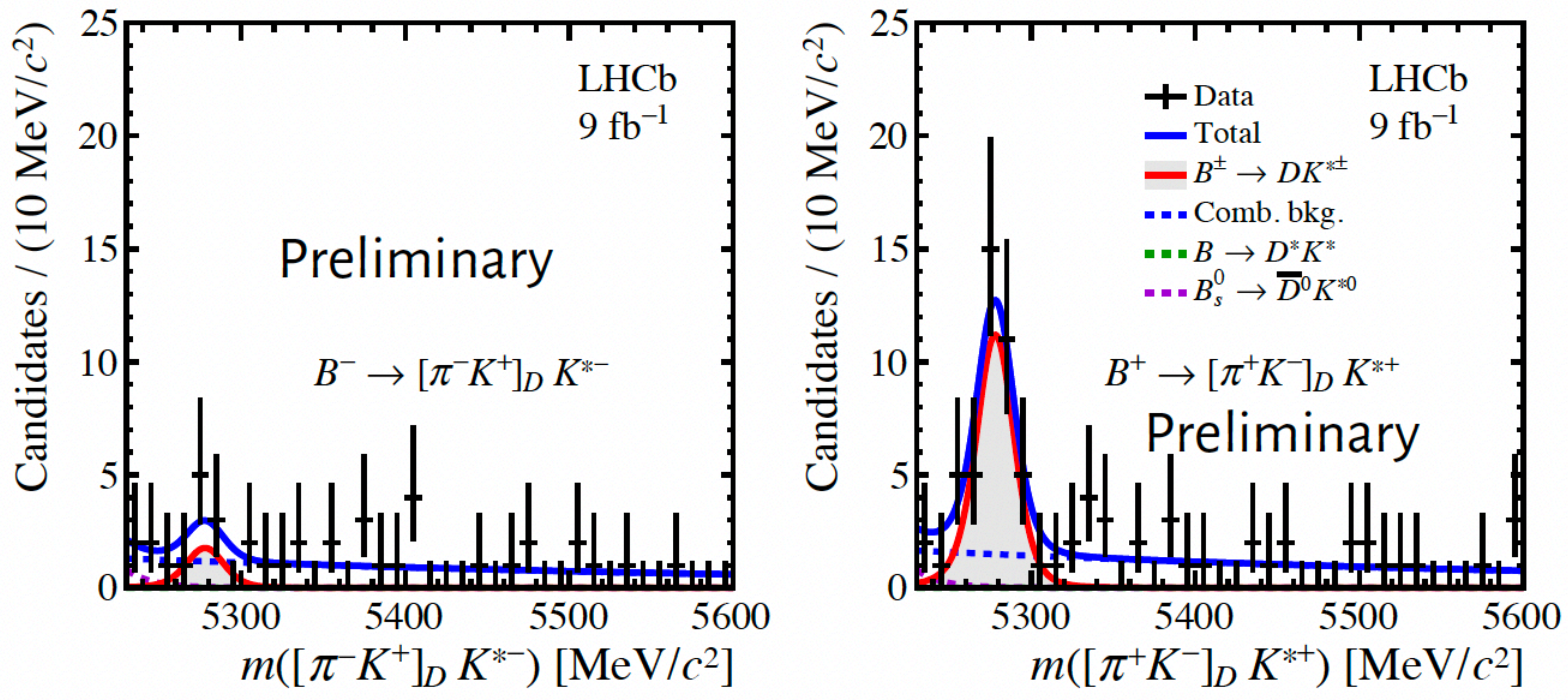
- CP eigenstates $D^0 \to \pi^+\pi^-, K^+K^-, \pi^+\pi^+\pi^-\pi^-$
- Suppressed decays $D^0 \to K^-\pi^+, \pi^+K^-\pi^+\pi^-$
- Self-conjuated multi-body decays $D^0 \to K_S^0 h^+h^-$
- Inputs for $D^0 \to K_S^0 h^+h^-, \pi^+\pi^+\pi^-\pi^-$ from BESIII

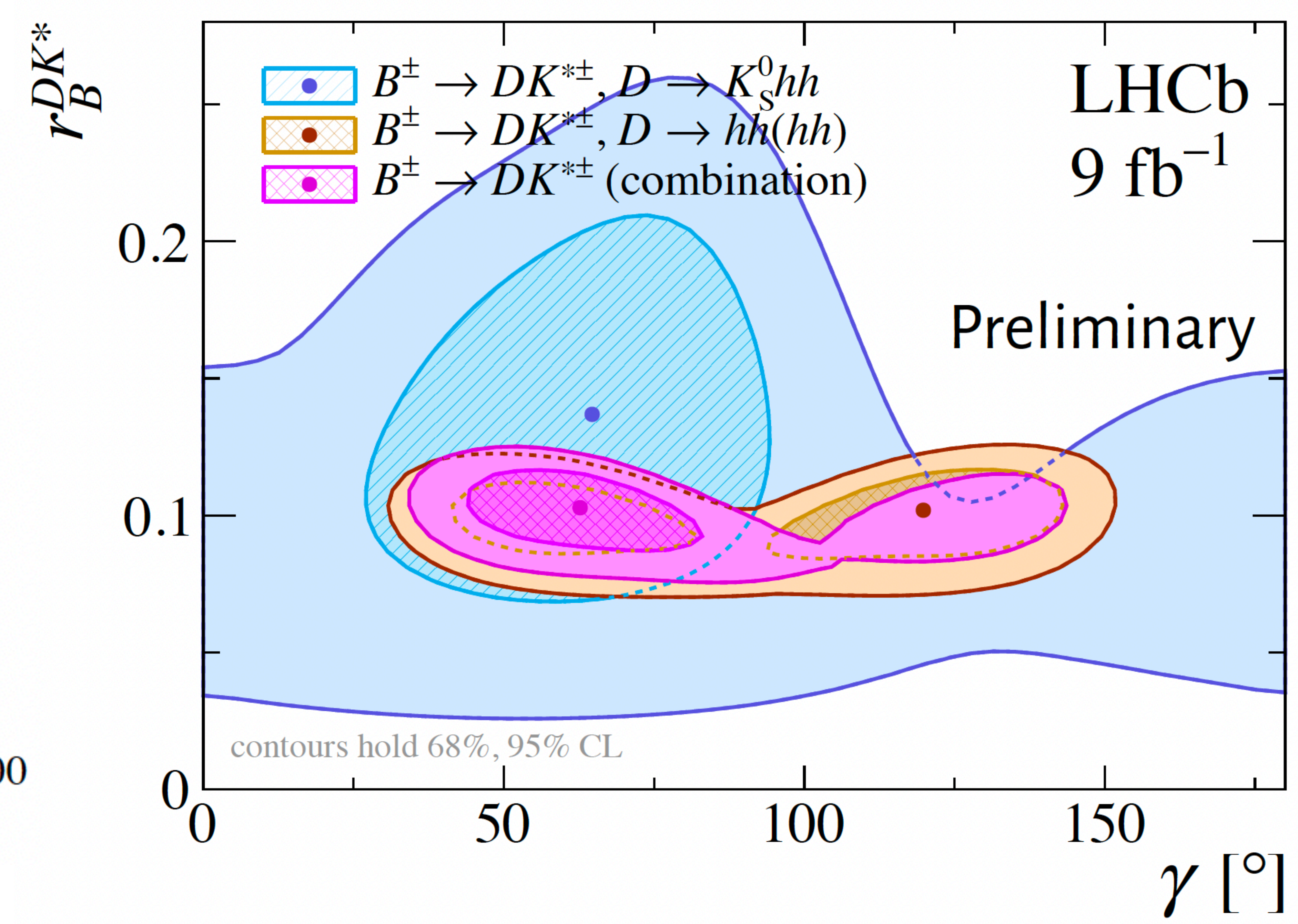
[PRD106.092004, PRD82(2010)112006, PRD102(2020)]



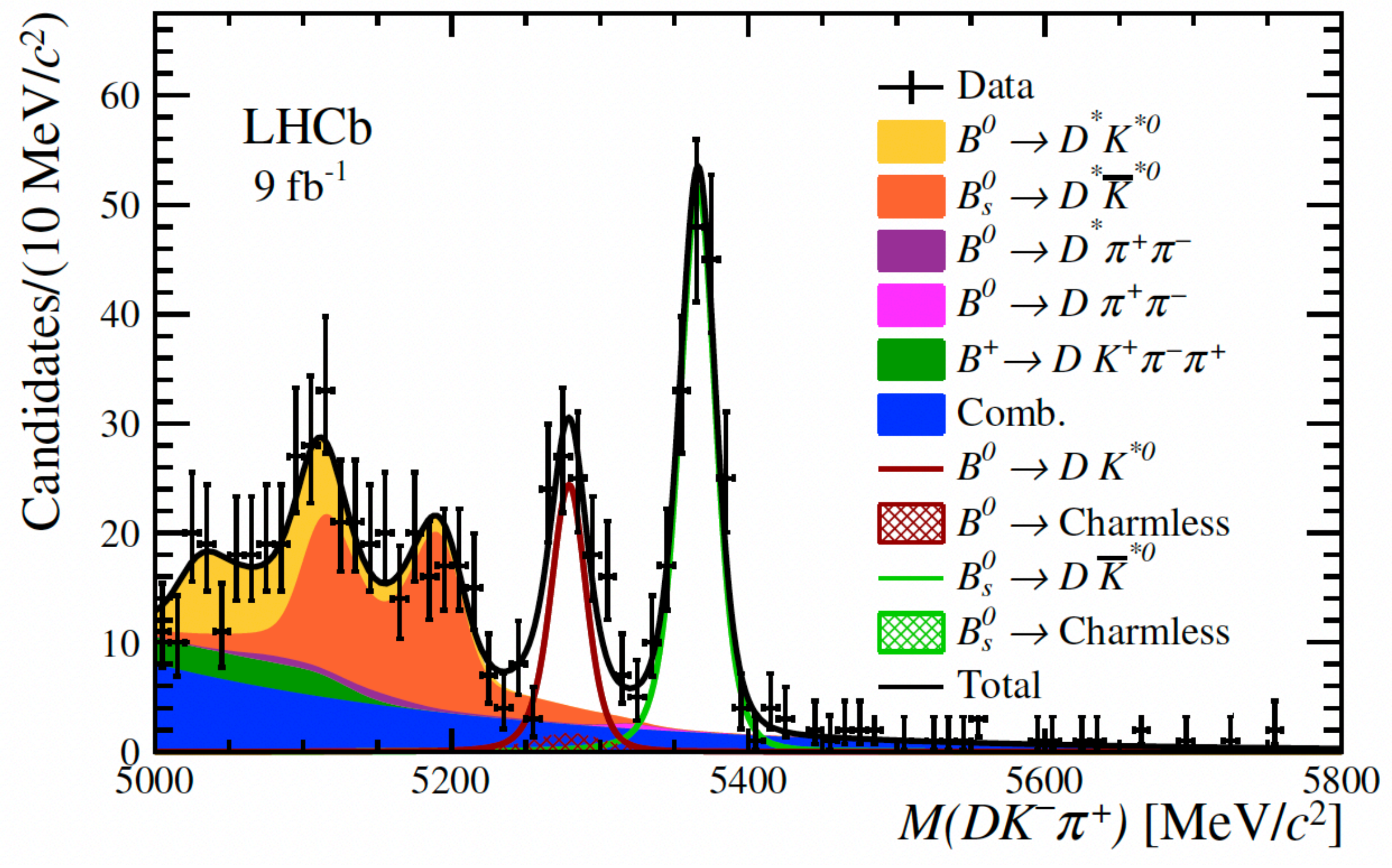
$\gamma = (63 \pm 13)°$

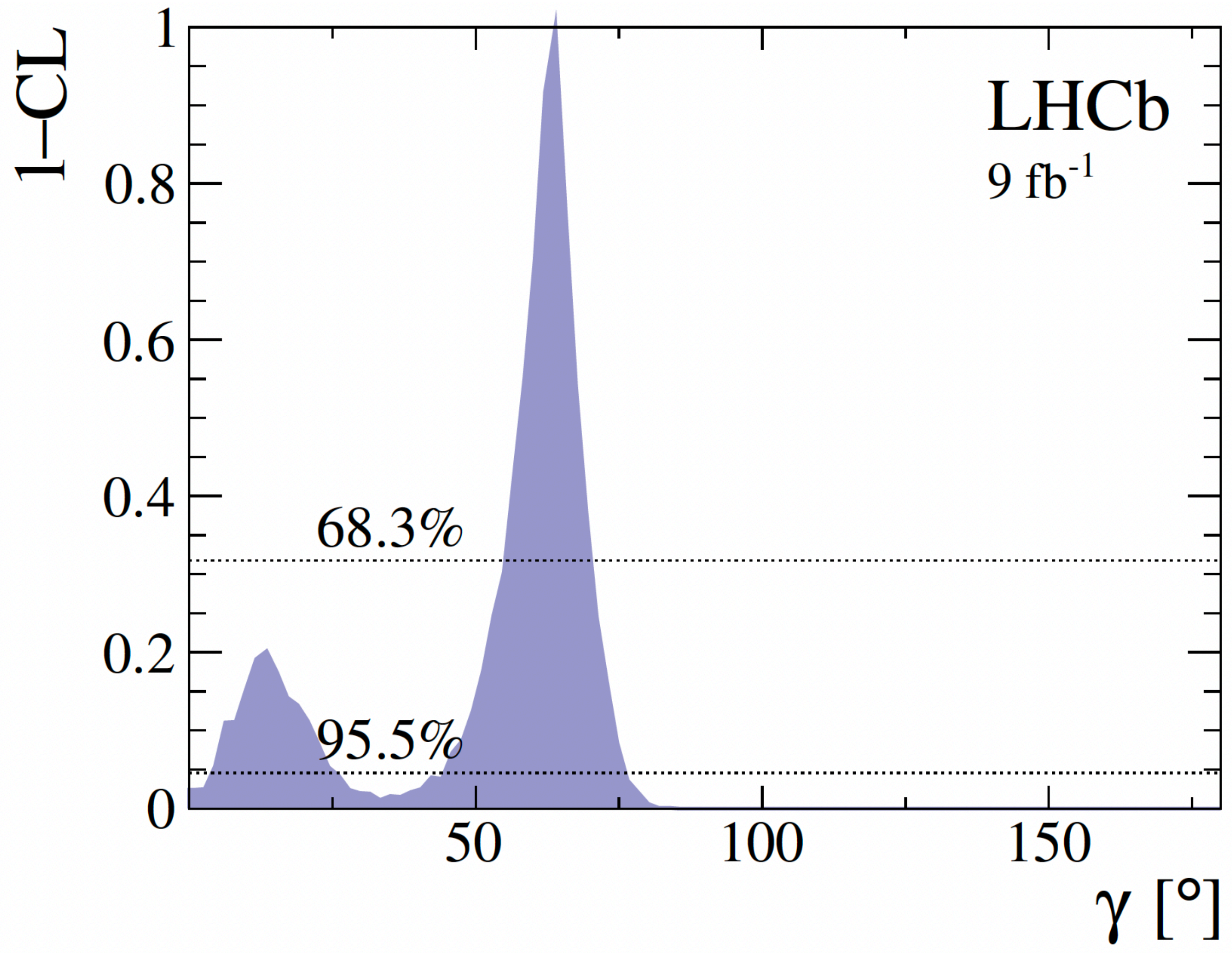
First observation of $B^+ \to [D^0]_{\pi K, \pi K\pi\pi} K^{*+}$





γ measurements

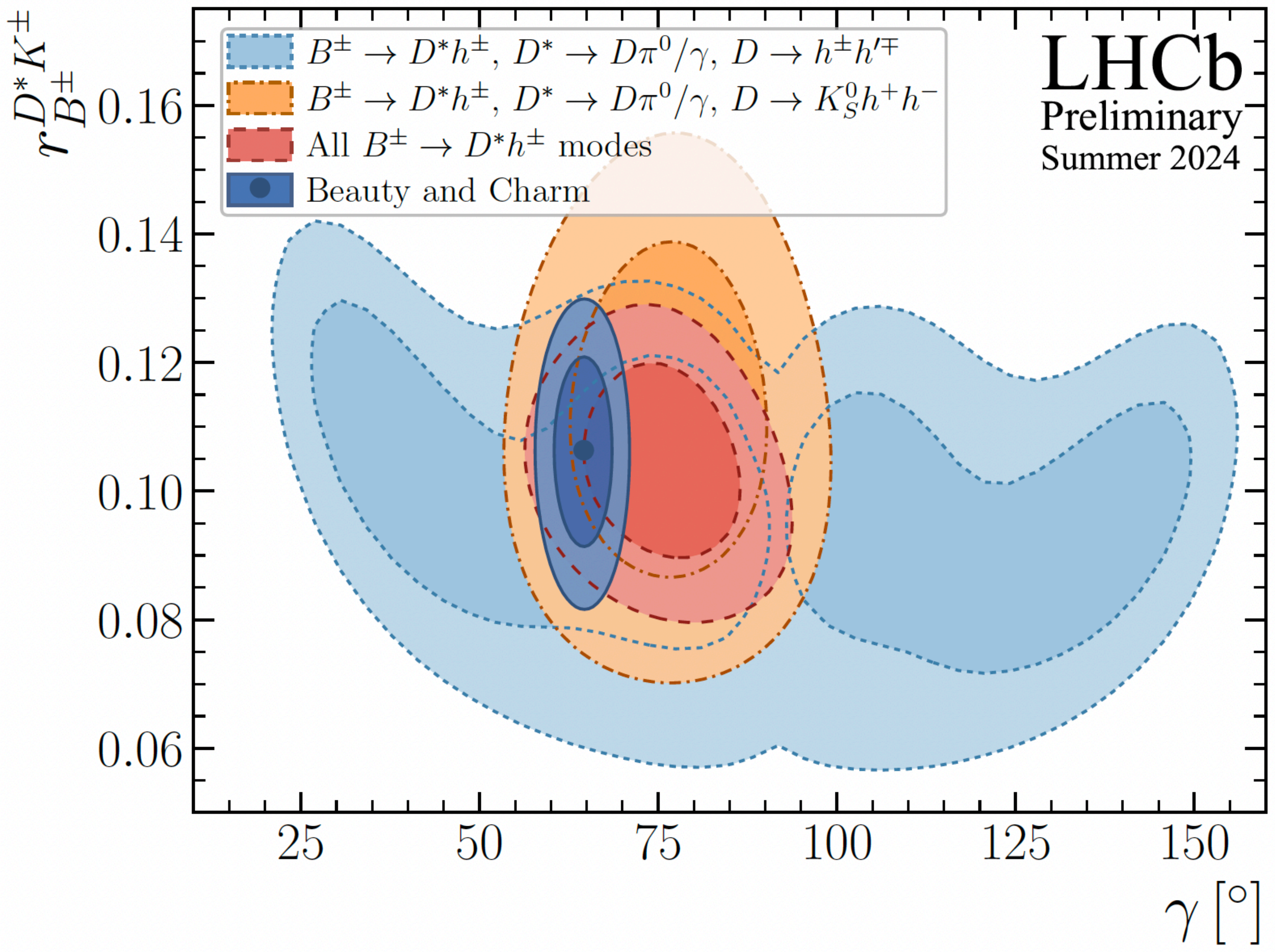




JHEP05(2024)025

- $B^0 \to D^0 K^*(892)^0$ with $D \to hh$ & $4h$ & $K_S^0 hh$

$$\gamma = (63.2^{+6.9}_{-8.1})^\circ$$



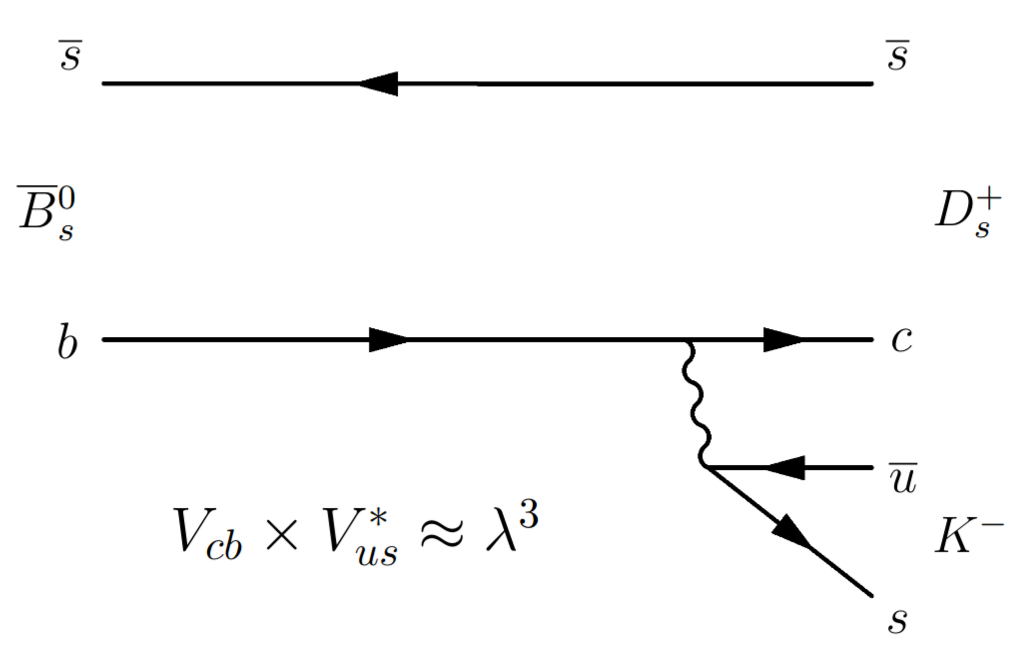
JHEP 04 (2021) 081

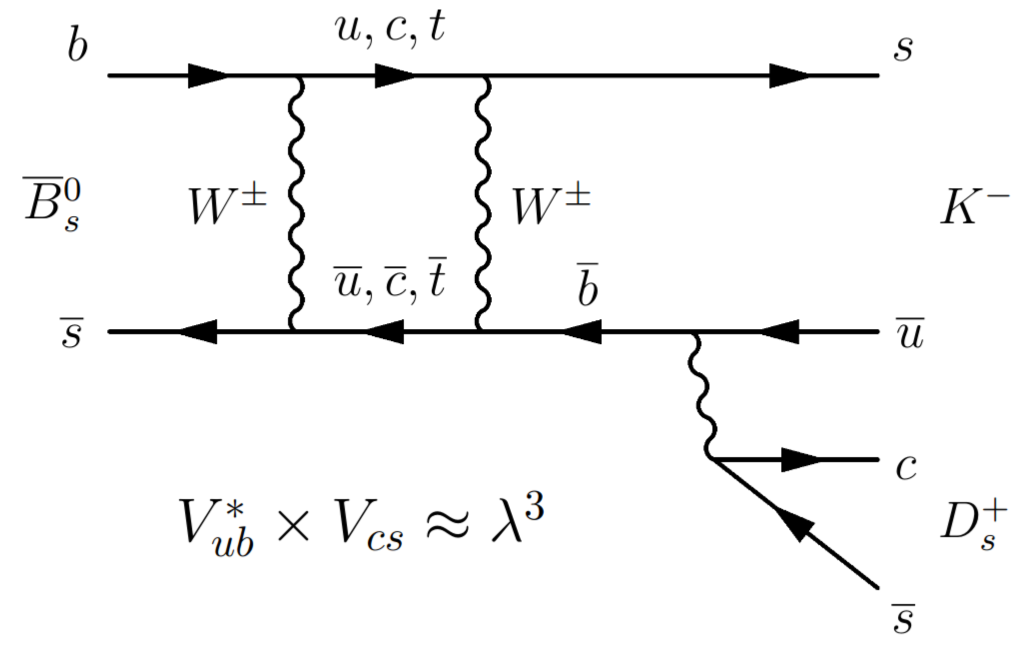
- $B^\pm \to D^{*0} h^\pm$ with $D^{*0} \to D(hh')\gamma/\pi^0$
- Partial reco. $B^\pm \to D^{*0} h^\pm$ with $D^{*0} \to D(K_S^0 hh)\gamma/\pi^0$ JHEP02(2024)118
- Full reco. $B^\pm \to D^{*0} h^\pm$ with $D^{*0} \to D(K_S^0 hh)\gamma/\pi^0$ JHEP12(2023)013

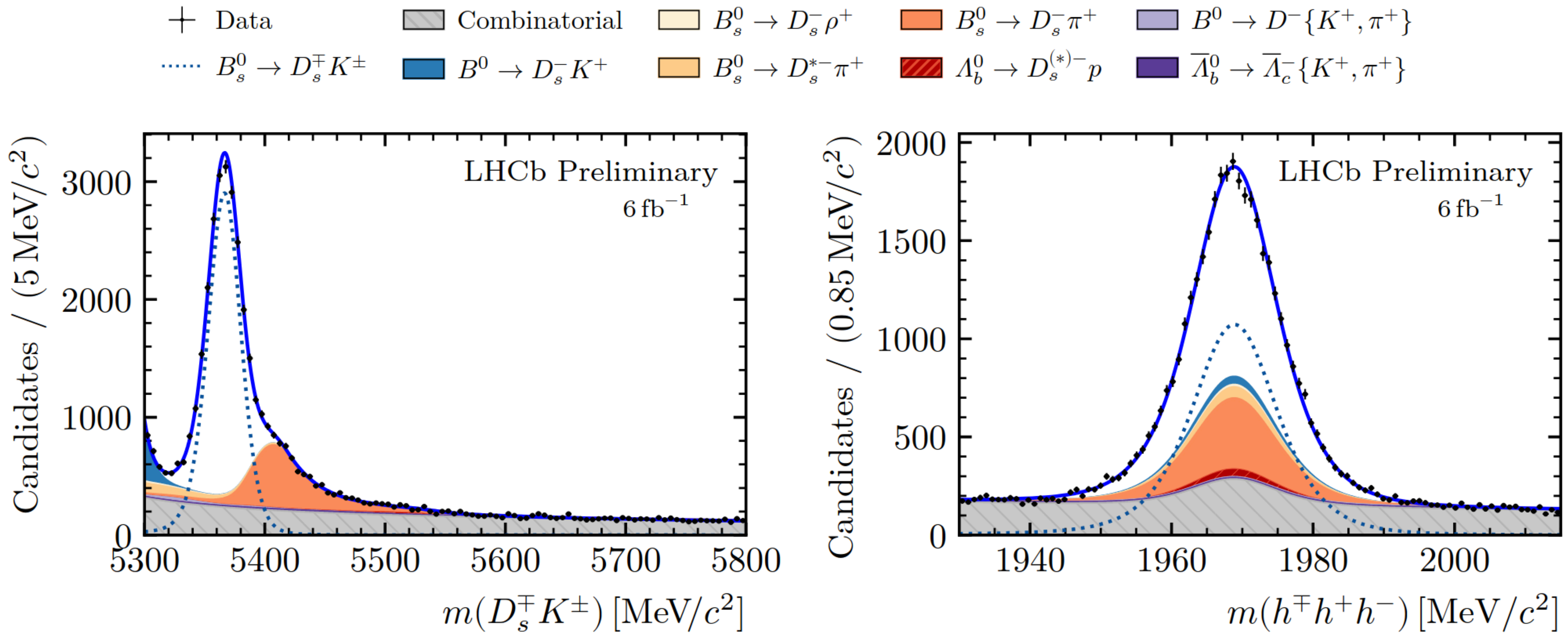
γ measurement in $B_s^0 \to D_s^{\mp} K^{\pm}$

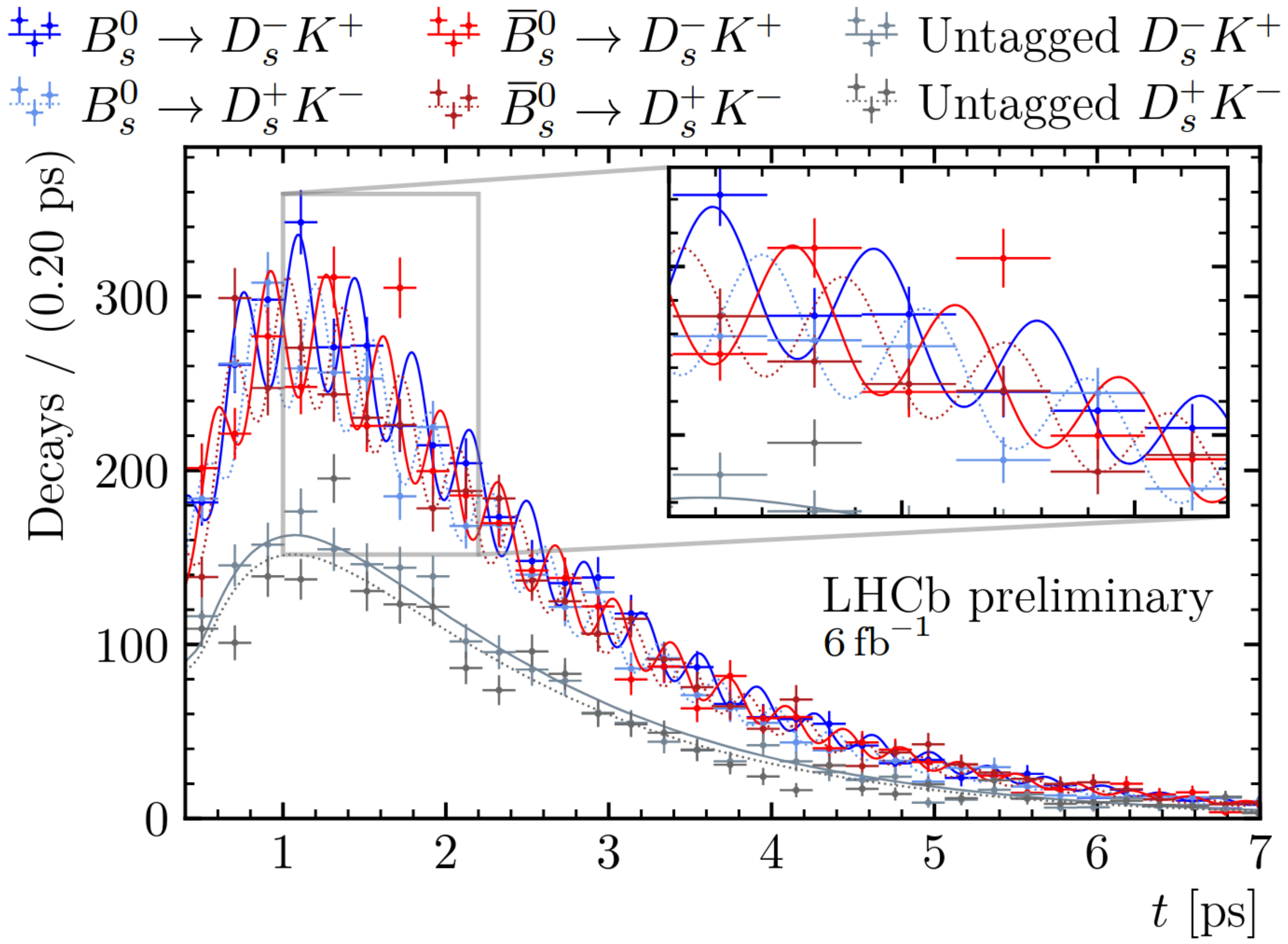
LHCb-PAPER-2024-020
in preparation

- Time-dependent CP violations measurement
- Interference between mixing and decay → relative phase difference of $\gamma - 2\beta_s$







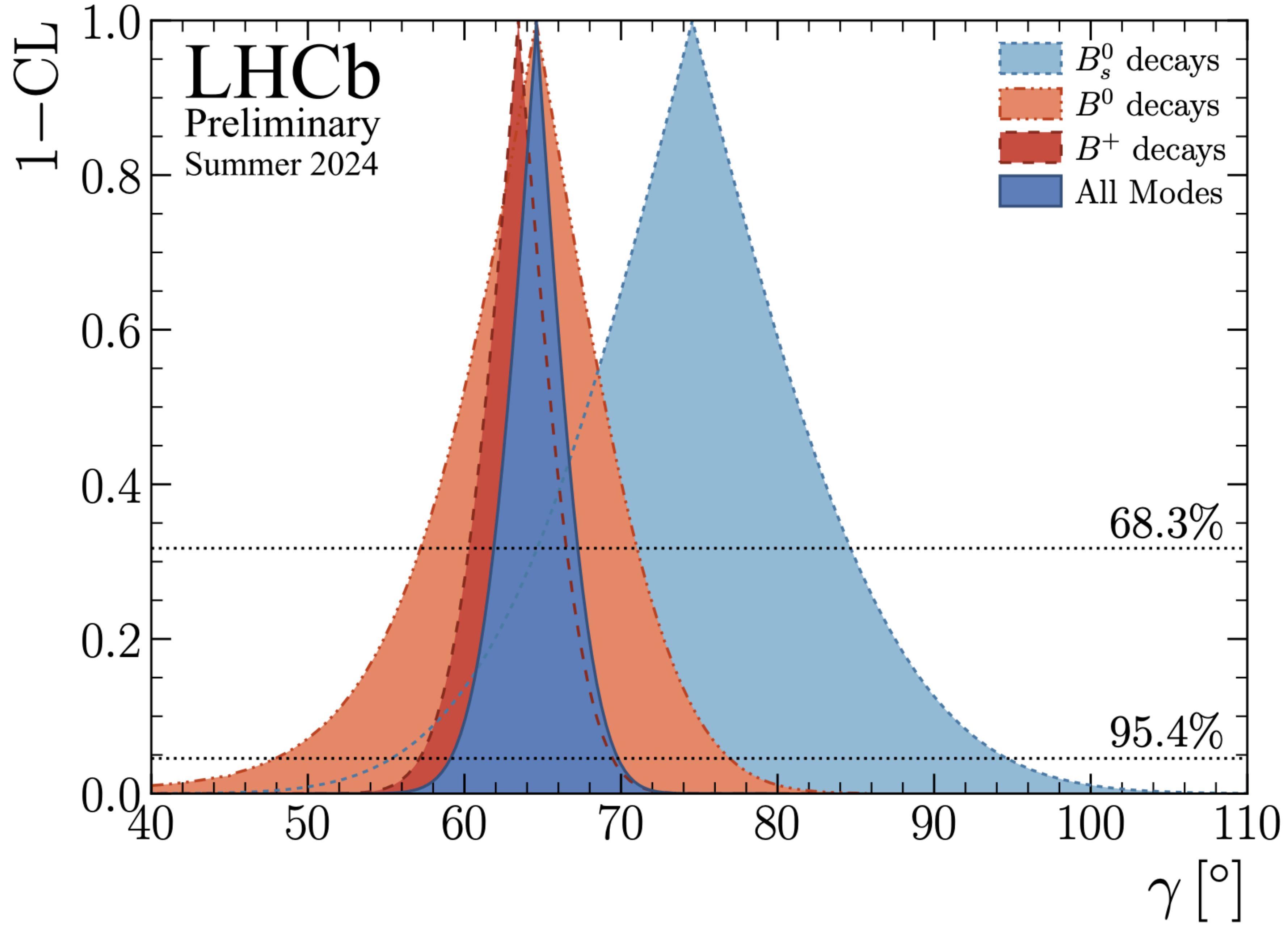


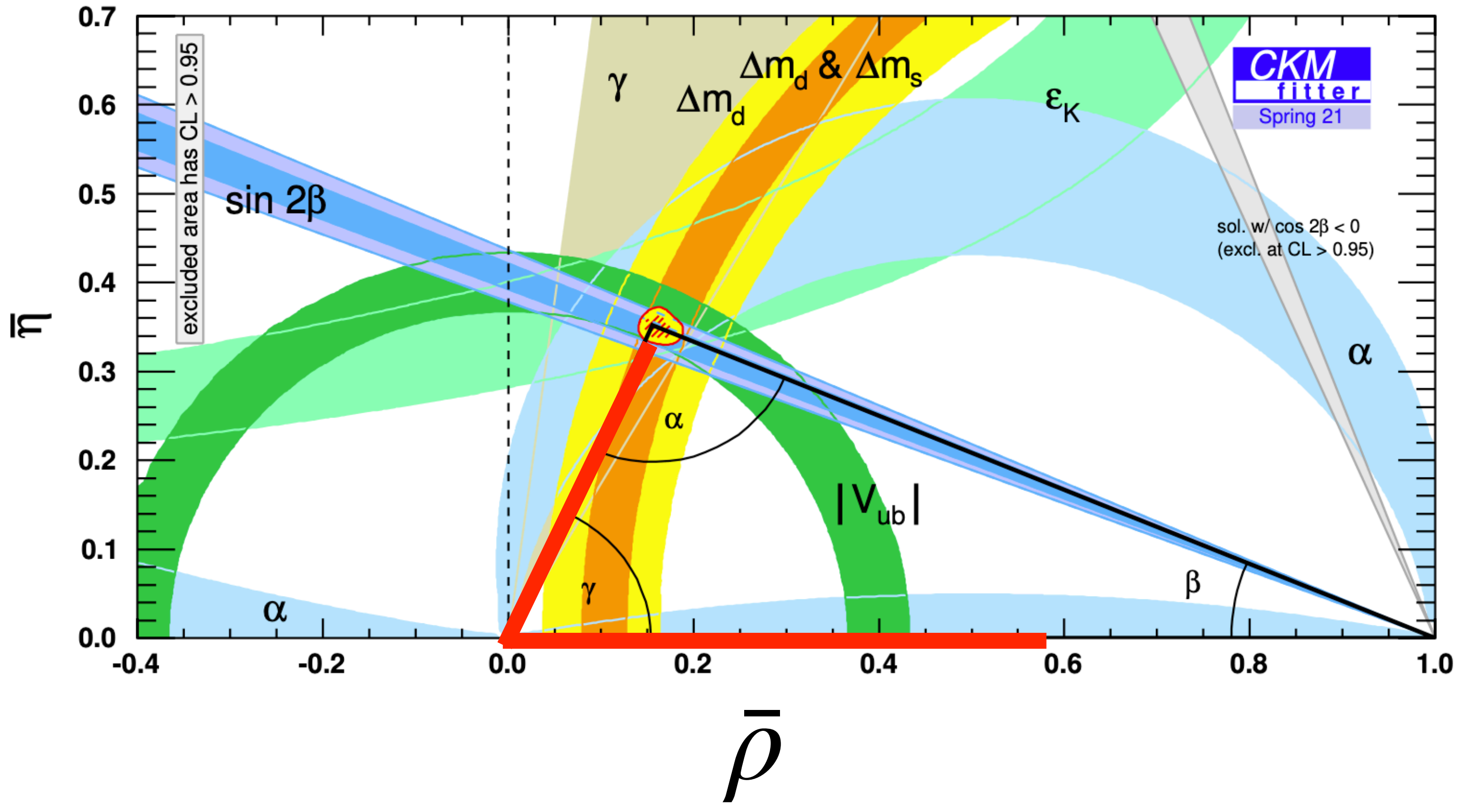
$$\gamma = (74 \pm 11)^{\circ}$$

Latest γ combination

LHCb-CONF-2024-004

$$\gamma = (64.6 \pm 2.8)^{\circ}$$

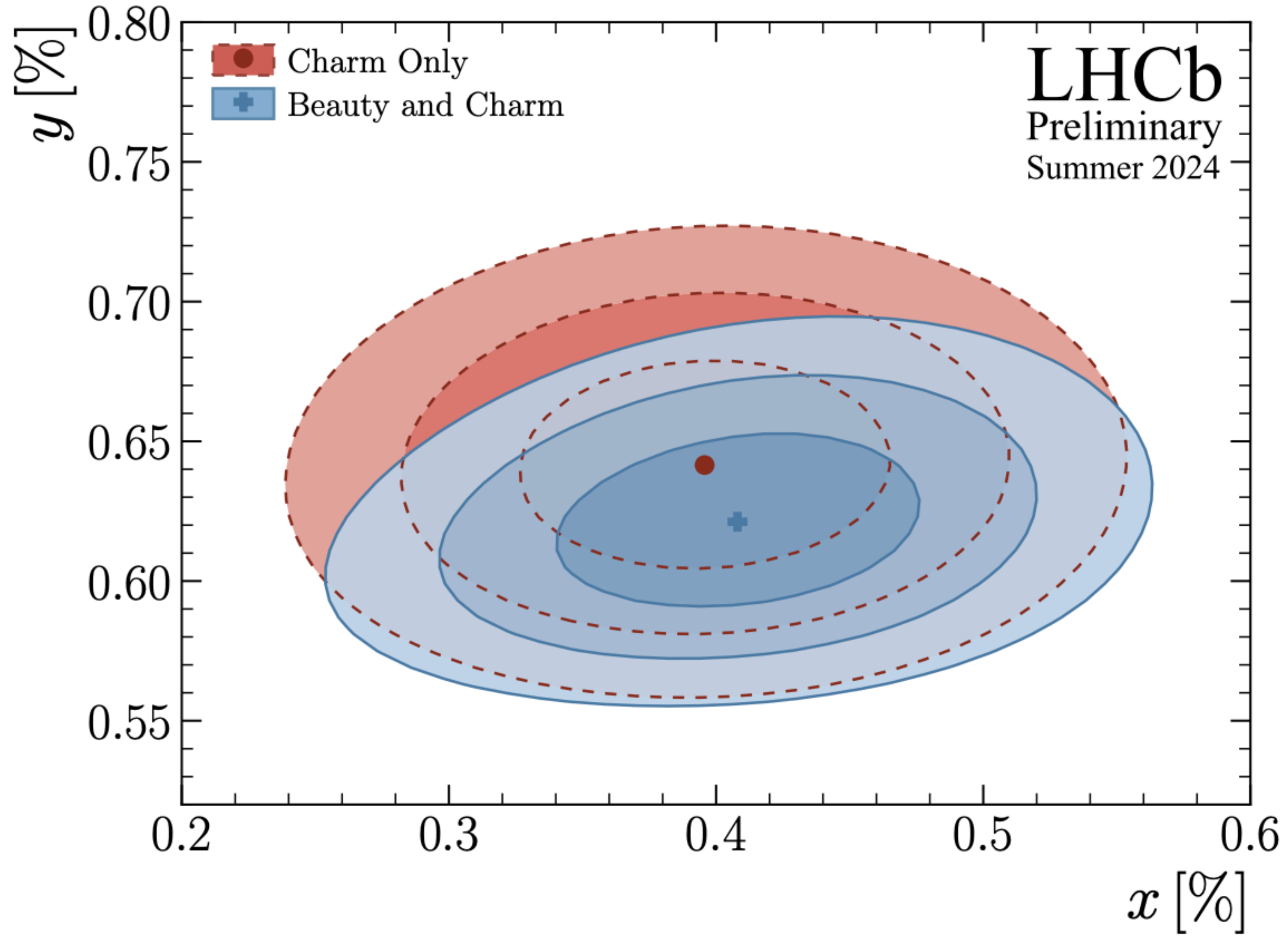


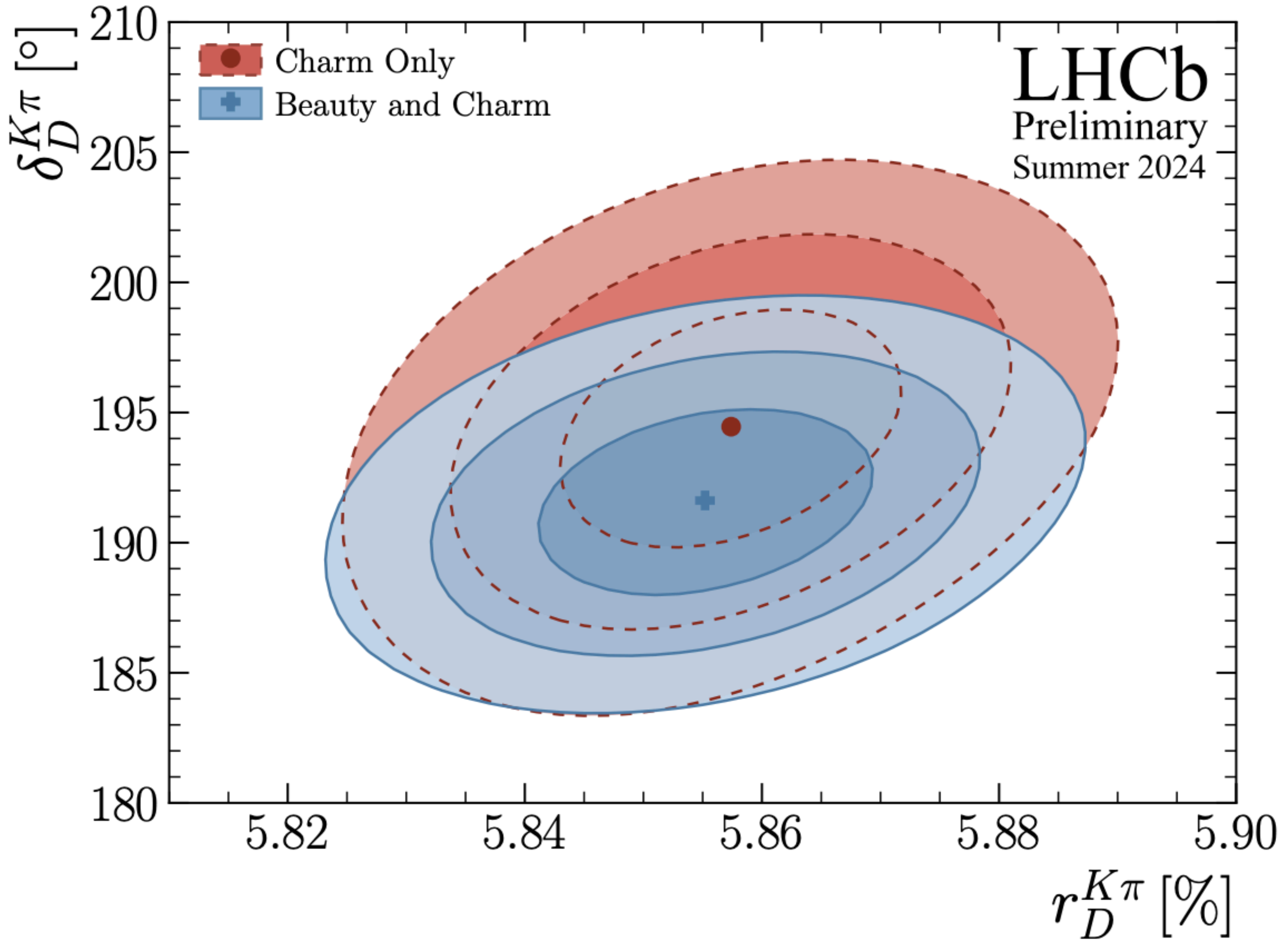


- A combination of all measurements of γ and $D^0 - \bar{D}^0$ mixing and CP asymmetries including 9 new results
- 20% improved precision w.r.t previous combination, consistent with global CKM fit predictions $(65.5^{+0.09}_{-2.65})^{\circ}$

$$x = (0.41 \pm 0.05)\,\% \qquad |q/p| = 0.989 \pm 0.015$$

$$y = (0.621^{+0.022}_{-0.021})\,\% \qquad \delta_D^{K\pi} = (191.6^{+2.5}_{-.4})^{\circ}$$

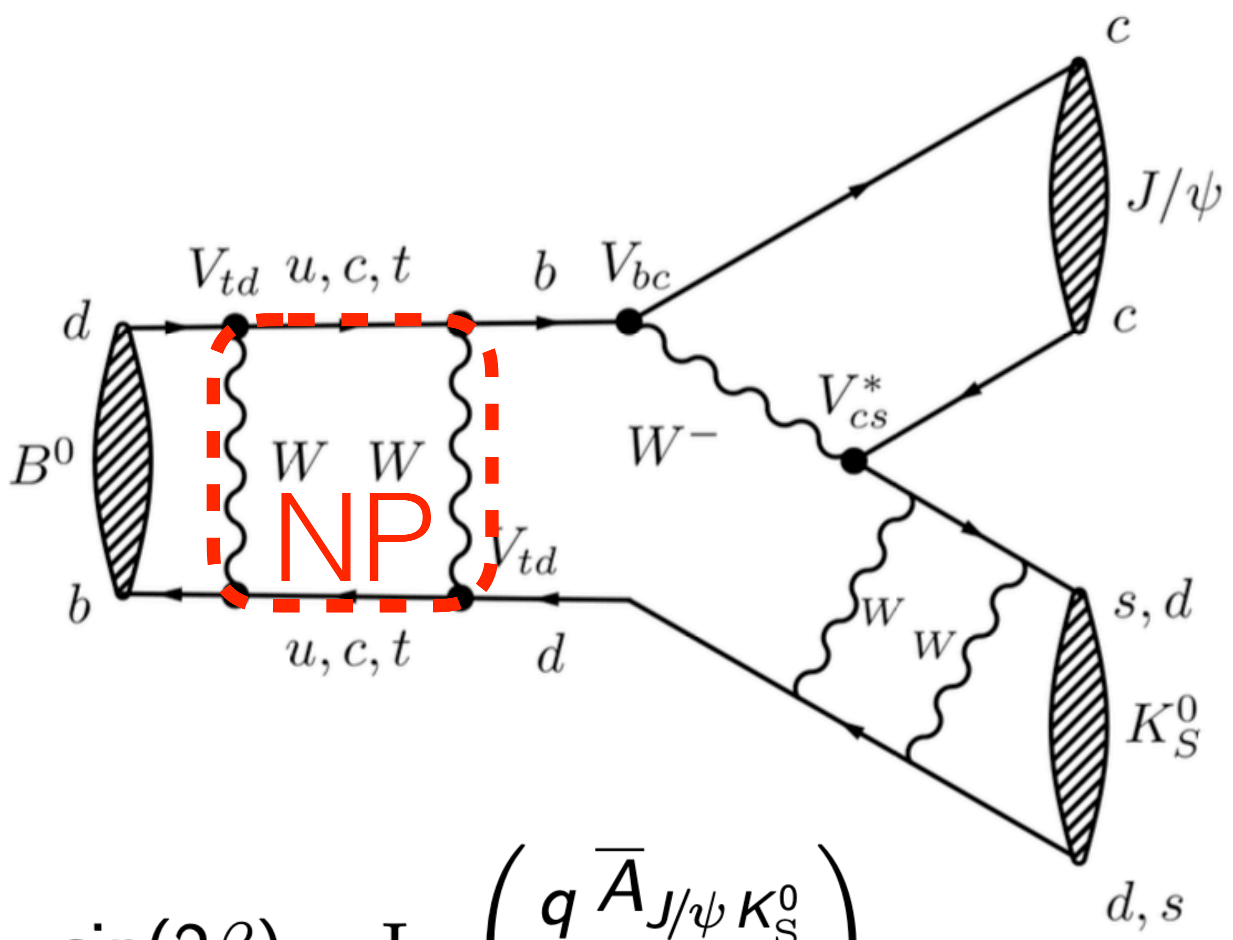




$\sin 2\beta$ in $B^0 \to \psi K^0_S$

Phys. Rev. Lett. 132 (2024) 021801

- Decay mode $B^0 \to \psi K^0_S$ *(CP-odd only)* offers a theoretically clean access to the CKM angle β



$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} \propto -\eta_f \cdot \sin 2\beta \cdot \sin(\Delta m t)$$

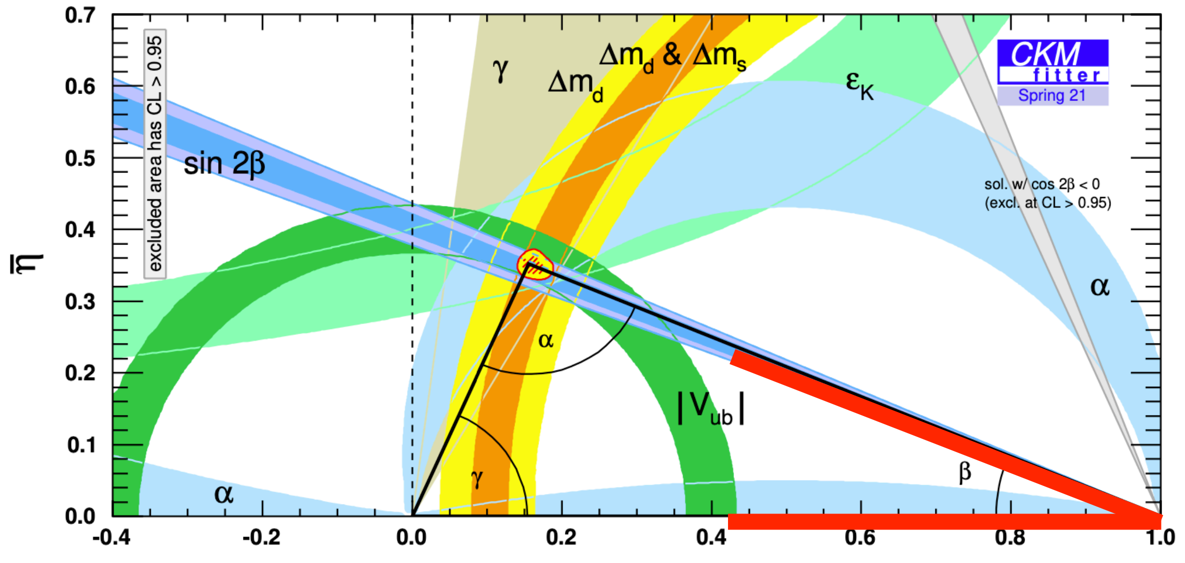
- Consistent with other measurements, still statistical uncertainty limited
- LHCb results dominate the latest World Average

$$\sin(2\beta) = \mathrm{Im}\left(\frac{q}{p}\frac{\bar{A}_{J/\psi K^0_S}}{A_{J/\psi K^0_S}}\right)$$

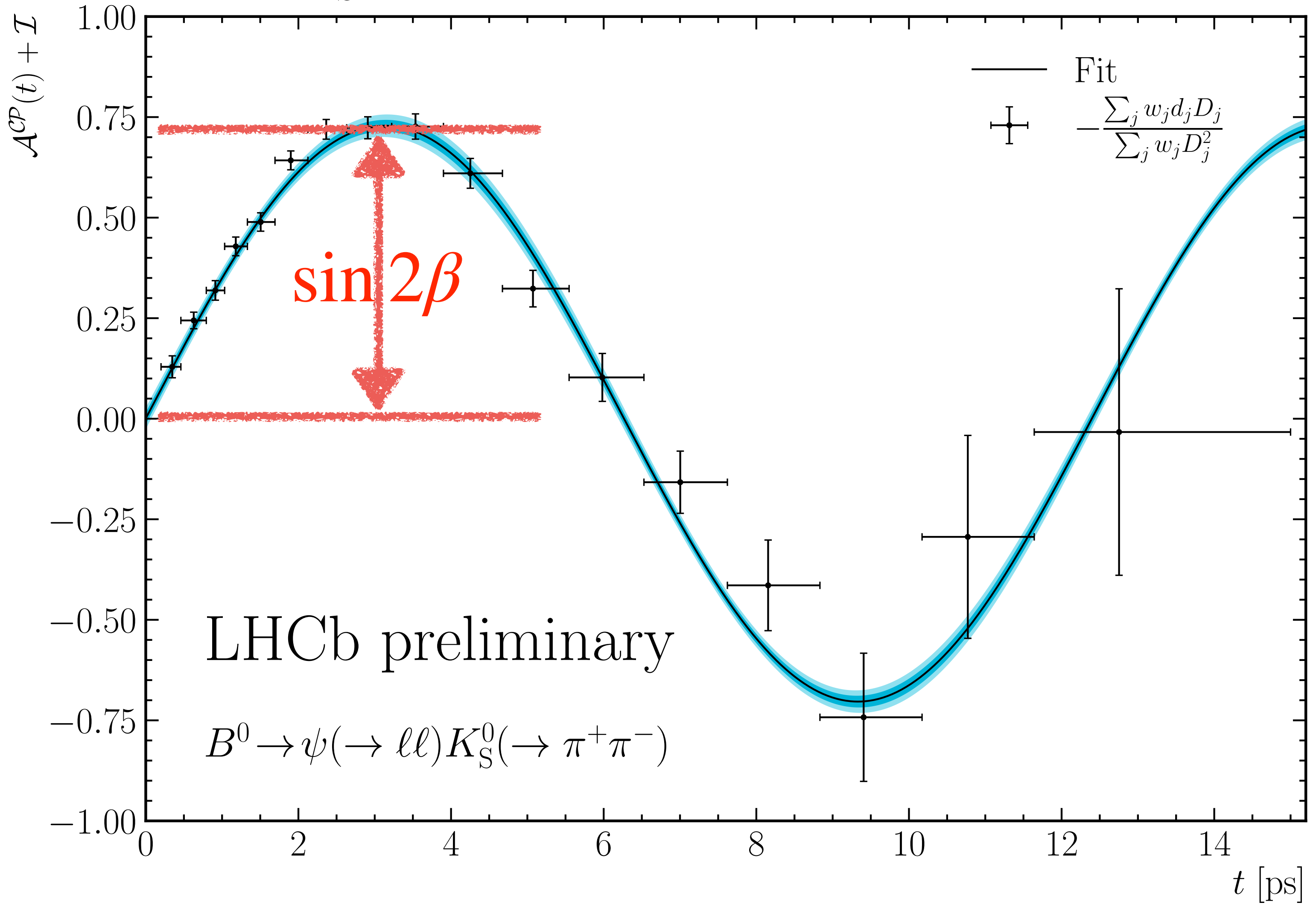
$$\beta = \arg\left(-\frac{V^*_{cb}V_{cd}}{V^*_{tb}V_{td}}\right)$$

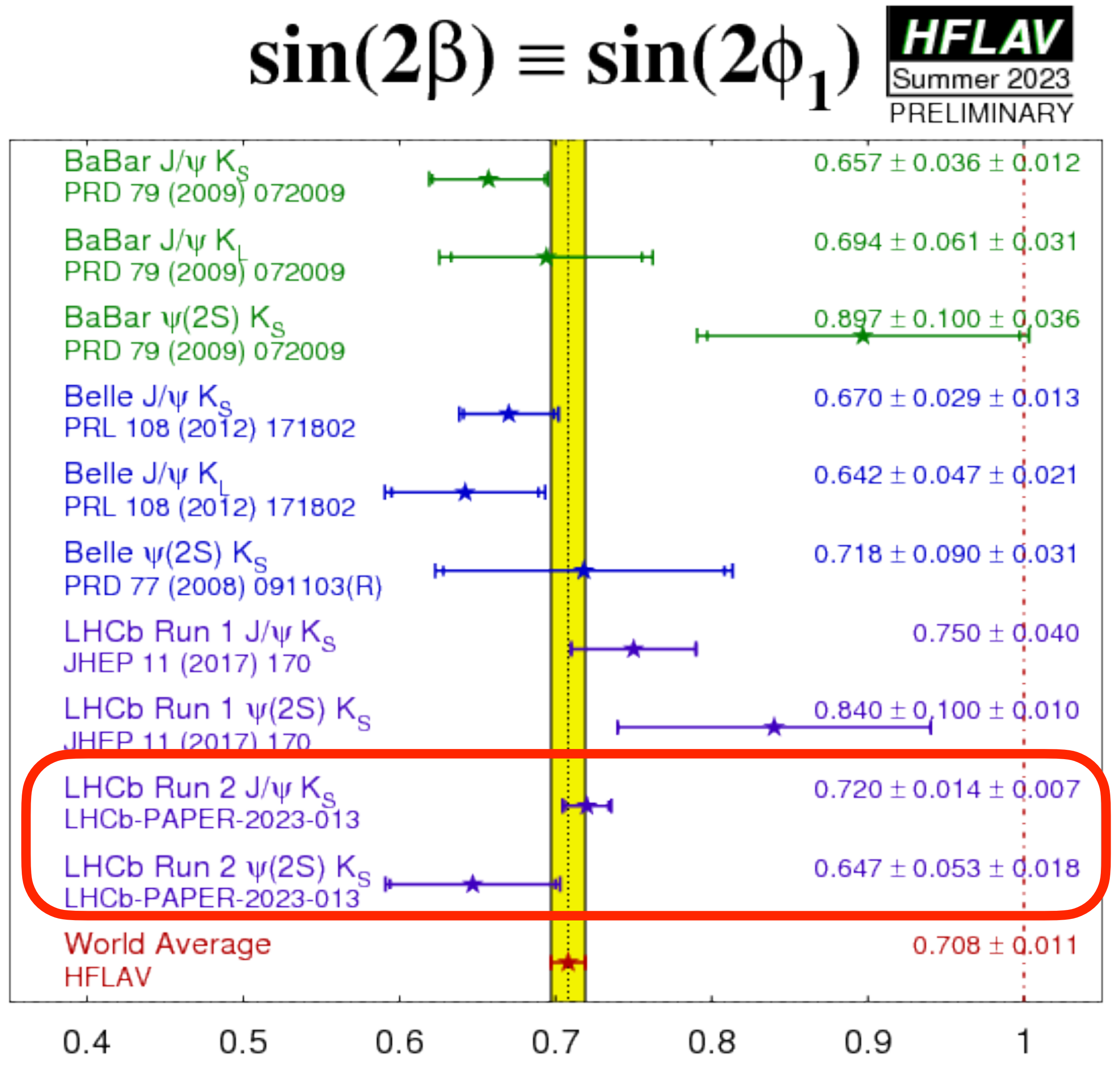
$$S^{\text{Run 2}}_{\psi K^0_S} = 0.716 \pm 0.013 \pm 0.008$$

$$C^{\text{Run 2}}_{\psi K^0_S} = 0.012 \pm 0.012 \pm 0.003$$



$\sin(2\beta) \neq 0 \Rightarrow CP$ violation



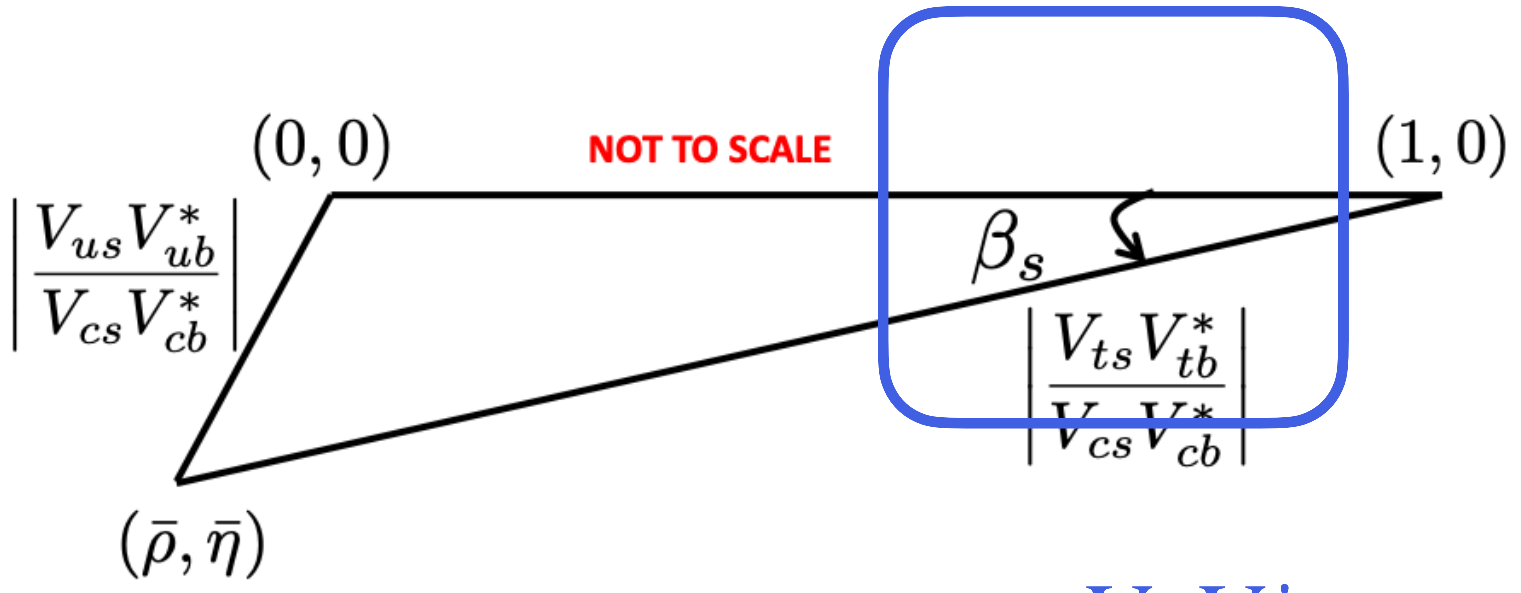


ϕ_s in $B_s^0 \to J/\psi\phi$

Phys. Rev. Lett. 132 (2024) 051802

- SM predicts: $\phi_s^{CKMFitter} \approx -2\beta_s = (-0.0368^{+0.0006}_{-0.0009})$ rad
  - Highly suppressed than in B^0 system (β ~22°)
  - Golden mode: $B_s^0 \to J/\psi\phi$

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



$$\phi_s \approx -2\beta_s = 2arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})$$

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} \propto -\eta_f \cdot \sin\phi_s \cdot \sin(\Delta m_s t)$$

(ignoring penguin contribution)

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Phys. Rev. Lett. 132 (2024) 051802

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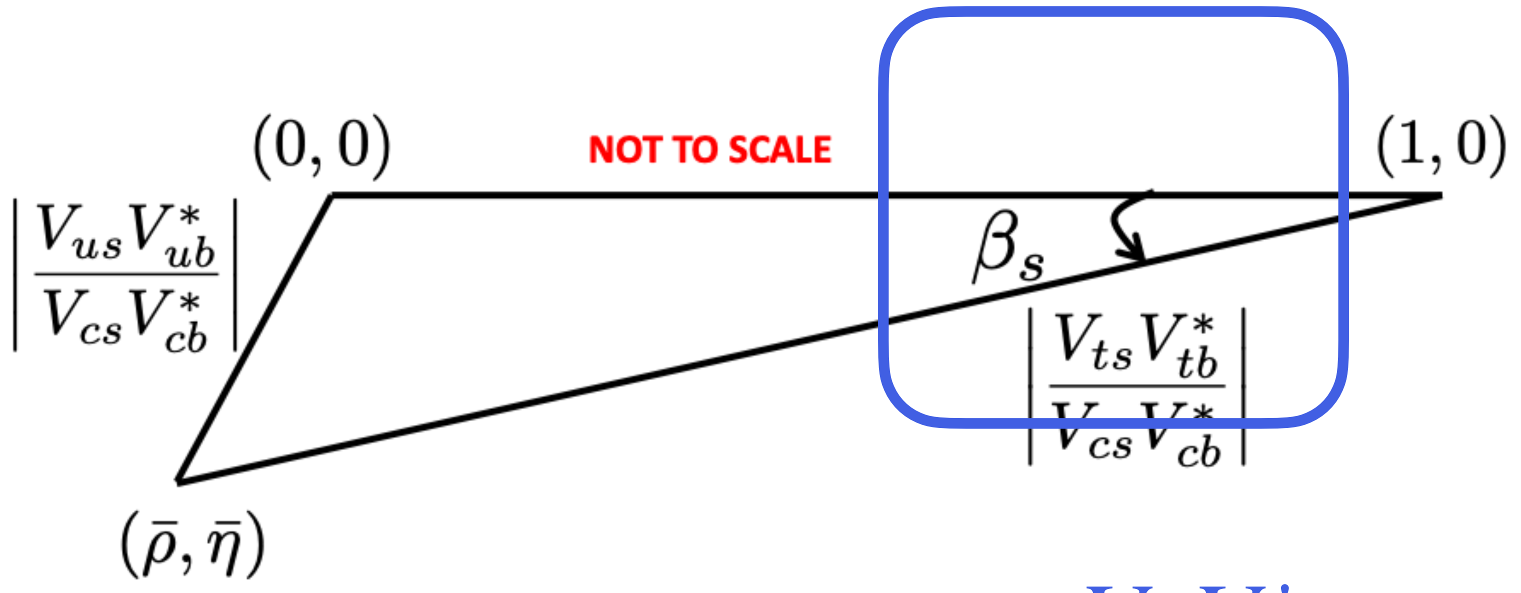

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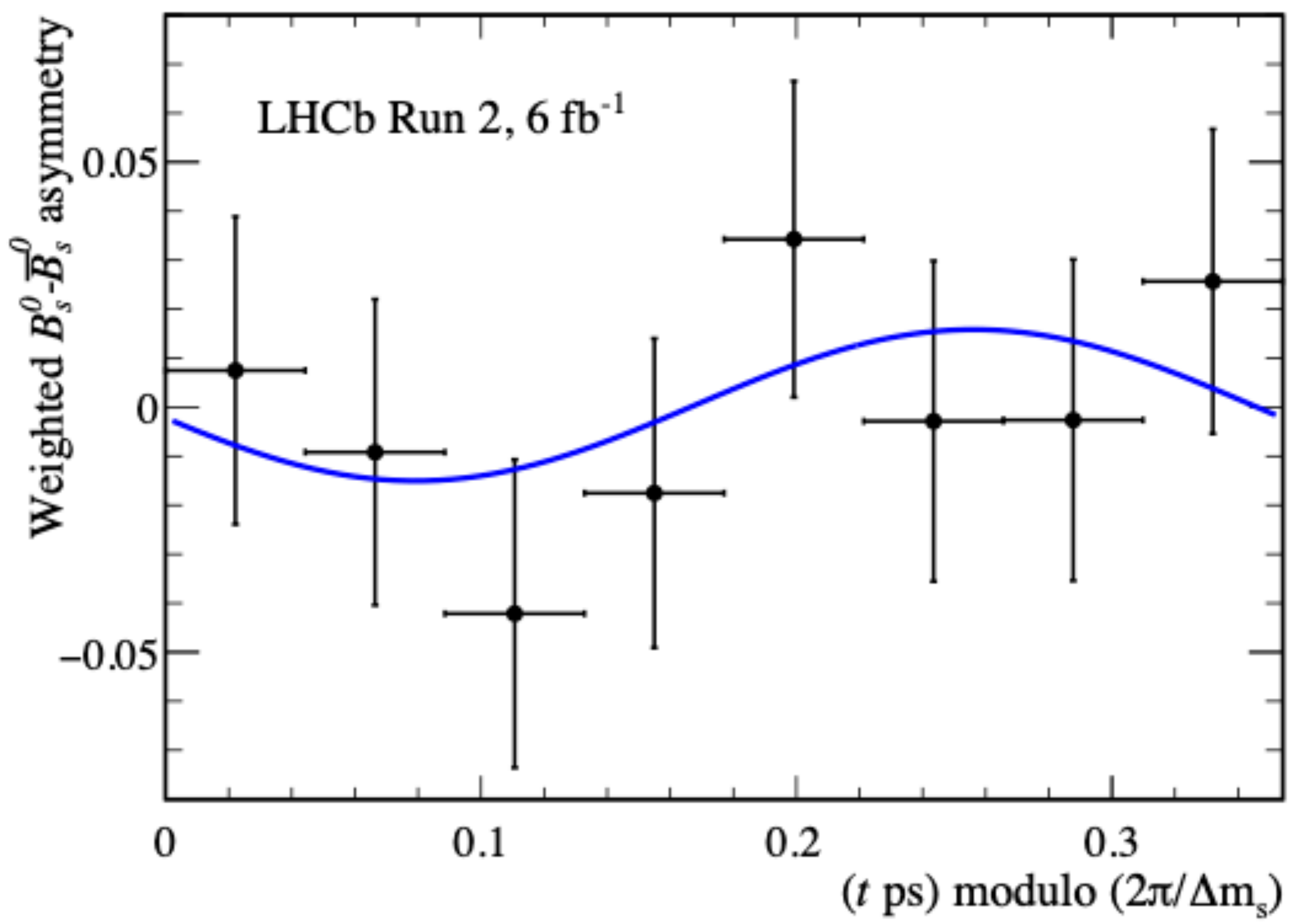
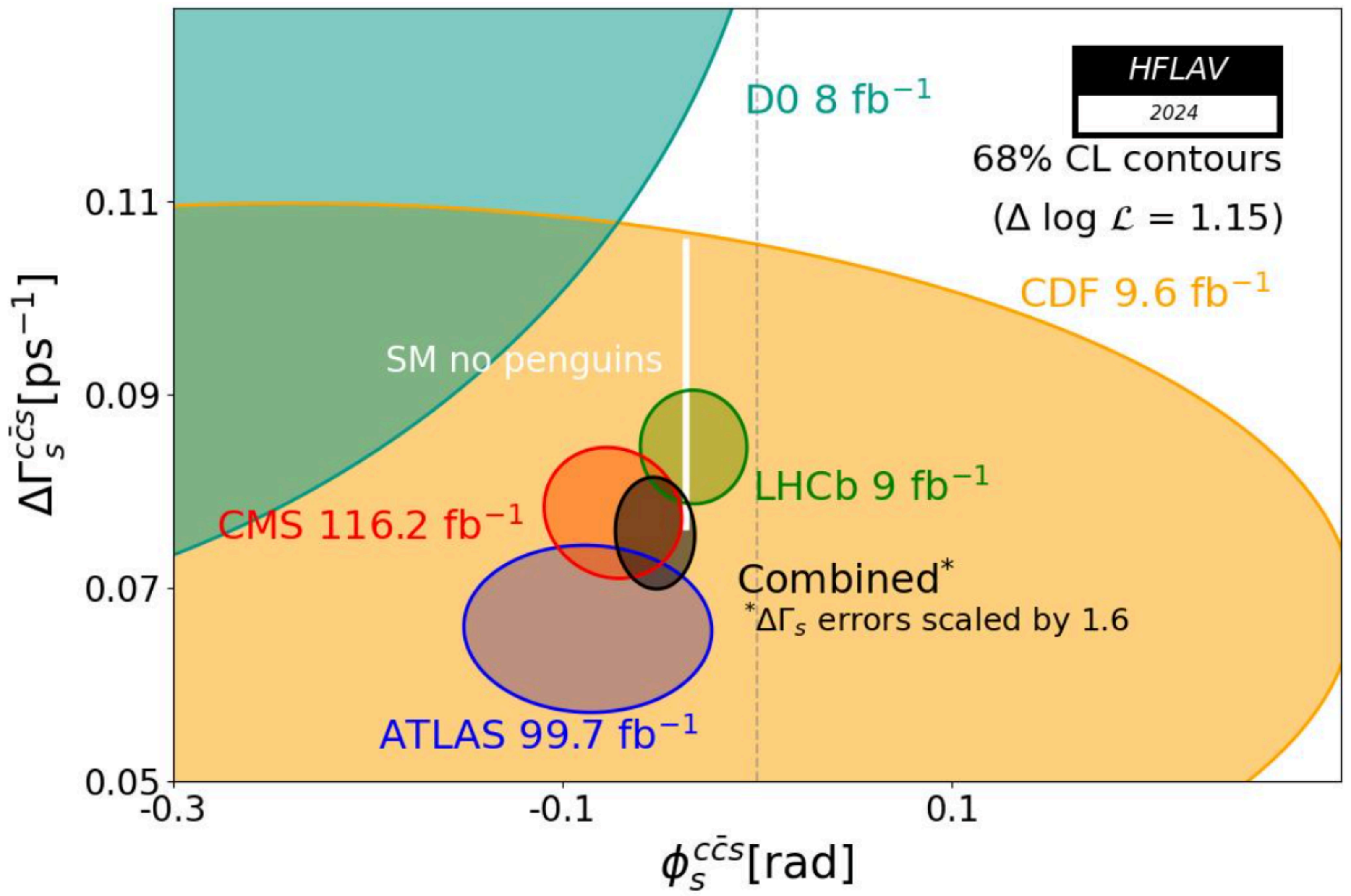
- World-best measurements, consistent with SM predictions
- Statistical limited still

World Average: $\phi_s^{c\bar cs} = -0.052 \pm 0.013$ rad

LHCb combination:
$\phi_s^{c\bar cs} = -0.031 \pm 0.018$ rad

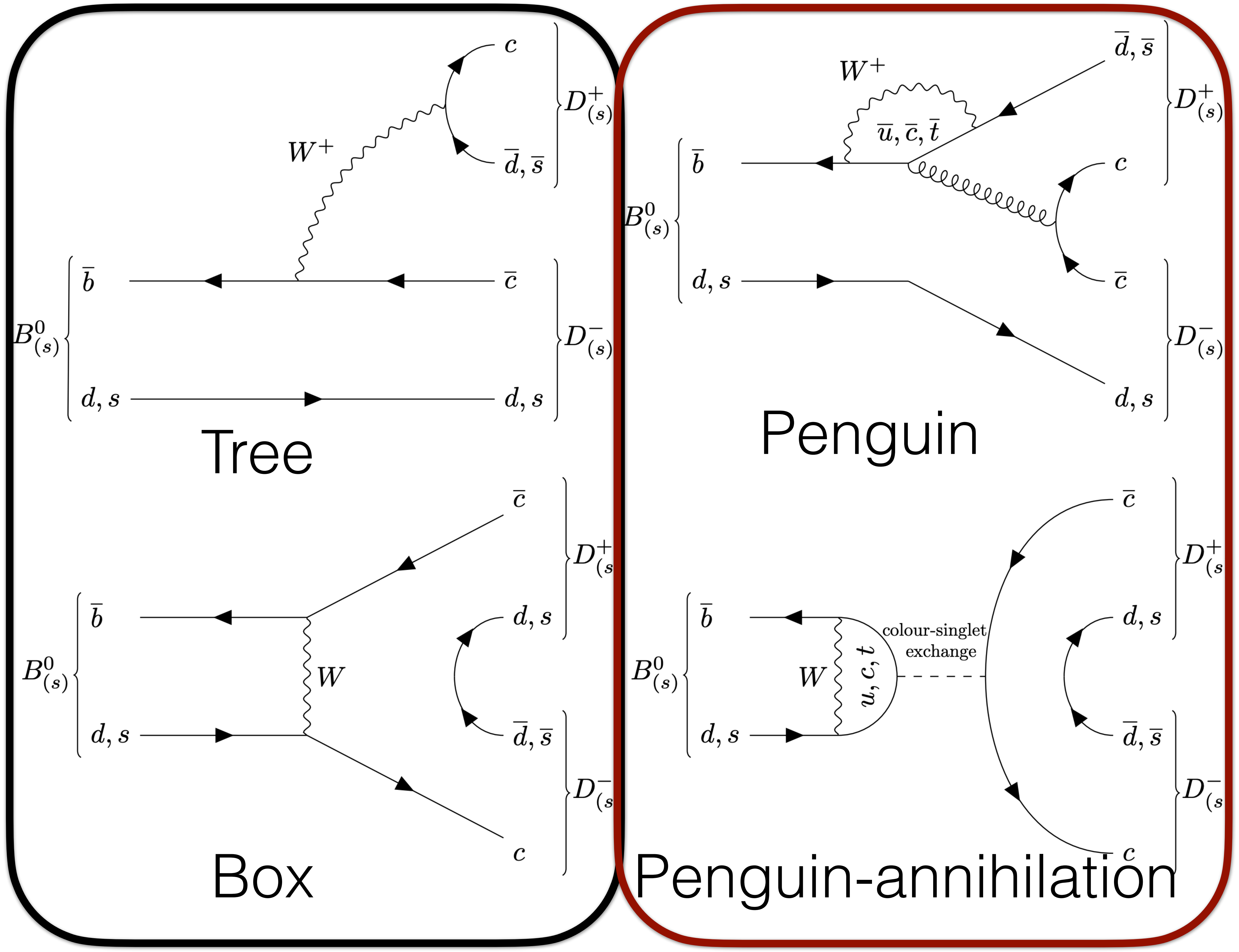


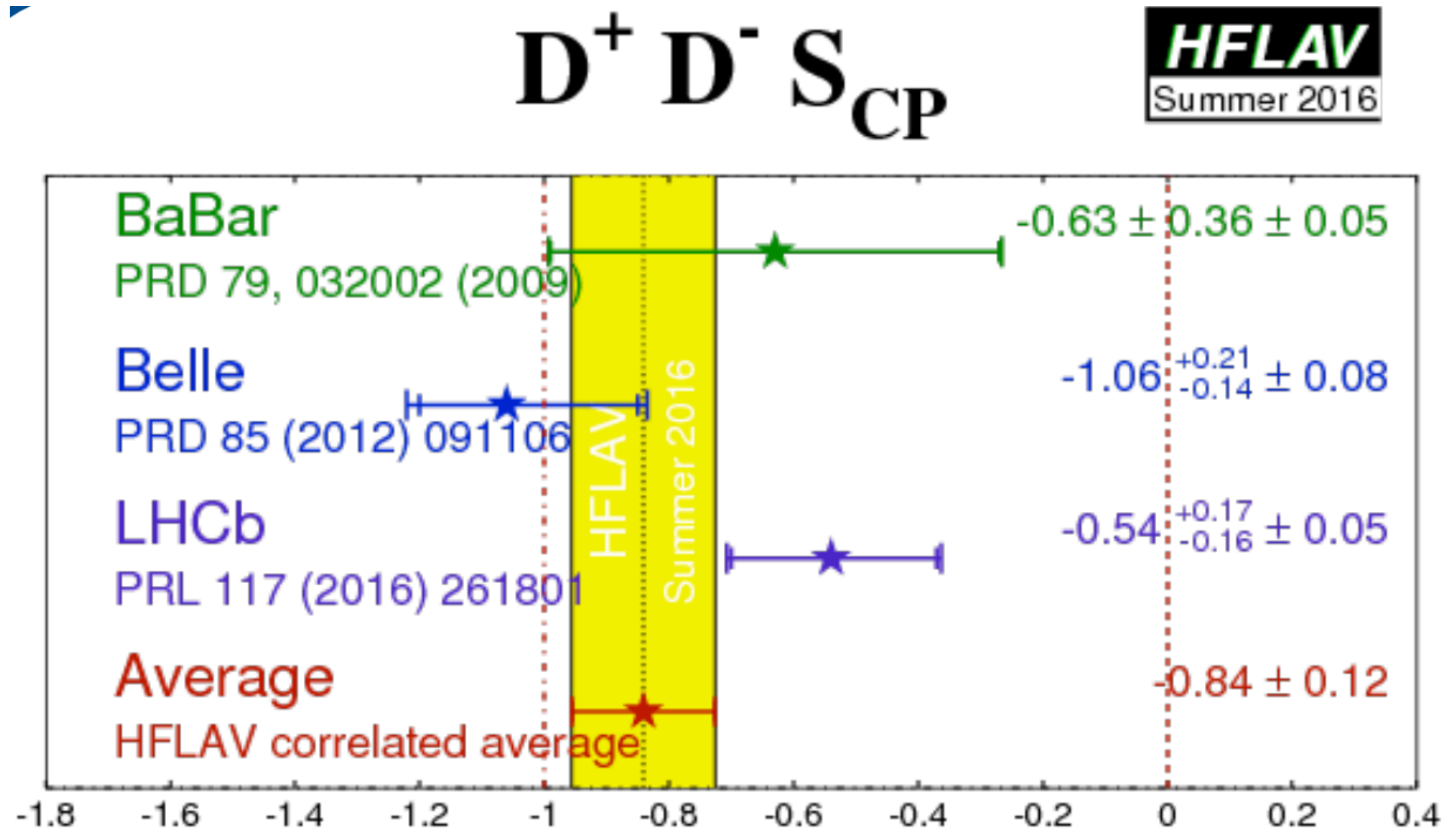


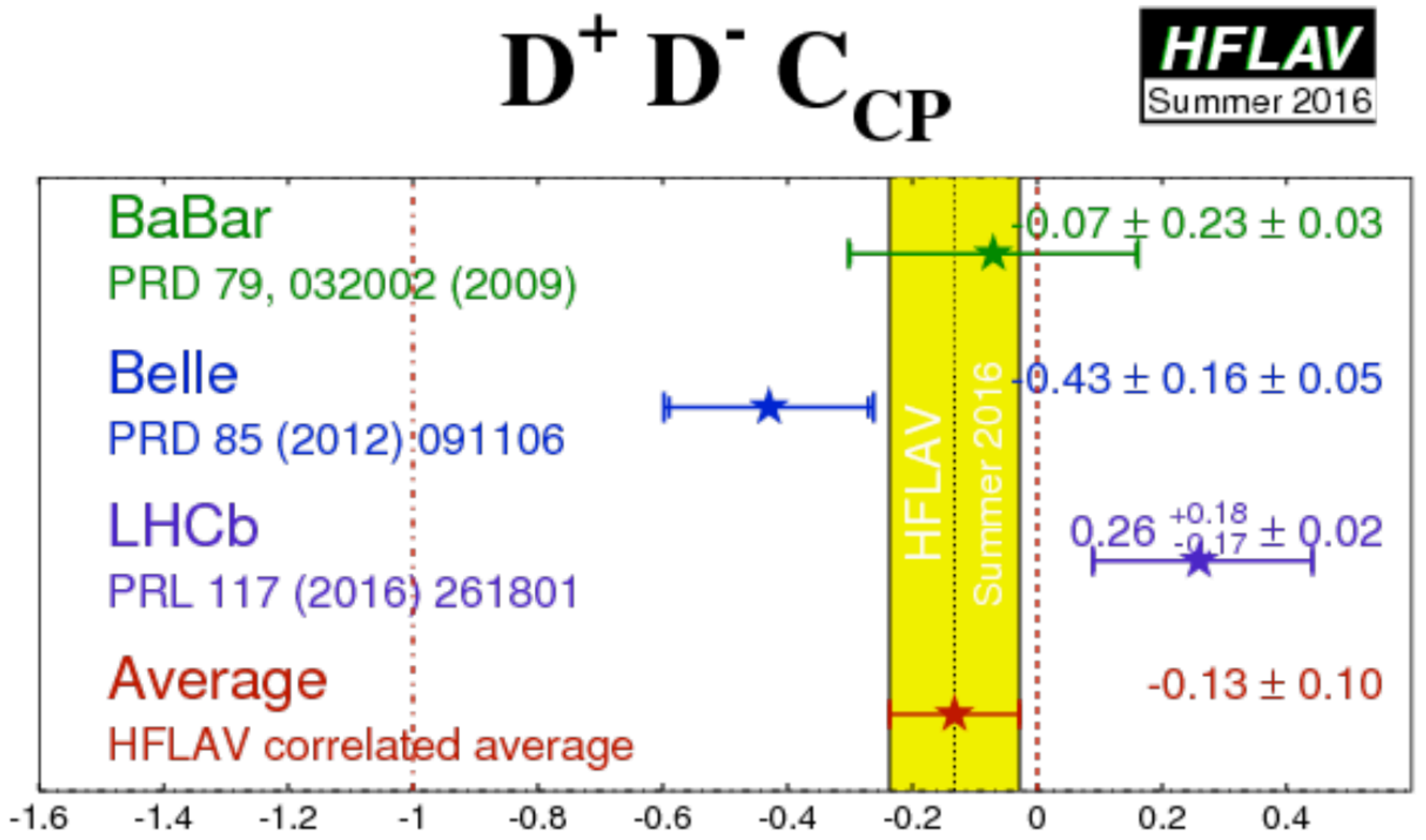
Time-dependent CPV in $B^0_{(s)} \to D^+_{(s)} D^-_{(s)}$

New arXiv: 2409.03009

- Different from the golden mode $B^0 \to J/\psi K^0_S$, the loop-mediated penguin contribution in $B^0 \to D^+D^-$ can not be ignored, effective phase $\sin(\phi_d^{eff} \equiv \sin(-2\beta + \Delta\phi_d) = -S_{D^+D^-}/\sqrt{1 - C^2_{D^+D^-}}$
- With external inputs $\Delta\phi_d$ can be measured to constrain $\Delta\phi_s$ in $B^0_s \to D^+_s D^-_s$ assuming U-spin symmetry





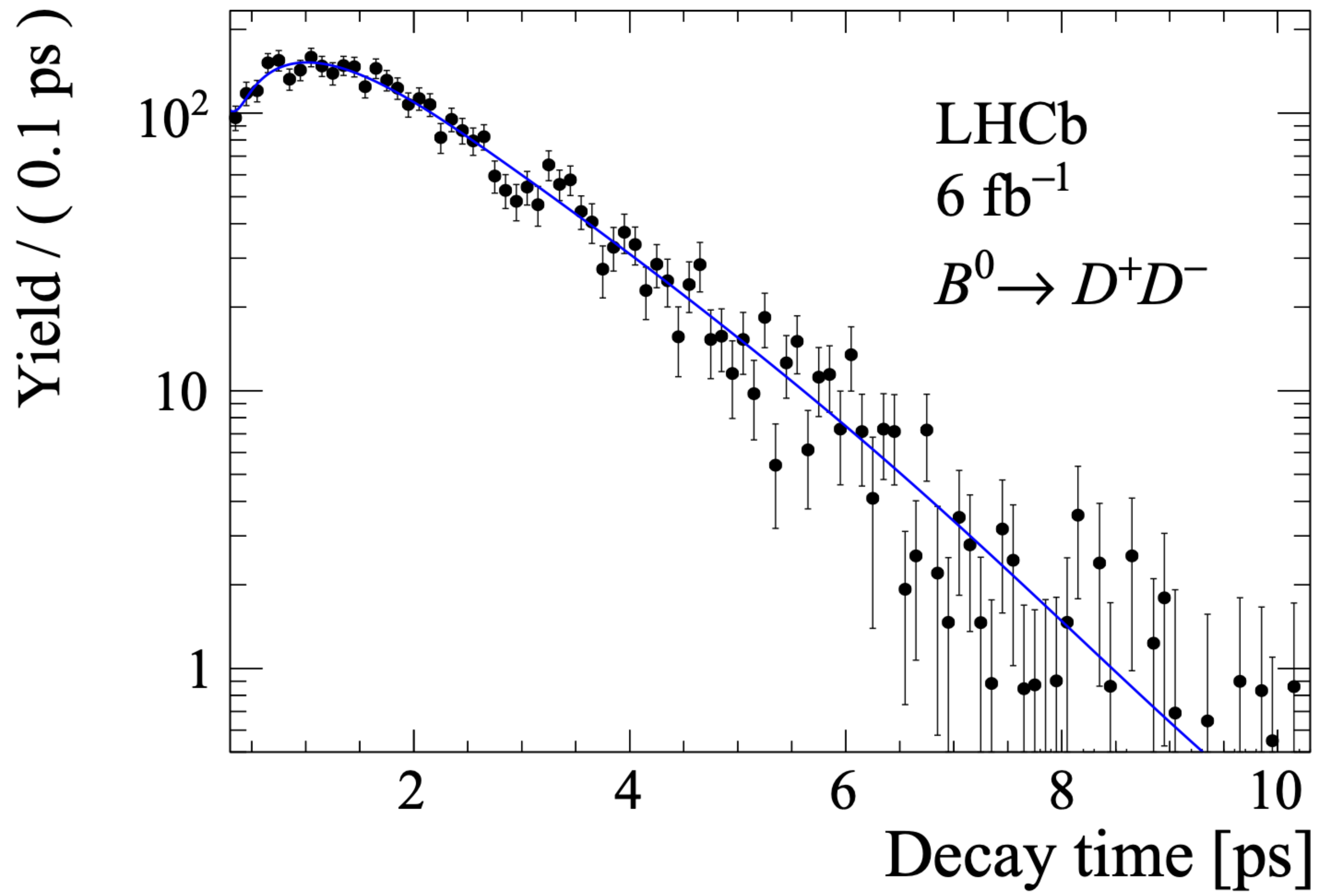


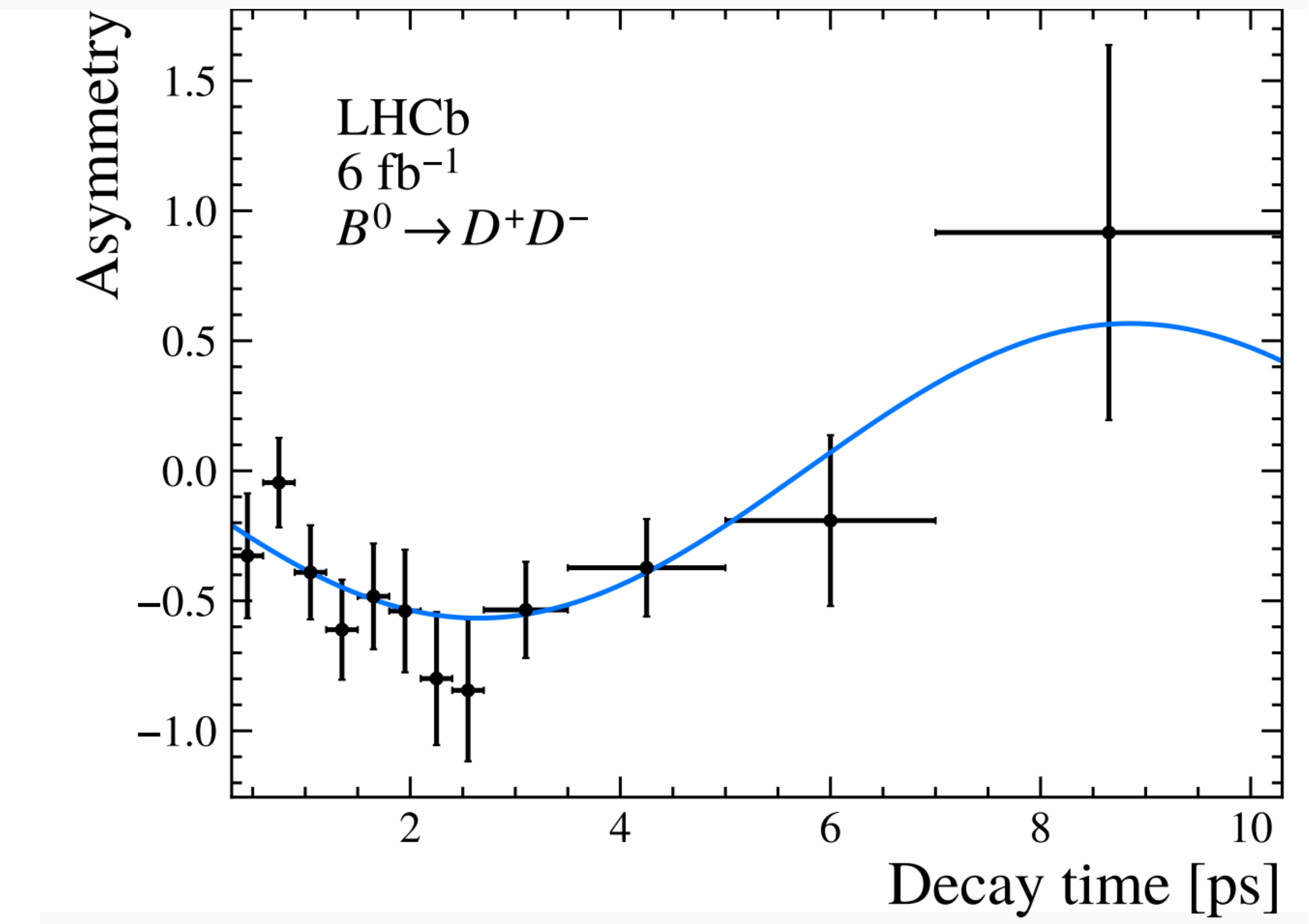
Time-dependent CPV in $B^0 \to D^+D^-$

New

arXiv: 2409.03009

$$\frac{d\Gamma(t,d)}{dt} \propto e^{-t/\tau_{B^0}}\left(1 + d\,C_{D^+D^-}\cos\Delta m_d t - d\,S_{D^+D^-}\sin\Delta m_d t\right)$$





- CP asymmetry observed in $B^0 \to D^+D^-$ for the first time with a significance exceeding 6σ

$$S_{D^+D^-} = -0.552 \pm 0.100\,(\text{stat}) \pm 0.010\,(\text{syst})$$
$$C_{D^+D^-} = 0.128 \pm 0.103\,(\text{stat}) \pm 0.010\,(\text{syst})$$

[PRL117 (2016) 261801, PRD79 (2009) 032002]

- In consistent with previous LHCb and BaBar results, and corresponding to a small contribution from higher-order SM corrections

[PRD85 (2012) 091106]

- Move the world average further away from the Belle result

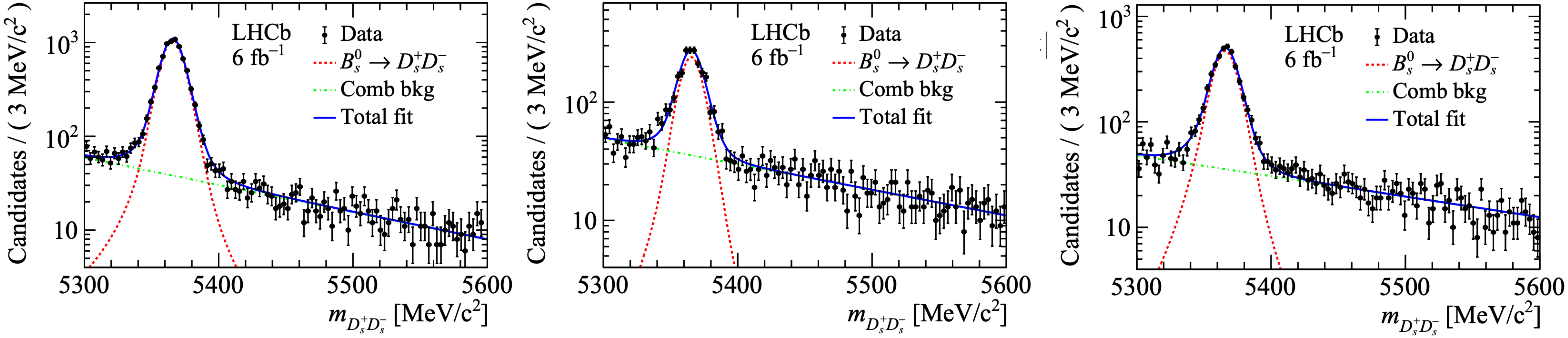
- Combined with previous LHCb result:

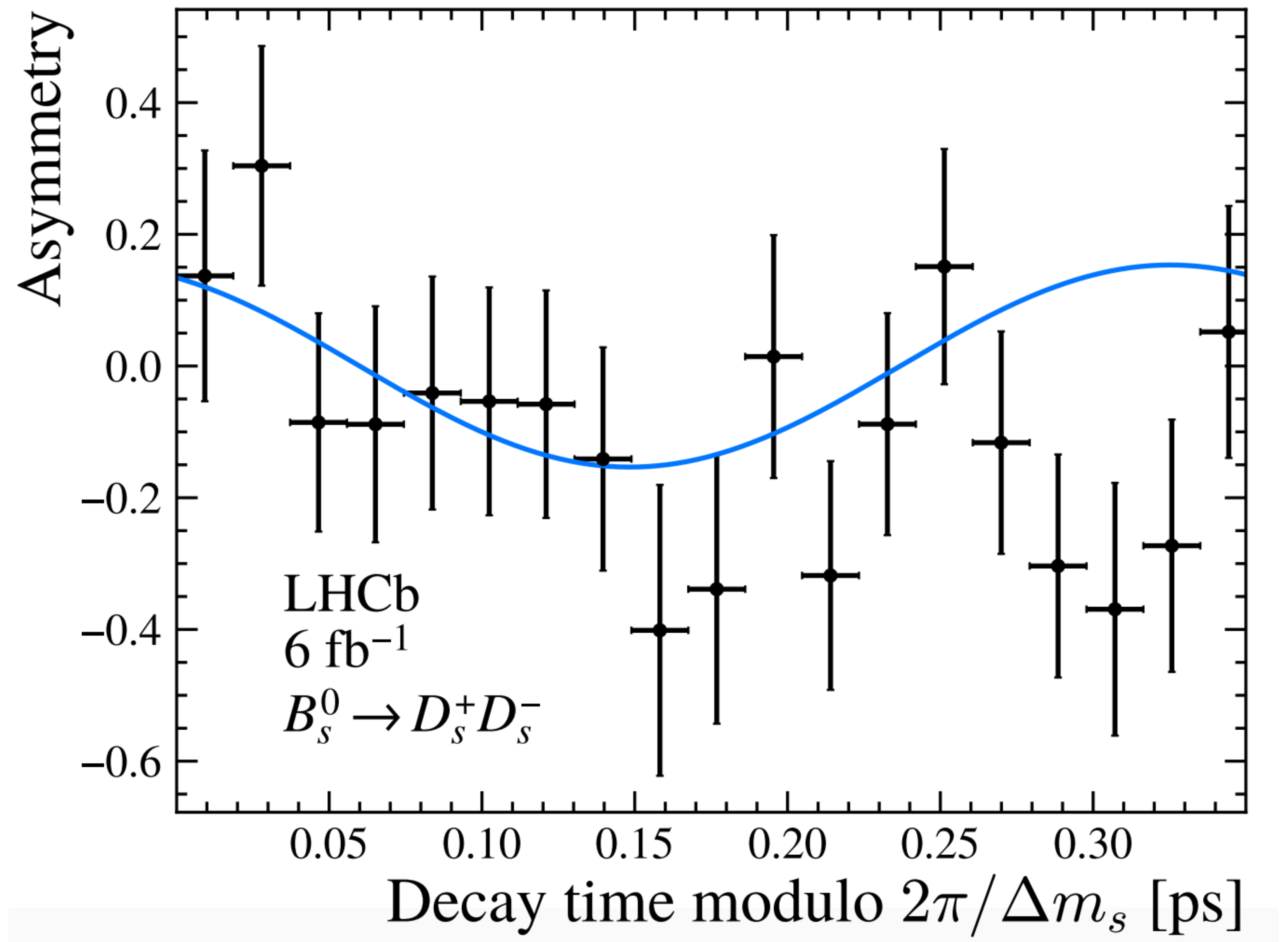
$$S_{D^+D^-} = -0.549 \pm 0.085\,(\text{stat}) \pm 0.015\,(\text{syst})$$
$$C_{D^+D^-} = 0.162 \pm 0.088\,(\text{stat}) \pm 0.009\,(\text{syst})$$

Time-dependent CPV in $B^0_{(s)} \to D^+_{(s)} D^-_{(s)}$

New

arXiv: 2409.03009





$$\phi_s = -0.086 \pm 0.106\,(\text{stat}) \pm 0.028\,(\text{syst})\ \text{rad},$$
$$|\lambda_{D^+_s D^-_s}| = 1.145 \pm 0.126\,(\text{stat}) \pm 0.031\,(\text{syst}).$$

- Agree with Run 1 LHCb result, and combined to be:

$$\phi_s = -0.055 \pm 0.090\,(\text{stat}) \pm 0.021\,(\text{syst})\ \text{rad}$$
$$|\lambda_{D^+_s D^-_s}| = 1.054 \pm 0.099\,(\text{stat}) \pm 0.020\,(\text{syst})$$

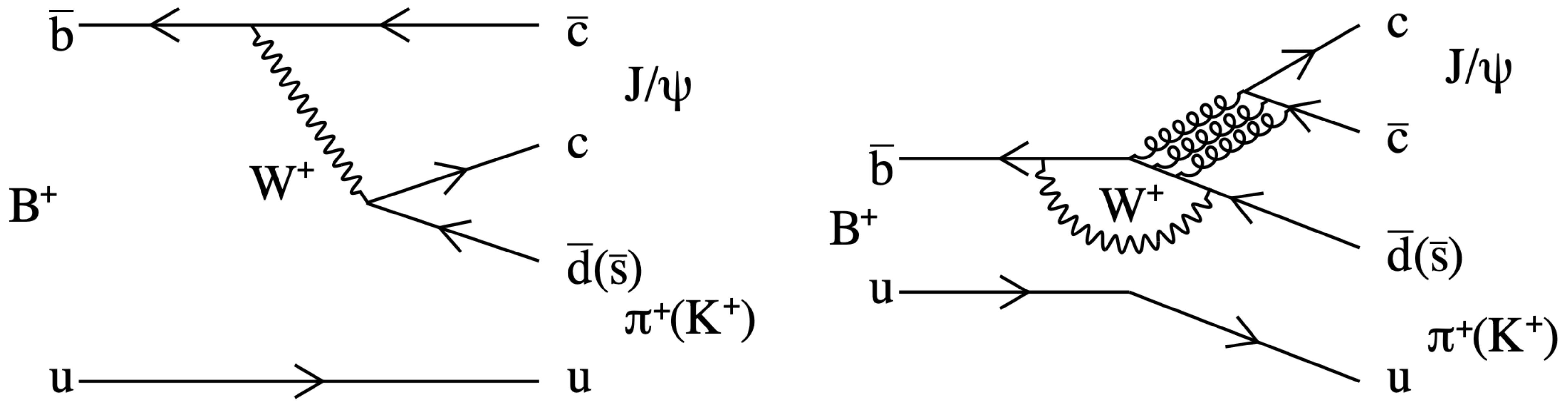
- No CP asymmetry observed

Direct CPV in $B^+ \to J/\psi\pi^+$

New LHCb-PAPER-2024-31 in preparation

- Proceeding via a $b \to c\bar{c}d$ transition, $B^+ \to J/\psi\pi^+$ is enriched with penguin contribution
  $\Rightarrow$ Expect O(1%) direct CP violation [PRD 49 (1994) 5904, PRD 52 (1995) 242]
- Ideal place to look for yet unobserved direct CP violation in B decays to charmonia
- Important control channel to understand penguin effects in $\sin 2\beta$ measurement in $B^0 \to J/\psi K^0$

[PRD 79 (2009) 014030, JHEP 03 (2015) 145]



$$\mathcal{R}_{\pi/K} \equiv \frac{\mathcal{B}(B^+ \to J/\psi\pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = \frac{N_\pi}{N_K} \times \frac{\epsilon_K}{\epsilon_\pi}$$

$$\mathcal{R}_{K/\pi} = (3.851 \pm 0.022 \pm 0.023) \times 10^{-2}$$

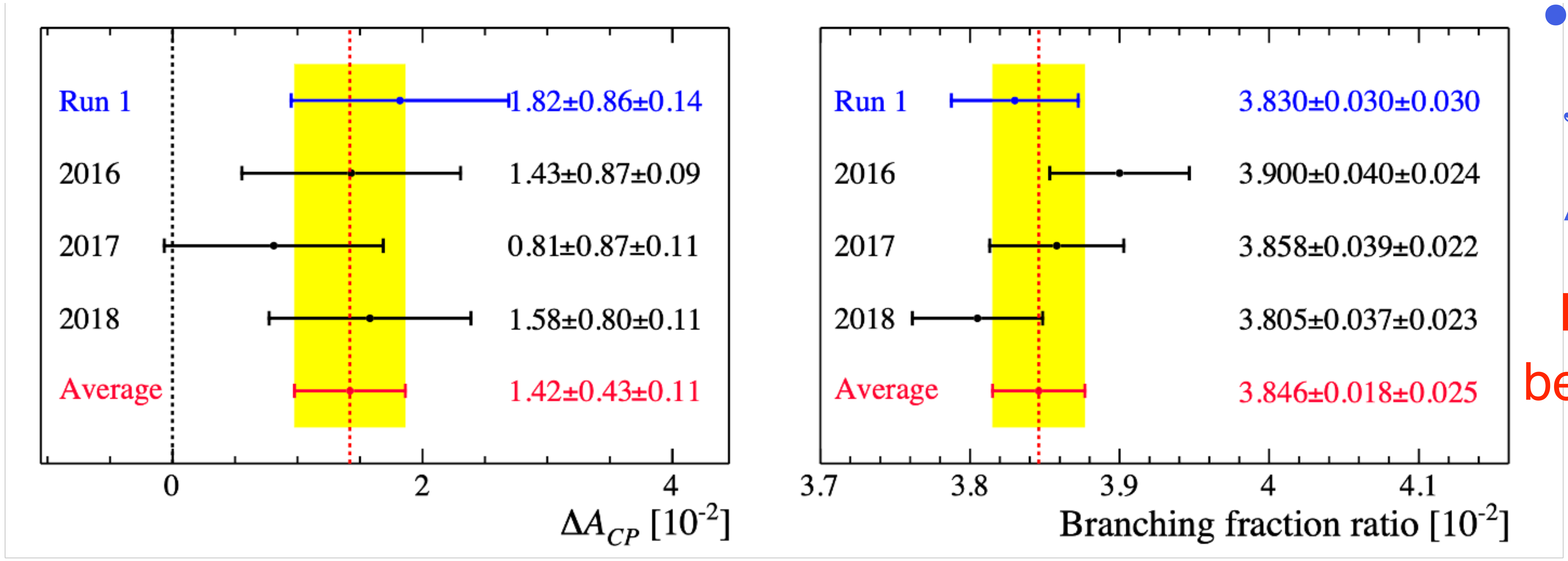
Direct CPV in $B^+ \to J/\psi\pi^+$

New LHCb-PAPER-2024-31 in preparation

- Run 2 result, conservatively assuming fully correlated systematic uncertainties

$$\Delta A^{CP} = A^{CP}(B^+ \to J/\psi\pi^+) - A^{CP}(B^+ \to J/\psi K^+) = (1.29 \pm 0.49 \pm 0.08) \times 10^{-2}$$

- Compatible with Run 1 result: $\Delta A^{CP} = (1.82 \pm 0.86 \pm 0.14)\times 10^{-2}$



- Combined with Run 1 result:

$$\mathcal{R}_{K/\pi} = (3.852 \pm 0.022 \pm 0.018) \times 10^{-2}$$

$$\Delta A^{CP} = (1.42 \pm 0.43 \pm 0.08) \times 10^{-2}$$

First evidence for direct CP violation in beauty decays to charmonium final states (3.2 σ)

[Phys. Rev. D 95, 052005 (2017)]

- Taking previous LHCb result of $A^{CP}(B^+ \to J/\psi K^+) = (0.09 \pm 0.27 \pm 0.07) \times 10^{-2}$ to extract:

$$A^{CP}(B^+ \to J/\psi\pi^+) = (1.51 \pm 0.50 \pm 0.11)\times 10^{-2}$$

agrees with PDG value $A^{CP}(B^+ \to J/\psi\pi^+) = (1.8 \pm 1.2) \times 10^{-2}$

Direct CPV in $B^+ \to J/\psi\pi^+$

New LHCb-PAPER-2024-31 in preparation

- Decay amplitudes of $B^+ \to J/\psi h^+$

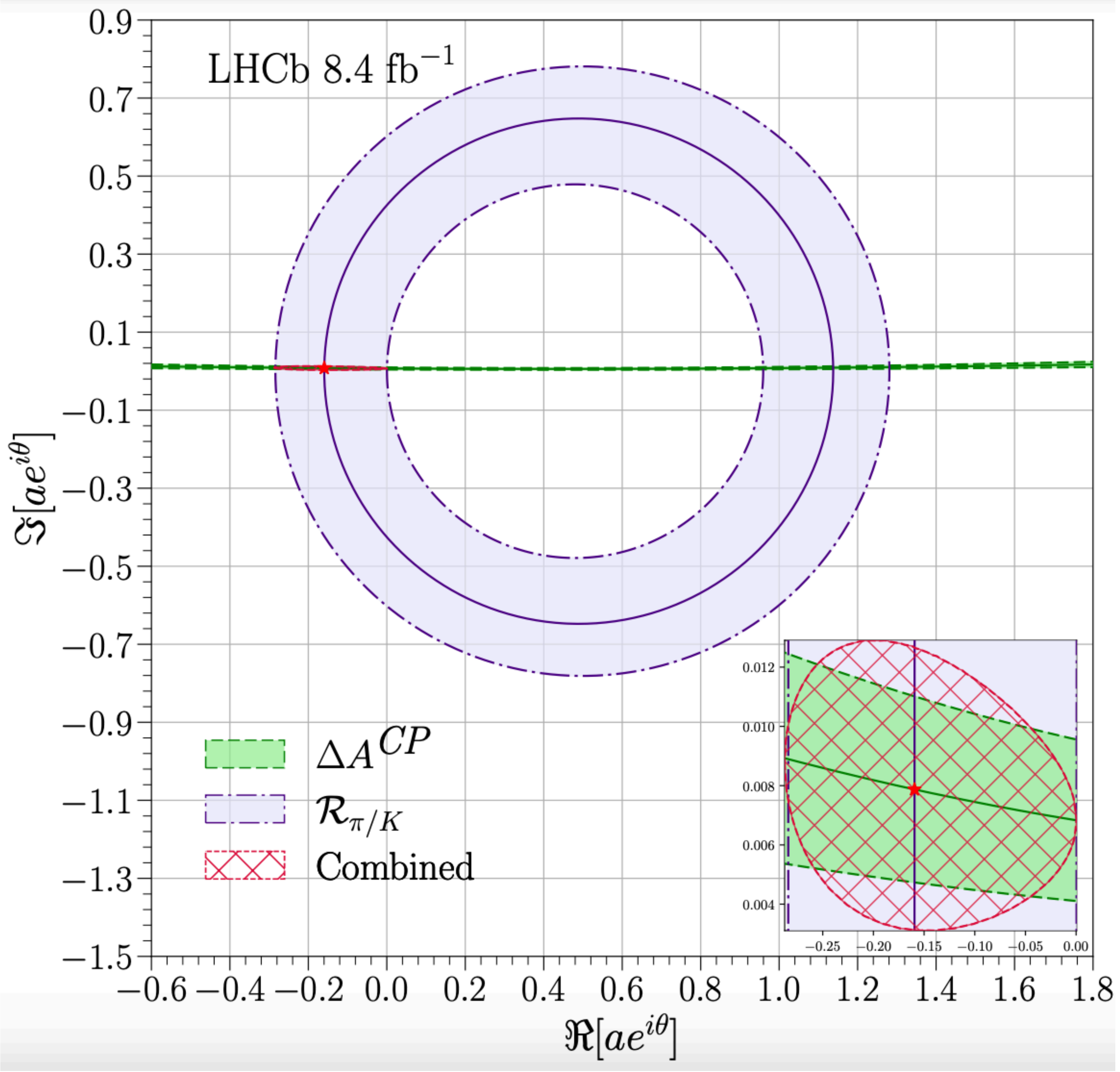
$$A(B^+ \to J/\psi\pi^+) = -\lambda\mathcal{A}(1 + ae^{i\theta}e^{i\gamma})$$

$$A(B^+ \to J/\psi K^+) = (1 - \lambda^2/2)\mathcal{A}'(1 + \epsilon a' e^{i\theta'} e^{i\gamma})$$

$\lambda = V_{us}$, $\epsilon = \lambda(1 - \lambda^2)$, $A^{(\prime)}$ is the hadronic matrix element

LHCb combined result of CKM angle $\gamma = (64.6 \pm 2.8)^\circ$

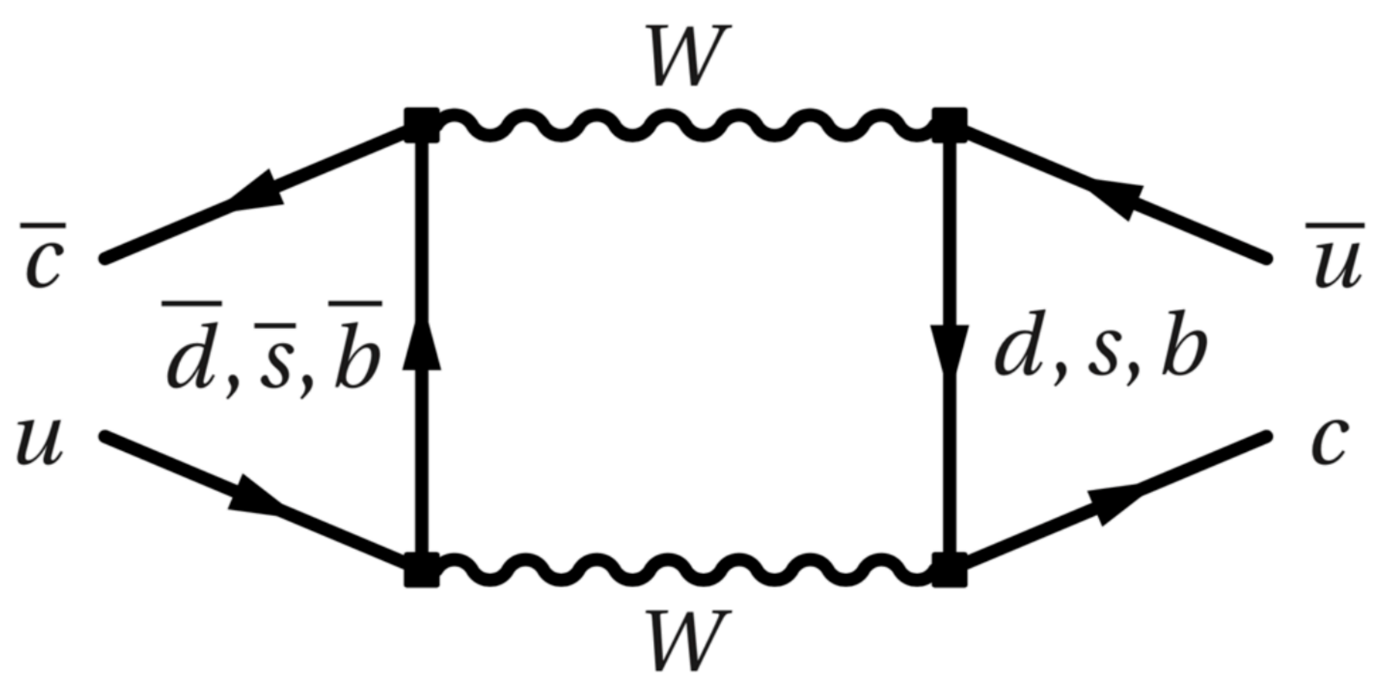
- SU(3) flavour symmetry: $a = a', \theta = \theta'$
- Constraints on the relative size (a) and strong phase difference (θ) between penguin and tree contributions

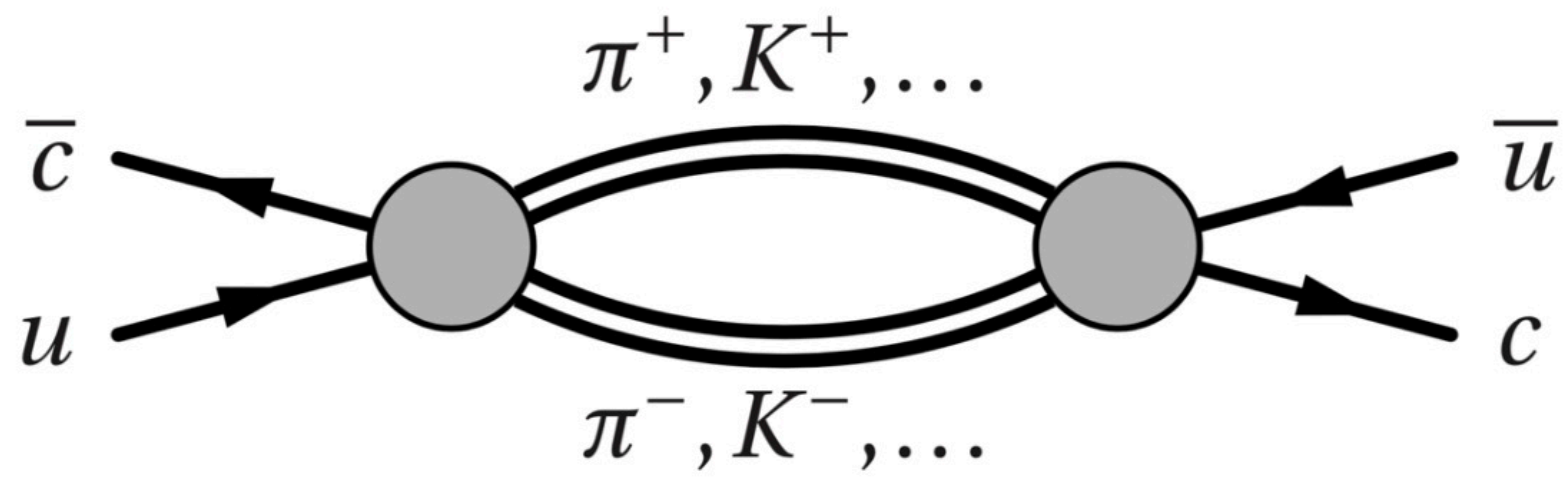


The 68% confidence-level contours in the complex plane

CP violation in charm sector

- GIM mechanism very effective for charm decays, SM loops highly suppressed
- Tiny weak phases in first two generations of CKM matrix (< λ_b~ 0.1%)
- Oscillation and CPV ($\leq 10^{-3}$)
- Long distance contribution comparable/larger than short distance





CP violation in charm sector

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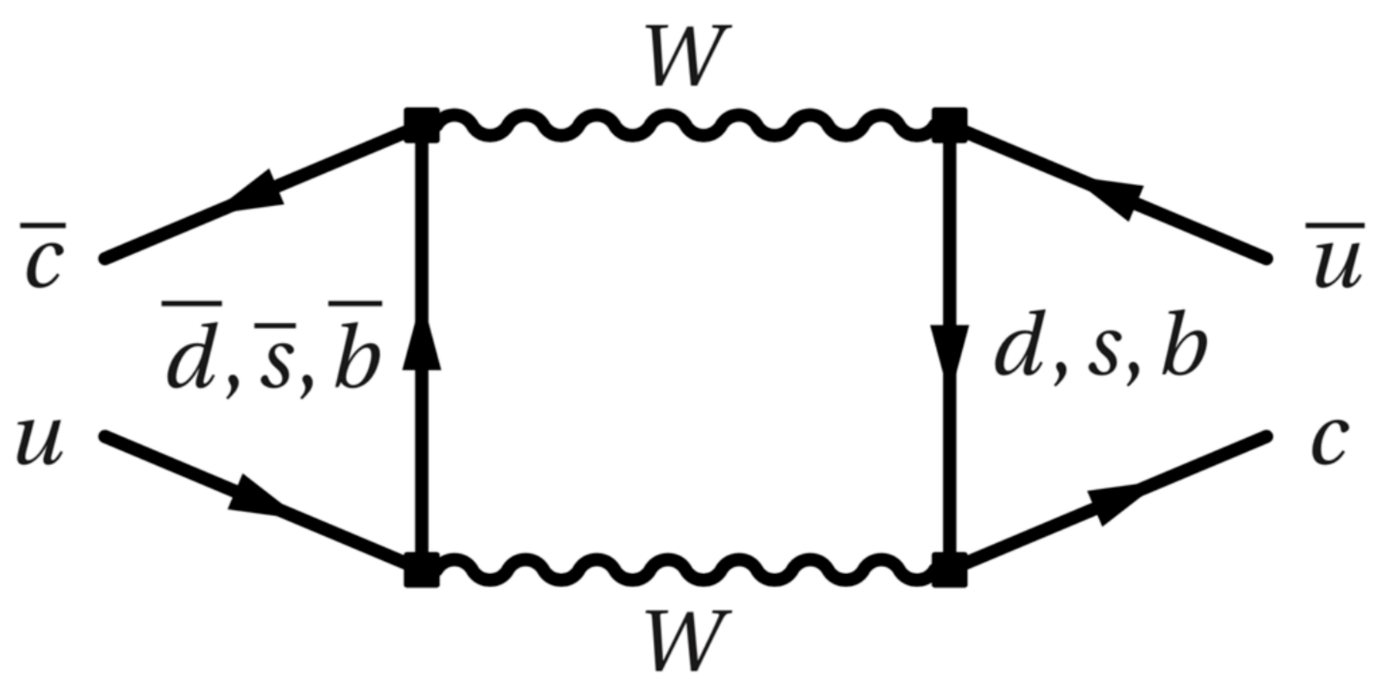
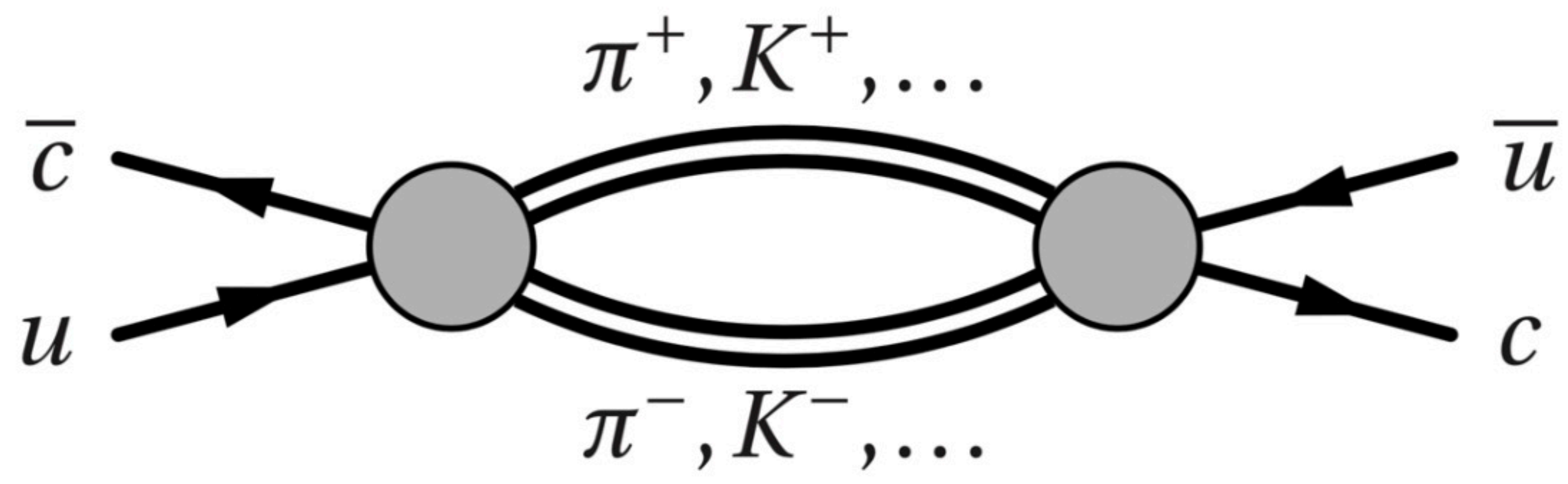




Breakthroughs by LHCb thanks to huge statistics:

First observation of CPV in $D^0 \to h^+h^-$ decays

$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9)\times 10^{-4}$ [PRL(2019)211803]

Evidence of CPV in $D^0 \to \pi^+\pi^-$ decay

$A_{CP}(\pi^+\pi^-) = (23.2 \pm 6.1)\times 10^{-4}$ (3.8σ) [PRL(2023)211803]

Direct CP violation in $D^+ \to K^+K^-\pi^+$

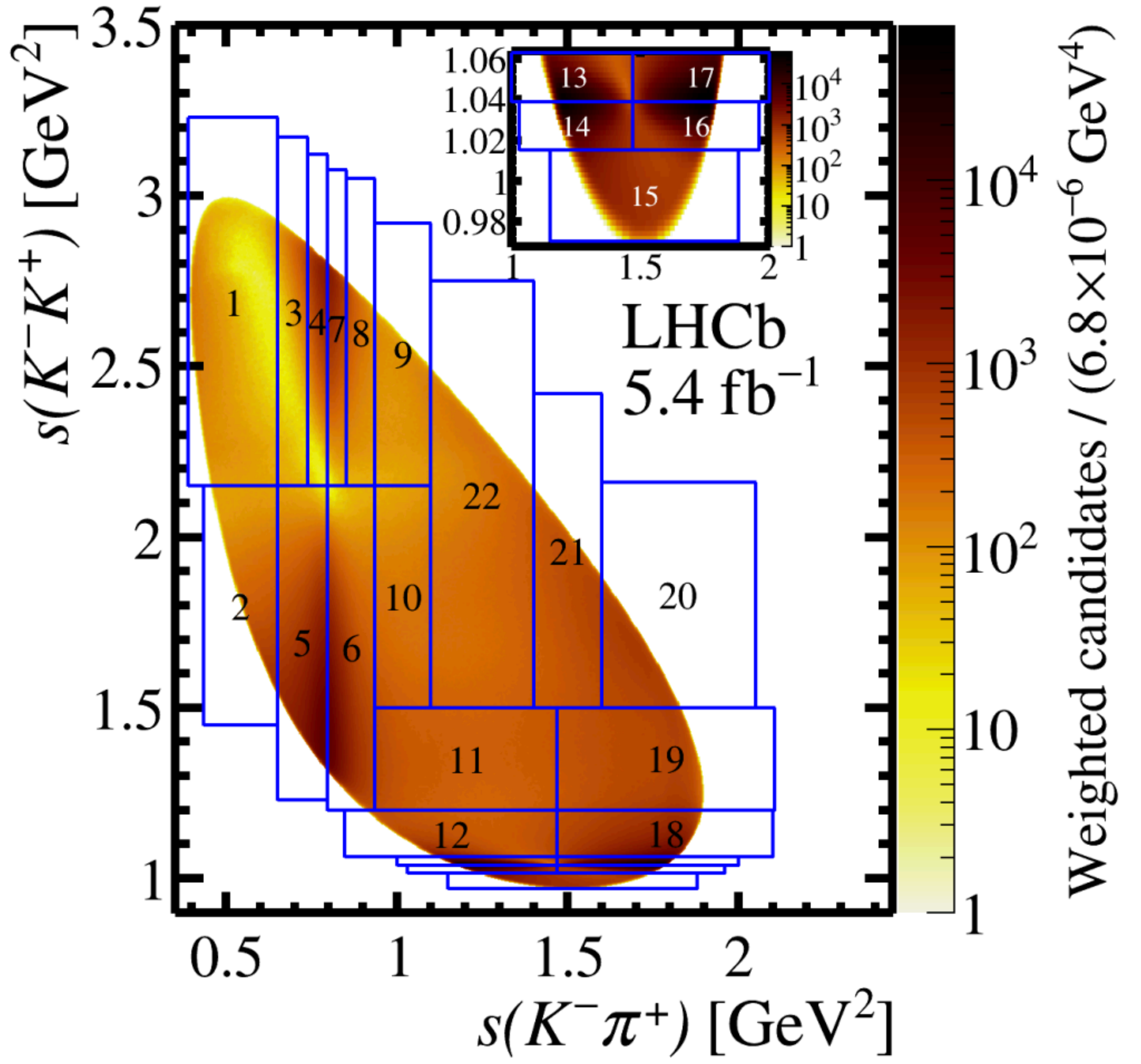
New arXiv:2409.01414

- Search for localised CP violation in the phase space of $D^+ \to K^+K^-\pi^+$ (S) decay
- Control channel $D_s^+ \to K^+K^-\pi^+$ (C) to subtract nuisance asymmetries

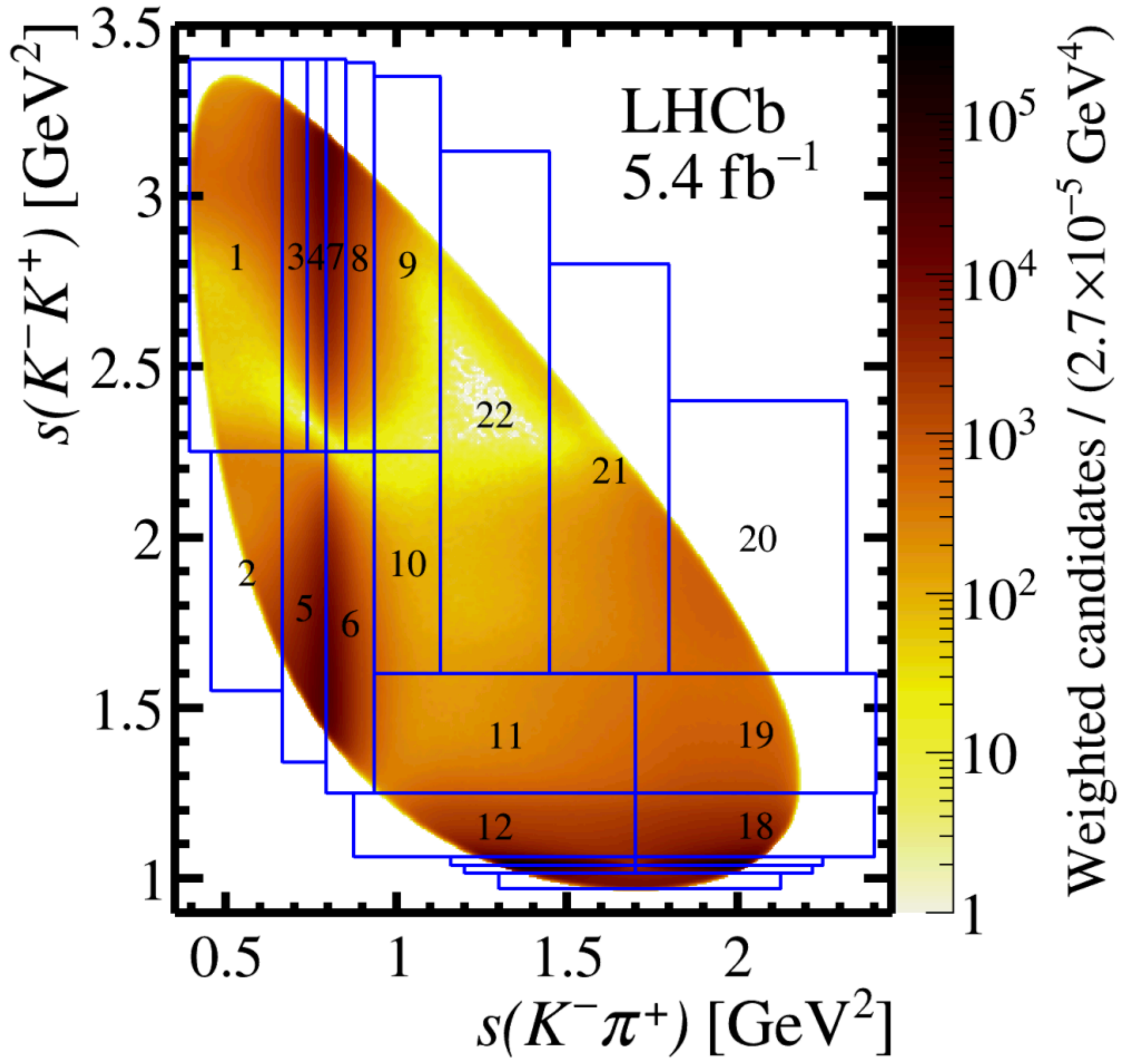
$$\Delta A_{CP}^{i} = A_{\text{raw}}^{i,S} - A_{\text{raw}}^{i,C} - \Delta A_{\text{raw}}^{\text{global}}$$

- Test-statistic to extract a p-value for the hypothesis of no localised CP violation

$$\chi^2(\mathcal{S}_{\Delta_{CP}}) = \sum_i^{N_{\text{bins}}} (\mathcal{S}_{\Delta_{CP}}^i)^2, \qquad \mathcal{S}_{\Delta_{CP}}^i = \frac{\Delta A_{CP}^i}{\sigma_{\Delta A_{CP}^i}}$$



$D^+ \to K^+K^-\pi^+$ (S)



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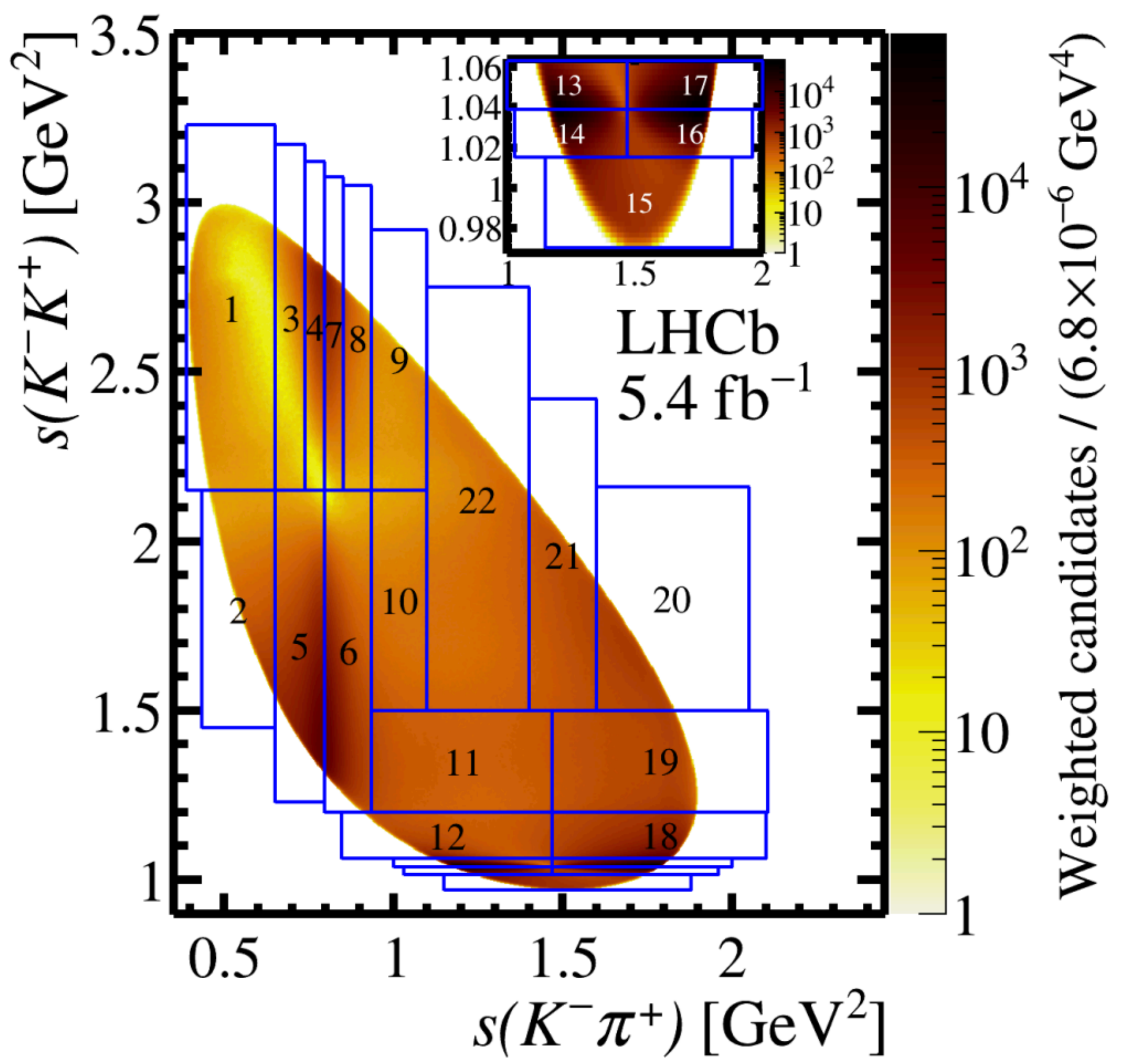

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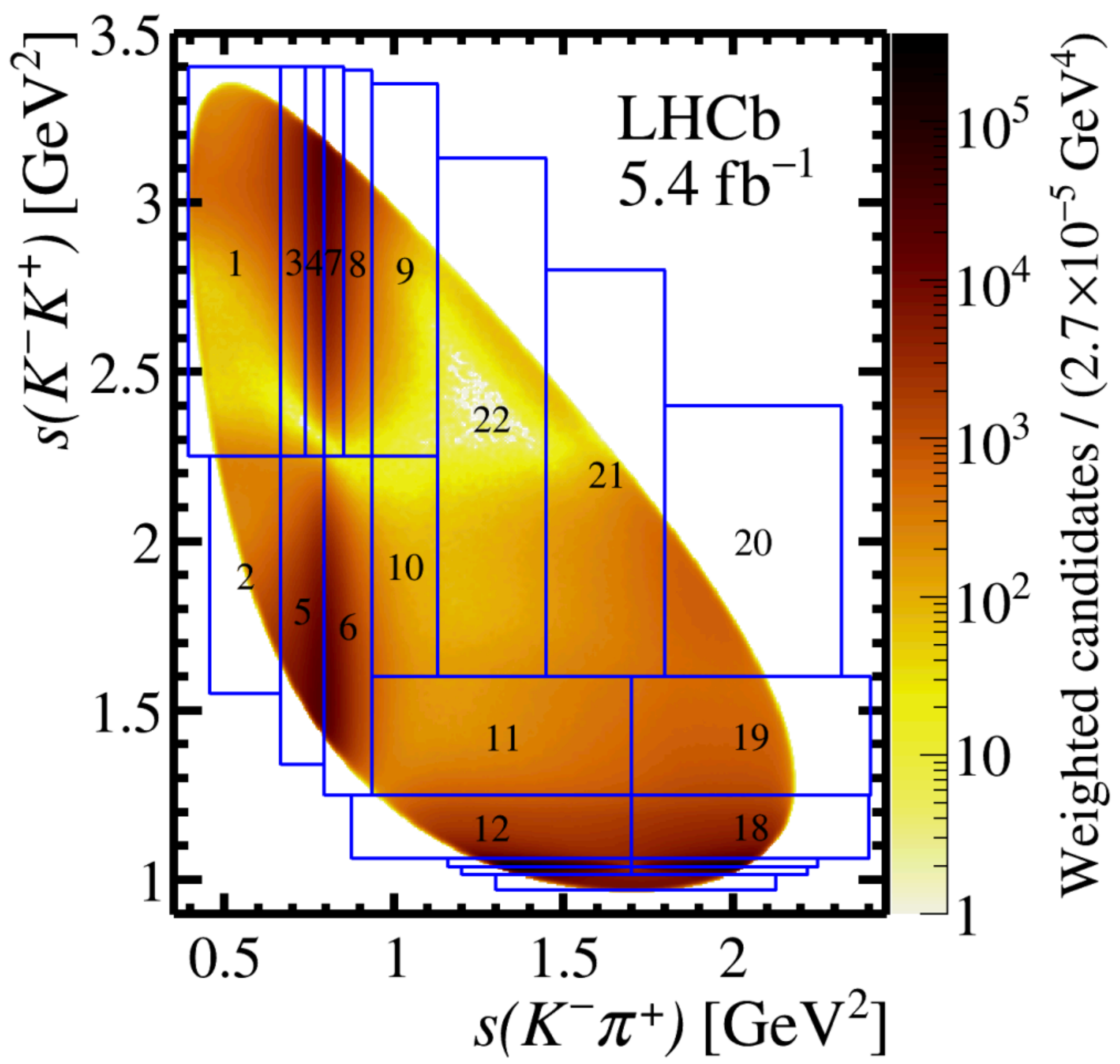
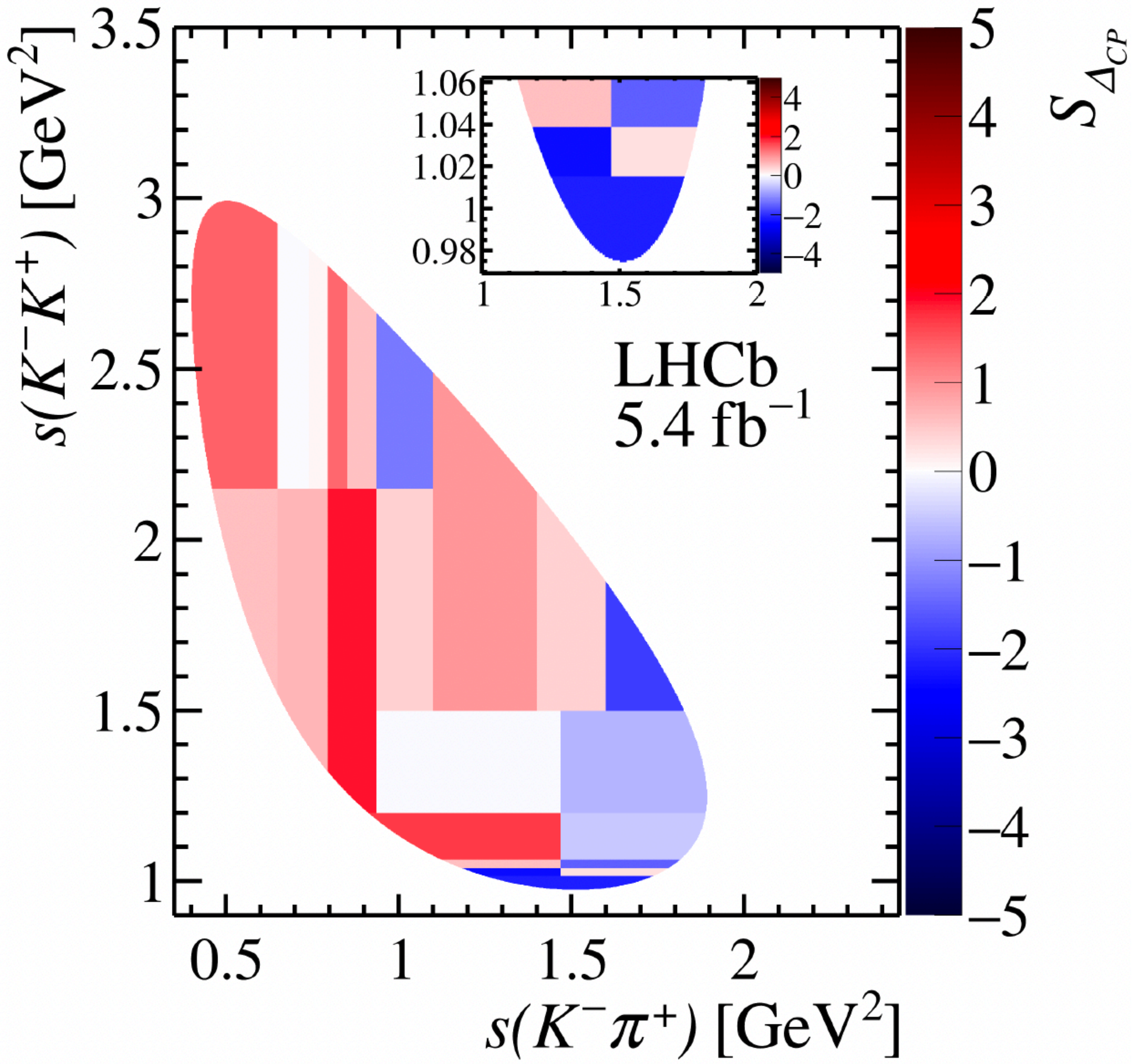


$D_s^+ \to K^+K^-\pi^+$ (C)

- p-values (2.3-14.1%) compatible with absence of localised CP violation in Dalitz plot



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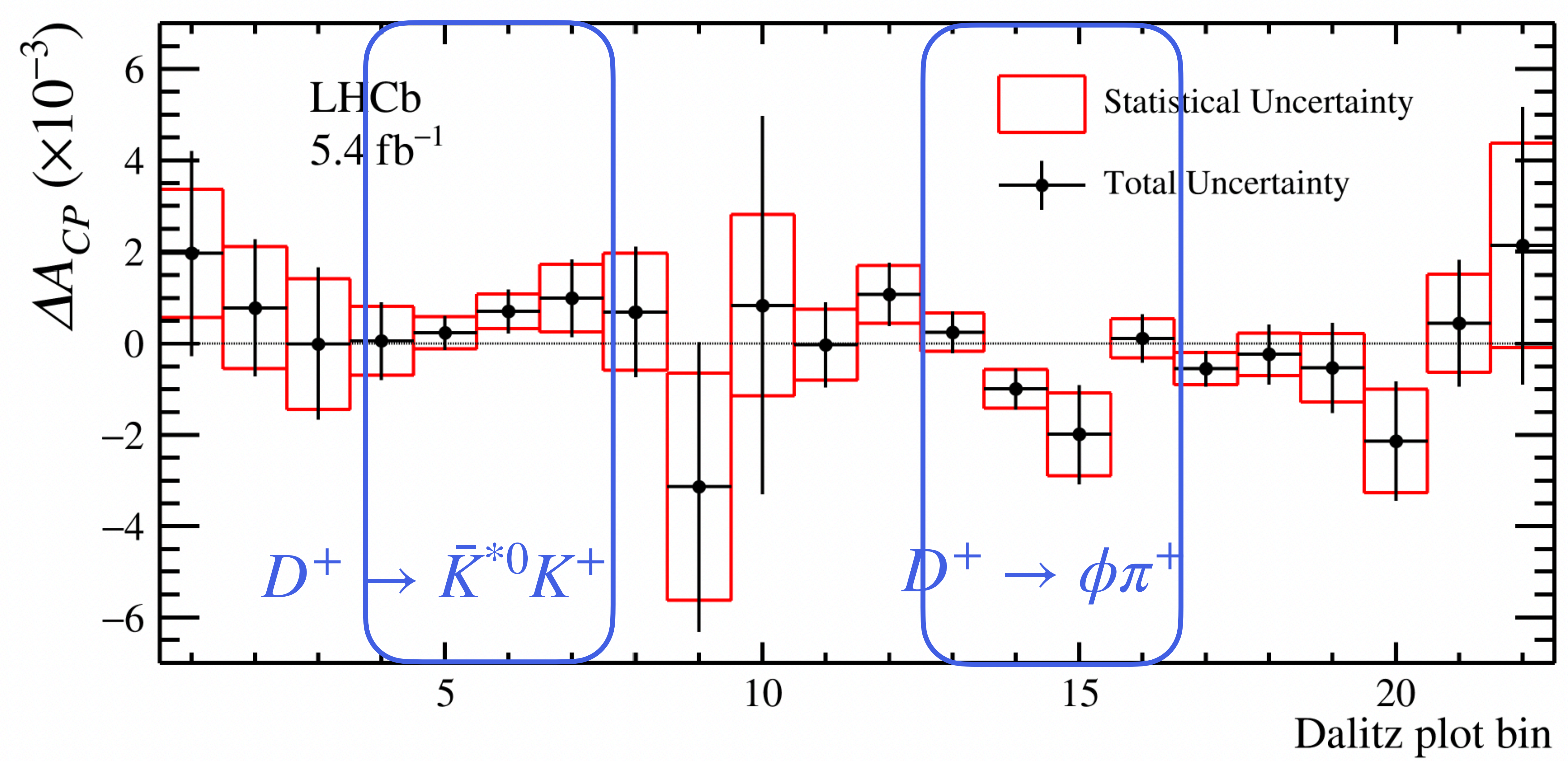
- Search for localised CP violation in the phase space of $D^+ \to K^+K^-\pi^+$ (S) decay
- Control channel $D_s^+ \to K^+K^-\pi^+$ (C) to subtract nuisance asymmetries

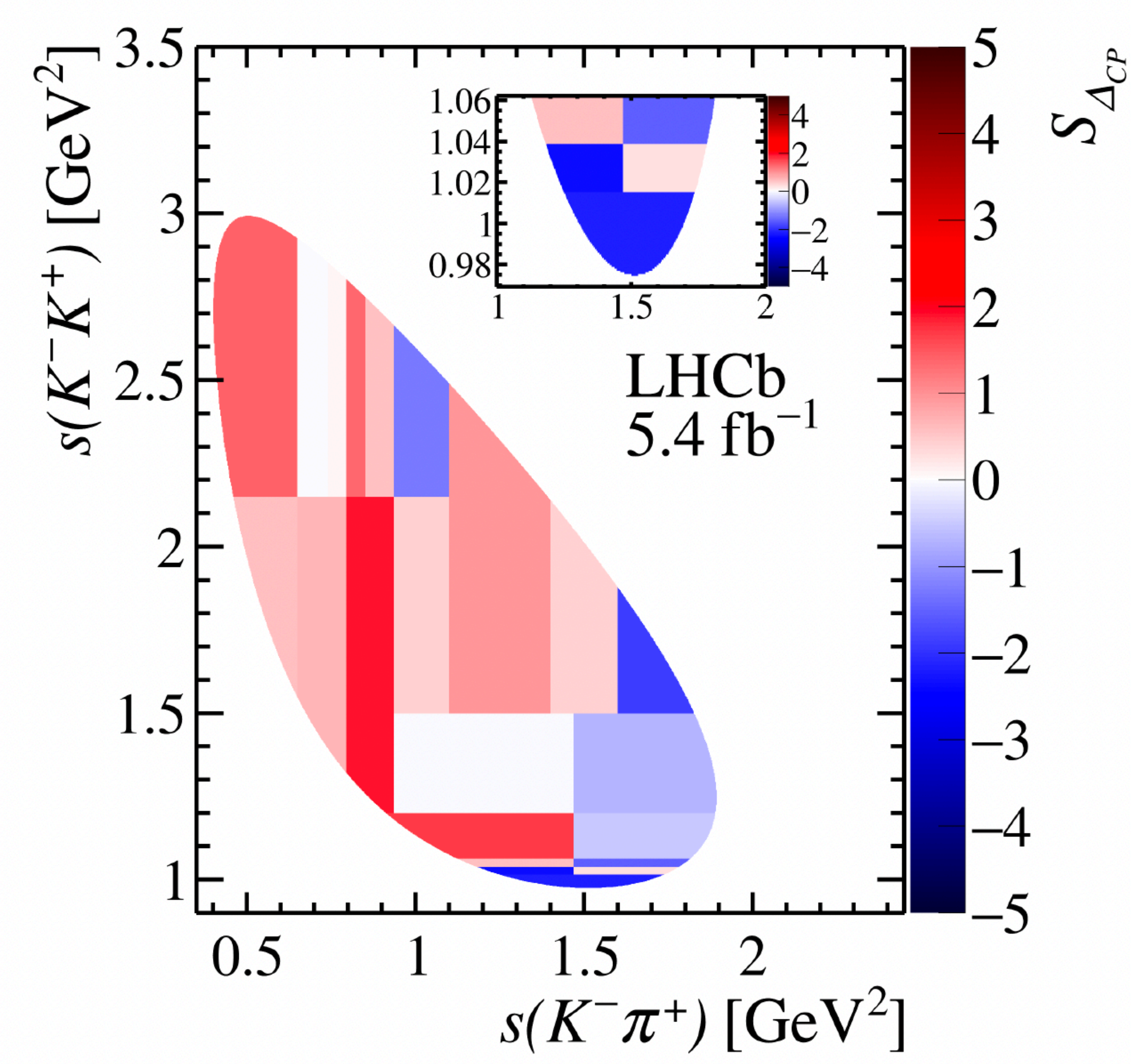
- ΔA^i_{CP} precision up to 10^{-3}

$$A^{\phi\pi^+}_{CP|S} = (0.95 \pm 0.43 \pm 0.26) \times 10^{-3}$$

$$A^{\bar{K}^{*0}K^+}_{CP|S} = (-0.26 \pm 0.56 \pm 0.18) \times 10^{-3}$$

- p-values (2.3-14.1%) compatible with absence of localised CP violation in Dalitz plot





Time-dependent CP violation in $D^0 \to K\pi$

LHCb-PAPER-2024-008

- Interference between mixing and decay for favoured RS and suppressed WS decays

$$R^{+}_{K\pi} = \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D^0} \to K^-\pi^+)}; \quad R^{-}_{K\pi} = \frac{\Gamma(\overline{D^0}(t) \to K^-\pi^+)}{\Gamma(D^0 \to K^+\pi^-)};$$

DCS over CF amplitude

$$R^{\pm}_{K\pi}(t) \approx \boxed{R_{K\pi}}(1 \pm A_{K\pi}) + R_{K\pi}(1 \pm A_{K\pi})(c_{K\pi} \pm \Delta c_{K\pi})\left(\frac{t}{\tau_{D^0}}\right) + (c'_{K\pi} \pm \Delta c'_{K\pi})\left(\frac{t}{\tau_{D^0}}\right)^2$$

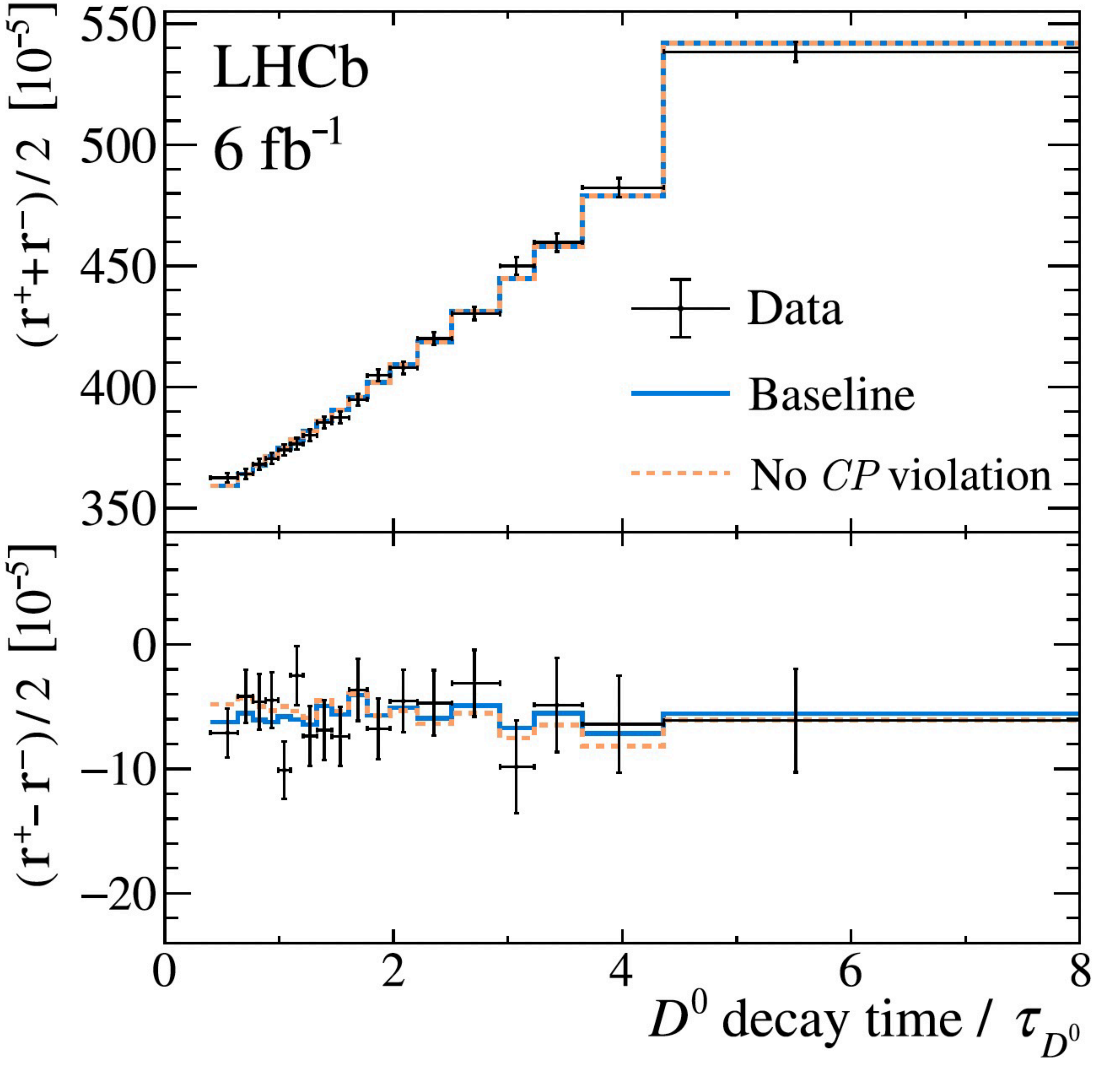
CPV observables: $A_{K\pi}$ (in decays), $\Delta c_{K\pi}$ (in interference), $\Delta c'_{K\pi}$ (in mixing).

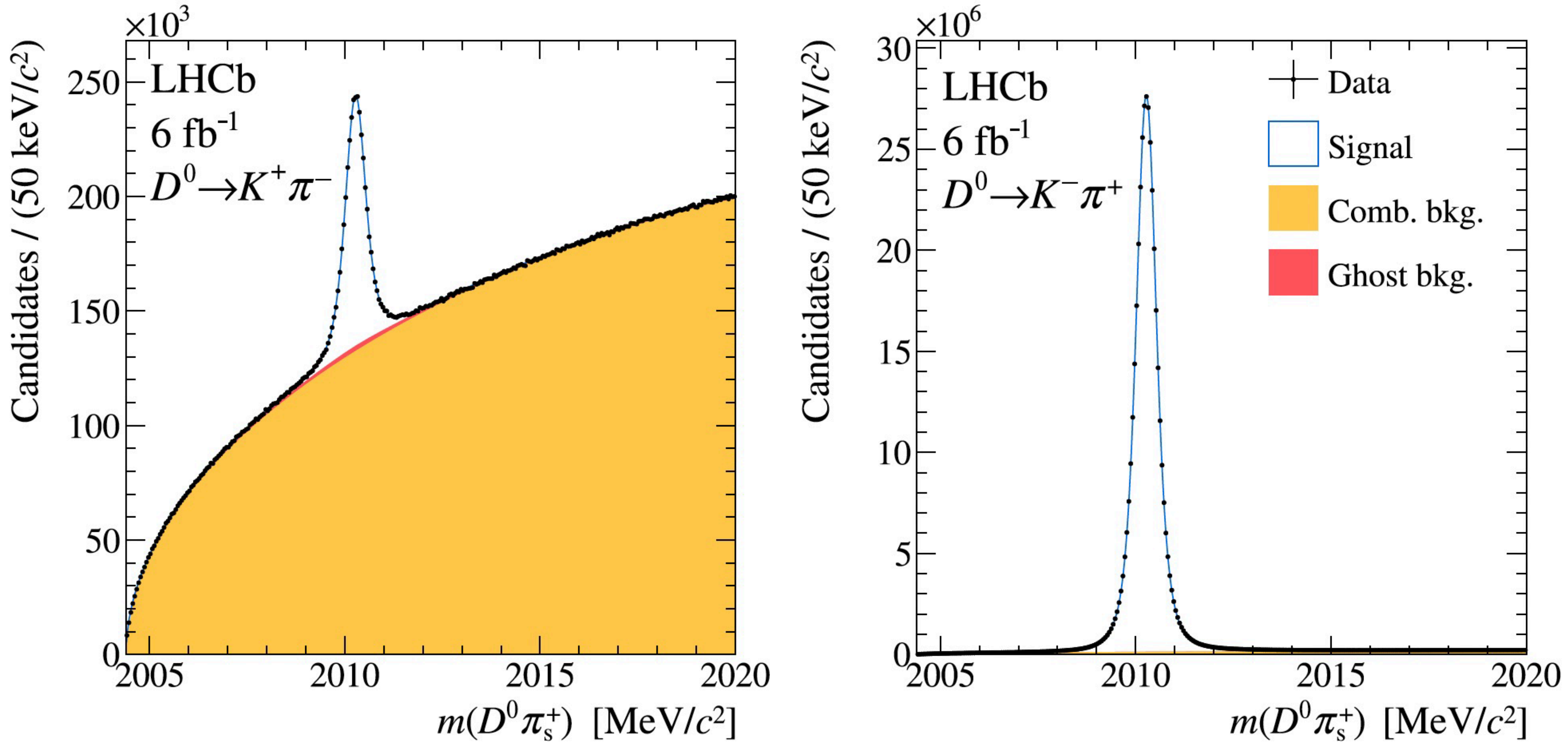
Mixing observables: $c_{K\pi}$, $c'_{K\pi}$

Time-dependent CP violation in $D^0 \to K\pi$

arXiv:2407.18001

- Measured with yields: RS ~400 M, WS ~1.6 M





$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$

Mixing parameter
Evidence of non 0

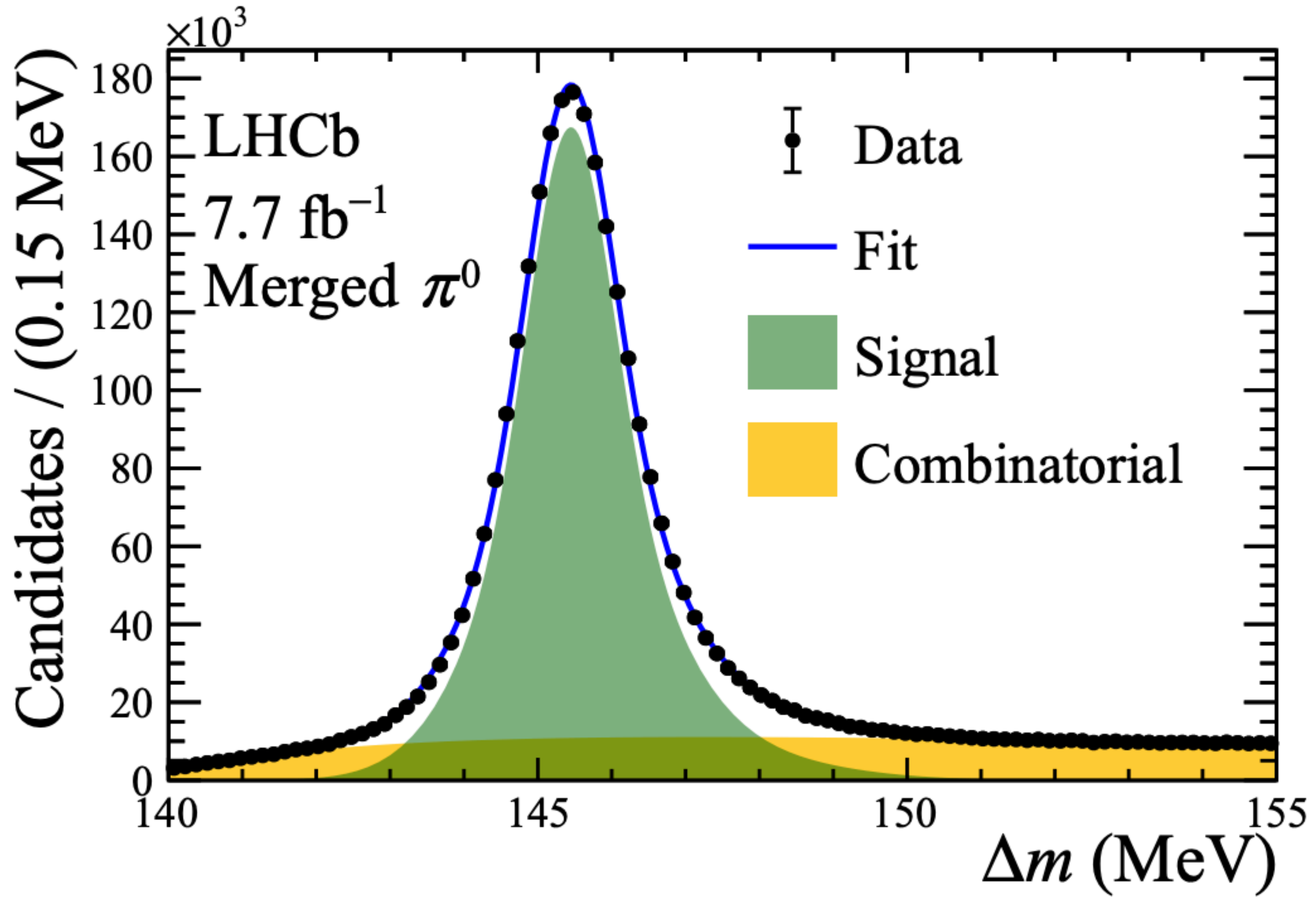
No CPV

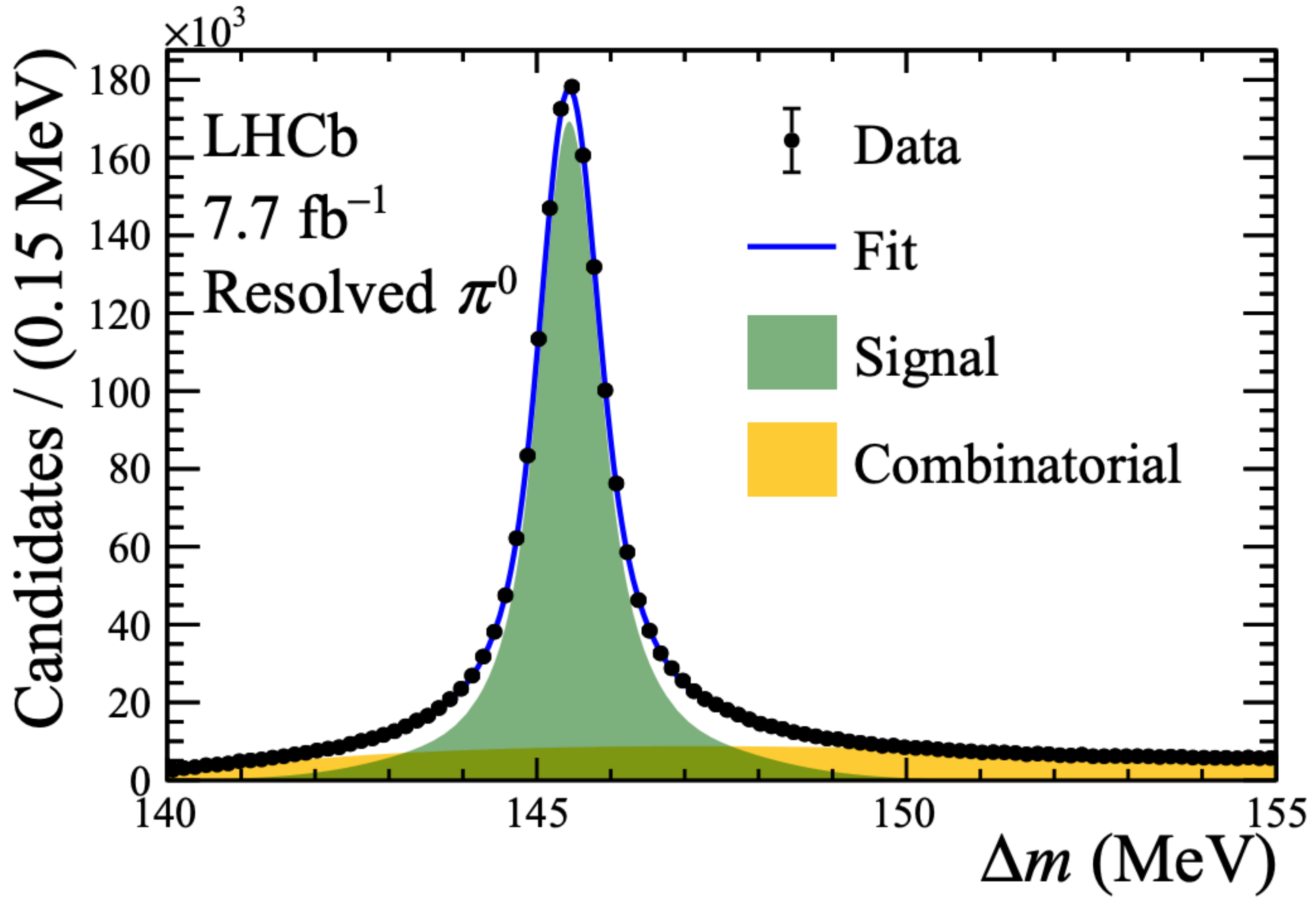
$$c_{K\pi} \approx y_{12} \cos\phi_f^\Gamma \cos\Delta_f + x_{12}\cos\phi_f^M \sin\Delta_f$$

Time-dependent CP violation in $D^0 \to \pi^+\pi^-\pi^0$

Phys. Rev. Lett. 133 (2024) 101803

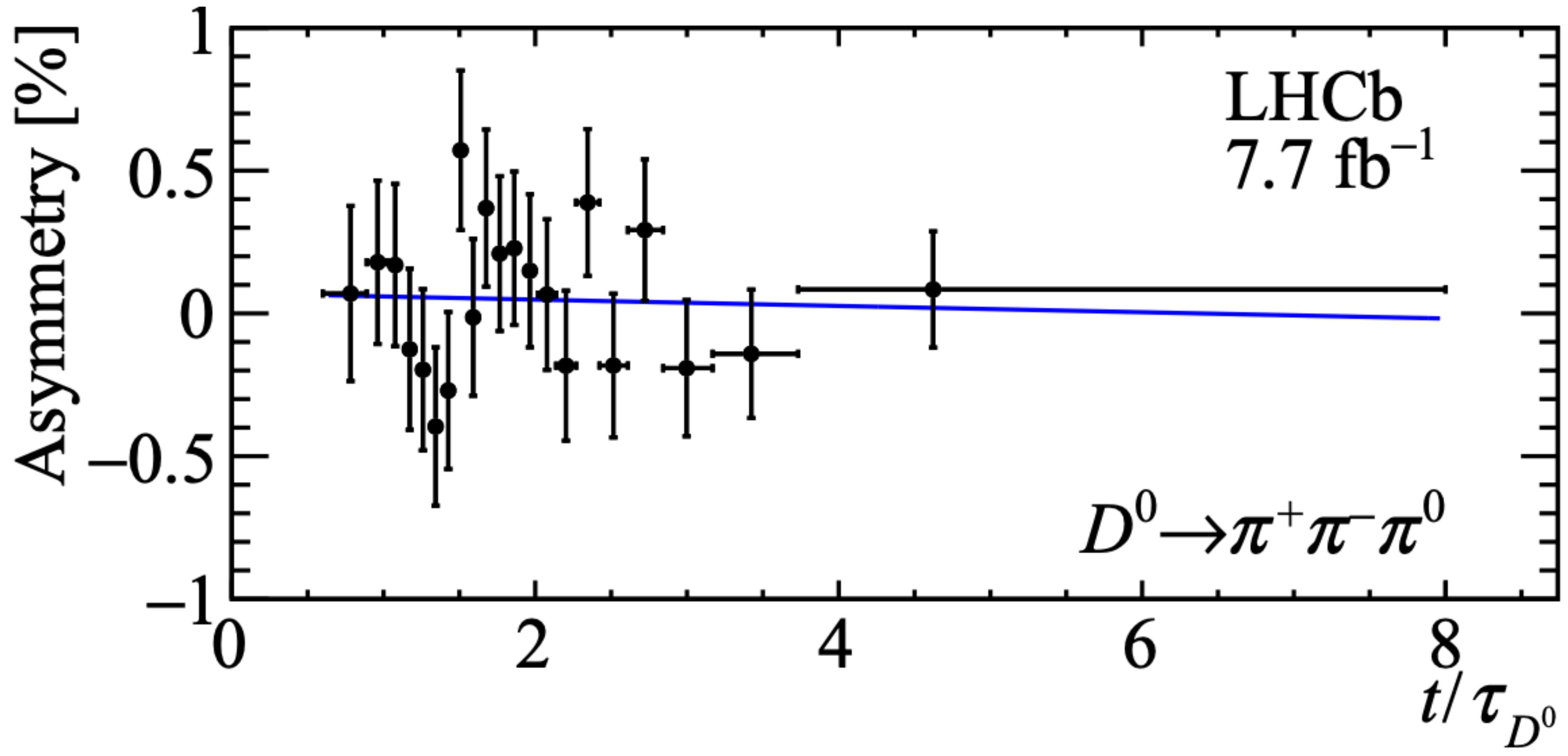
- First measurement of time-dependent CP violation in SCS mode





$$A_{CP}(f_{CP}, t) \equiv \frac{\Gamma_{D^0\to f_{CP}}(t) - \Gamma_{\bar{D}^0\to f_{CP}}(t)}{\Gamma_{D^0\to f_{CP}}(t) + \Gamma_{\bar{D}^0\to f_{CP}}(t)} \approx a^{\text{dir}}_{f_{CP}} + \Delta Y_{f_{CP}} \frac{t}{\tau_{D^0}}.$$

$$A_{\text{meas}}(\langle t/\tau_{D^0}\rangle_i) \equiv \frac{N^i_{D^0} - N^i_{\bar{D}^0}}{N^i_{D^0} + N^i_{\bar{D}^0}}$$



$$\Delta Y_{f_{CP}} \approx \frac{\eta_{f_{CP}}}{2}\left[\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi\right]$$

- No evidence for time-dependent CP violation, constant with world average

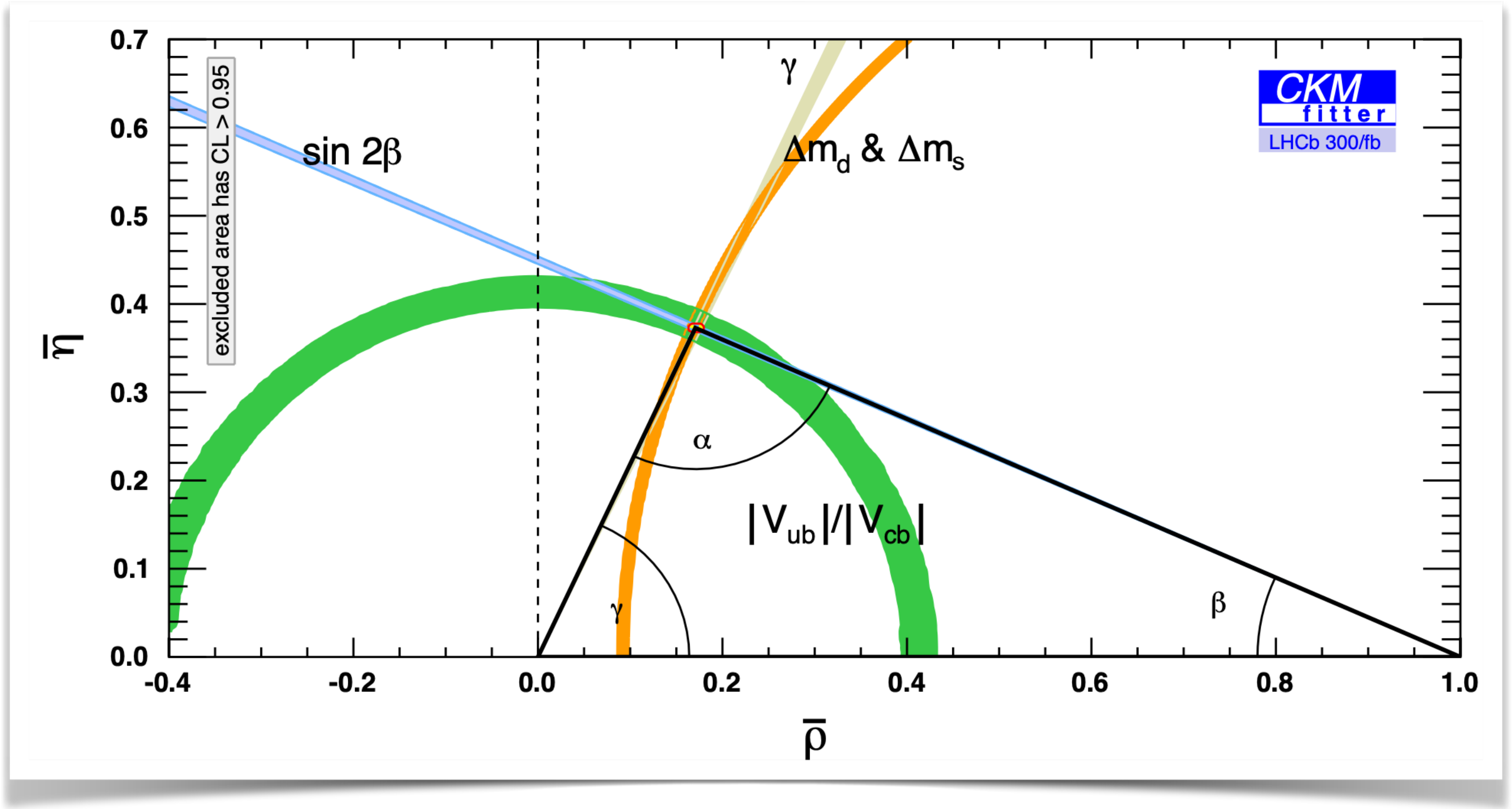
$$\Delta Y \equiv \eta_{CP}\Delta Y_{f_{CP}} = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$$

Looking at Run 3 and beyond

LHCb-PUB-2018-009

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1<q^2<6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	
R_{K^*} $(1<q^2<6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	
CKM tests					
γ, with $B_s^0 \to D_s^+K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
$a_{\rm sl}^s$	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
Charm					
$\Delta A_{CP}(KK-\pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x\sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x\sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x\sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

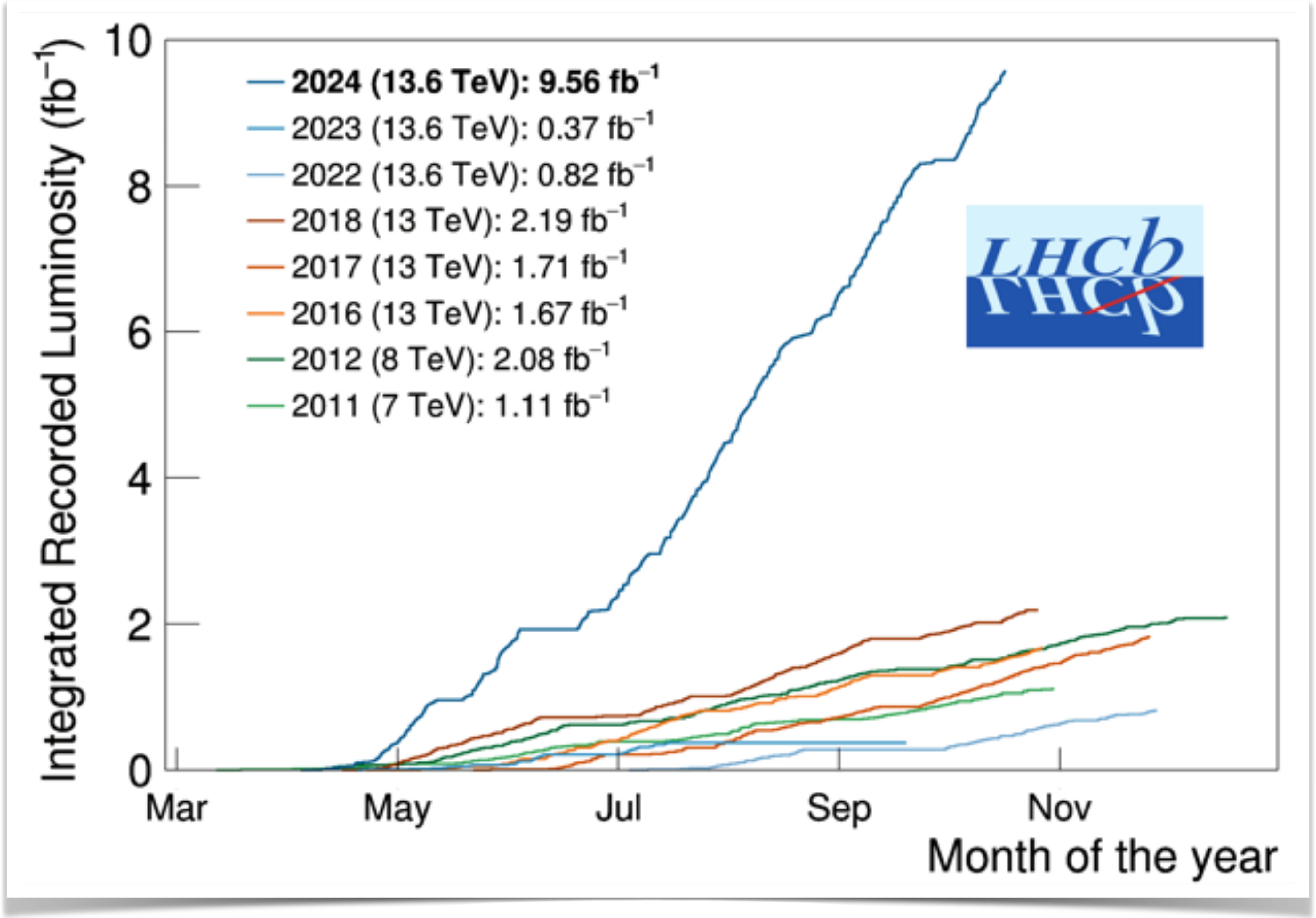
Great opportunities for much more precise measurements and NP searches

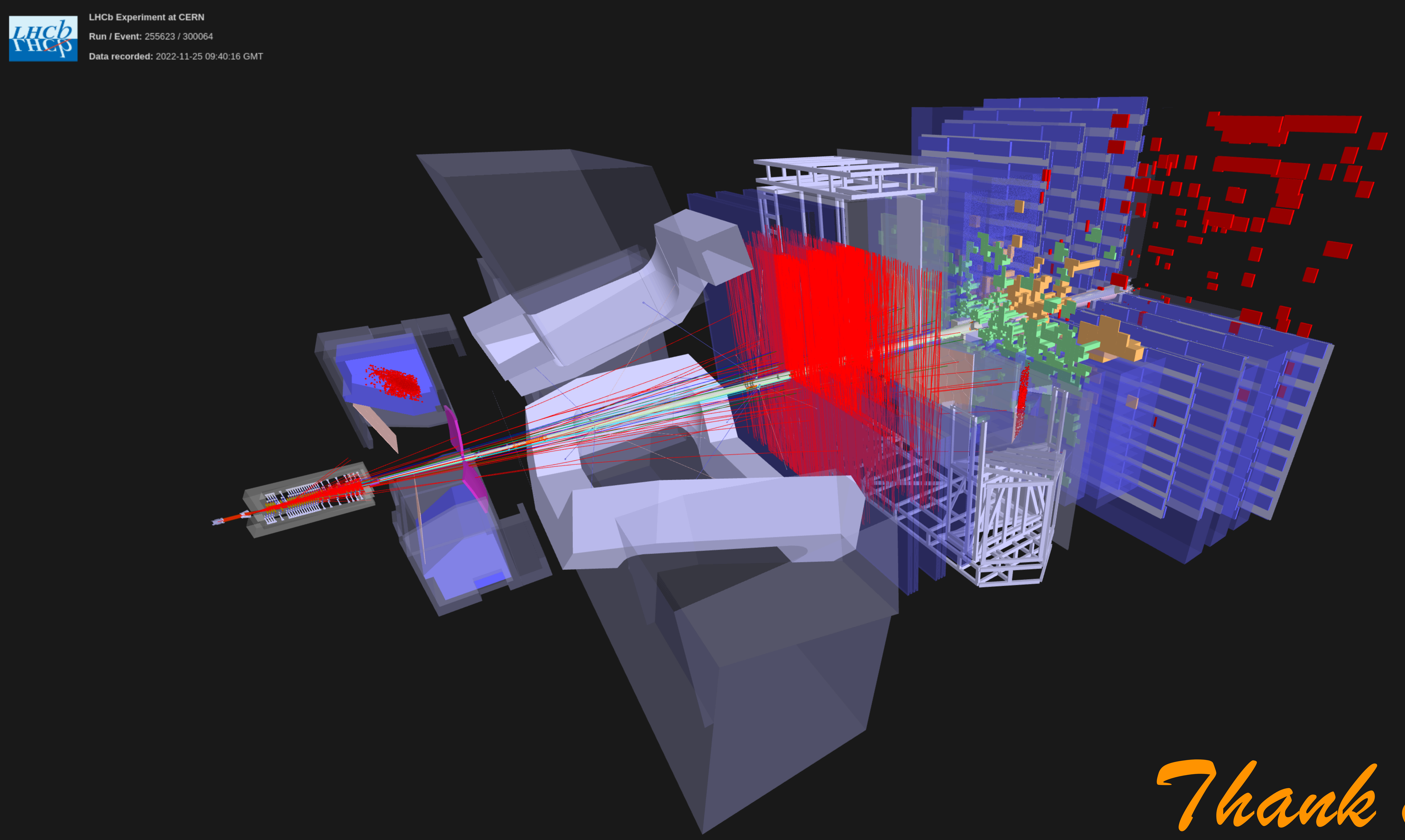


Summary

- ✓ LHCb dominates the world average of many measurements in CKM and CPV
- ✓ Various measurement of CP violation in $B^0_{(s)}$ and D^0 decays with LHCb Run 1+2 data samples, providing the most precise results
- ✓ Run 3 is running, looking forward to further test of the SM and search for new physics

Run 3 has collected more data than Run 1+2, a lot of new results to come!




LHCb Experiment at CERN
Run / Event: 255623 / 300064
Data recorded: 2022-11-25 09:40:16 GMT

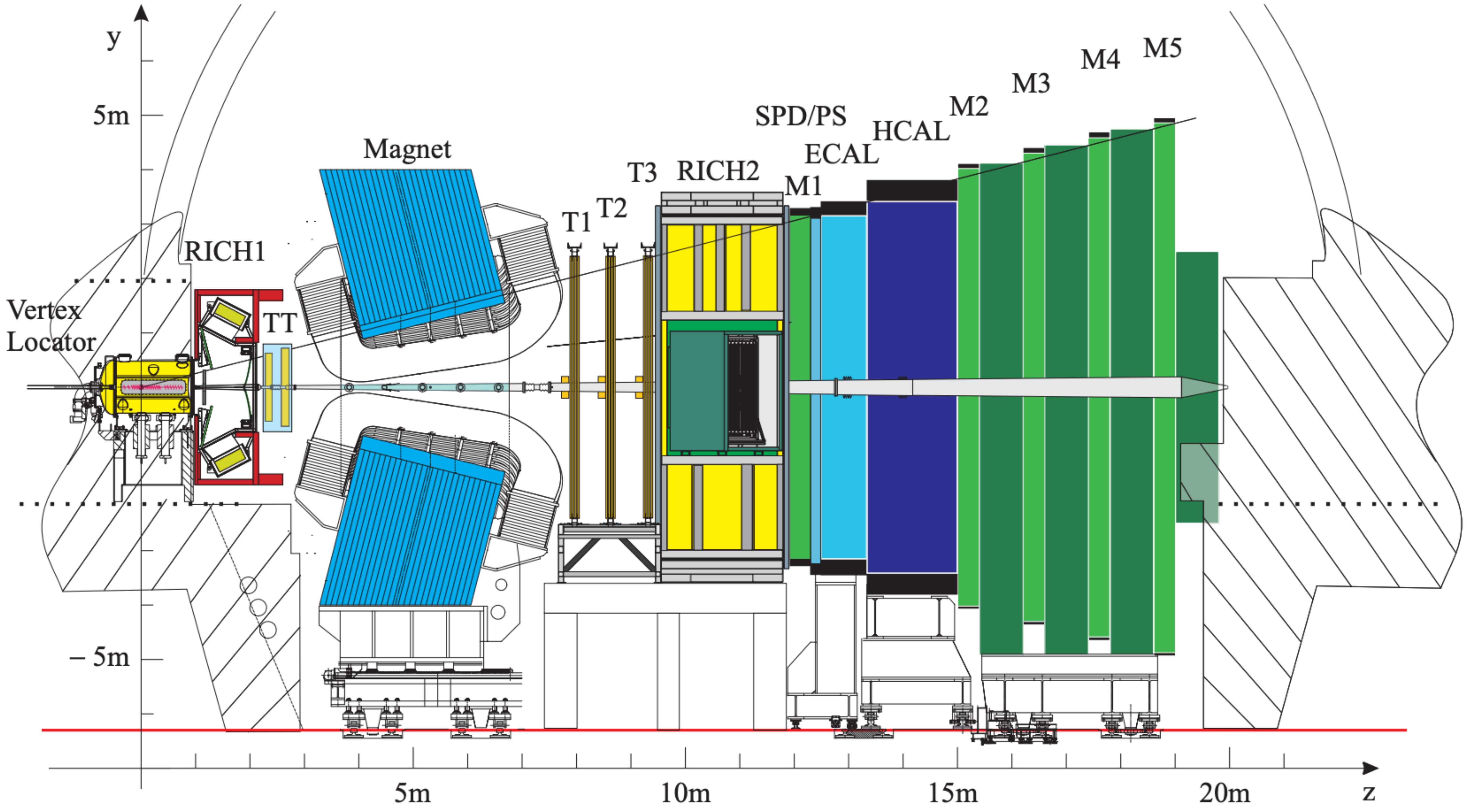
Thank you

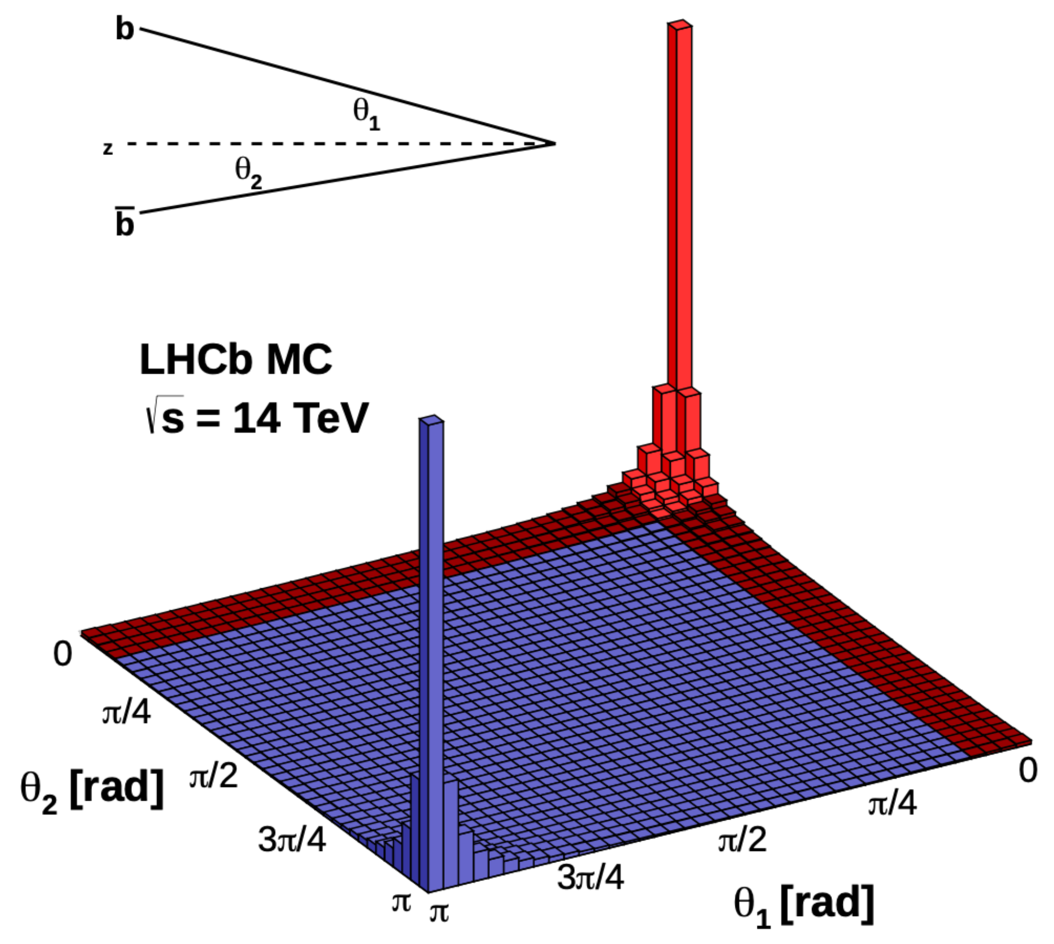
Back up slides

LHCb detector

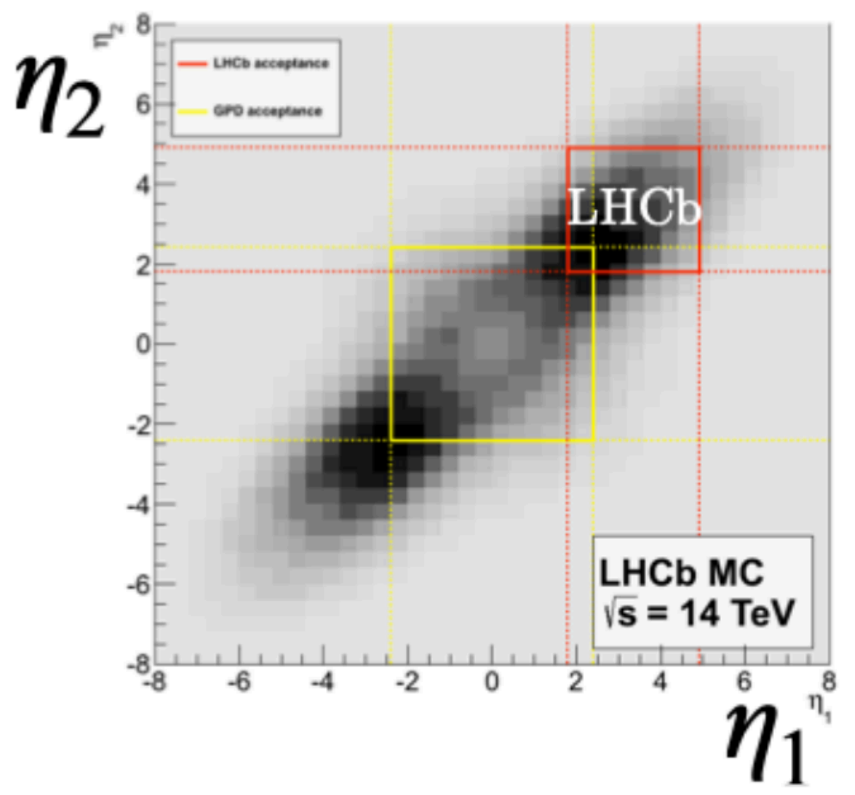
General purpose detector specialised in beauty and charm hadrons

proton beam





$2 < \eta < 5$

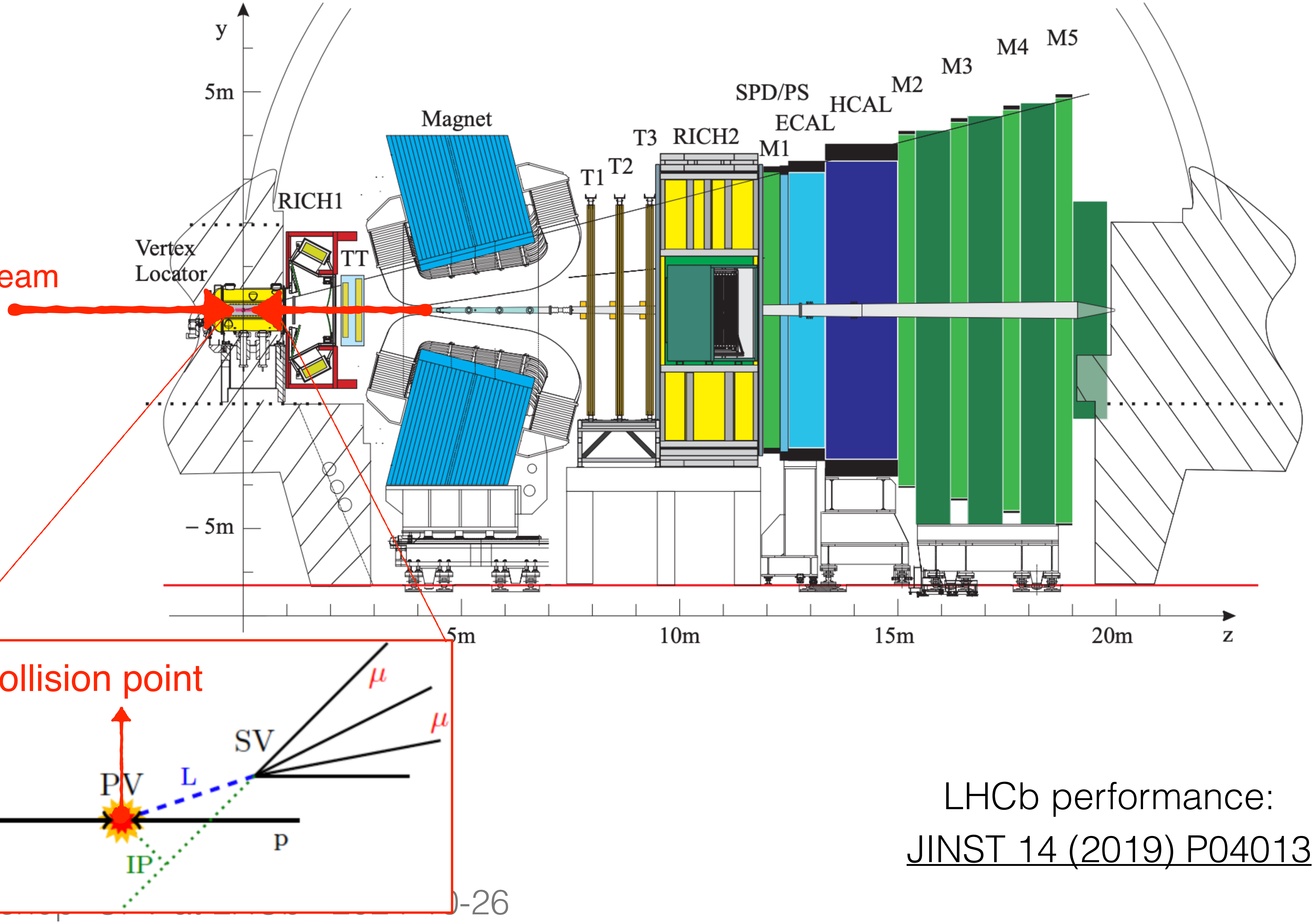


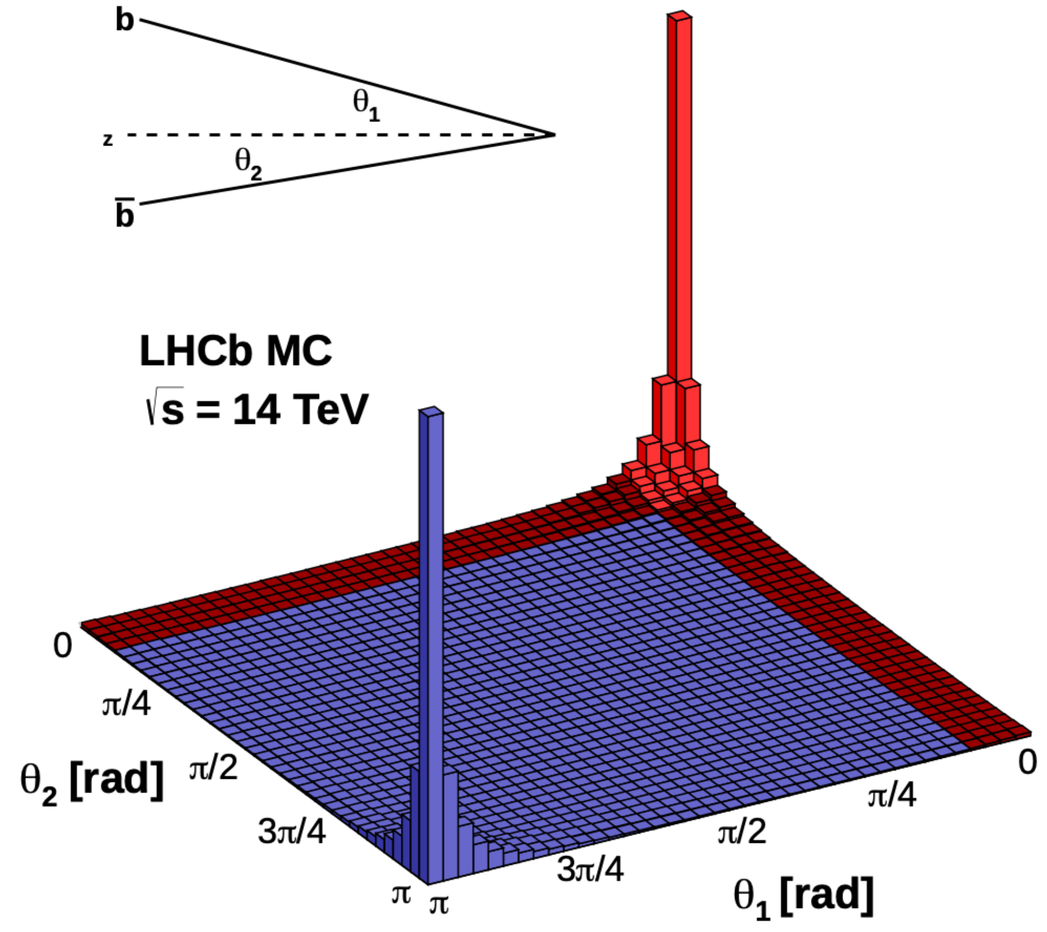
LHCb performance:
JINST 14 (2019) P04013

LHCb detector

General purpose detector specialised in beauty and charm hadrons

- Daughters of b & c hadron decays: $p_T \sim \mathcal{O}(1\ \mathrm{GeV}/c)$, flight distance L~1mm





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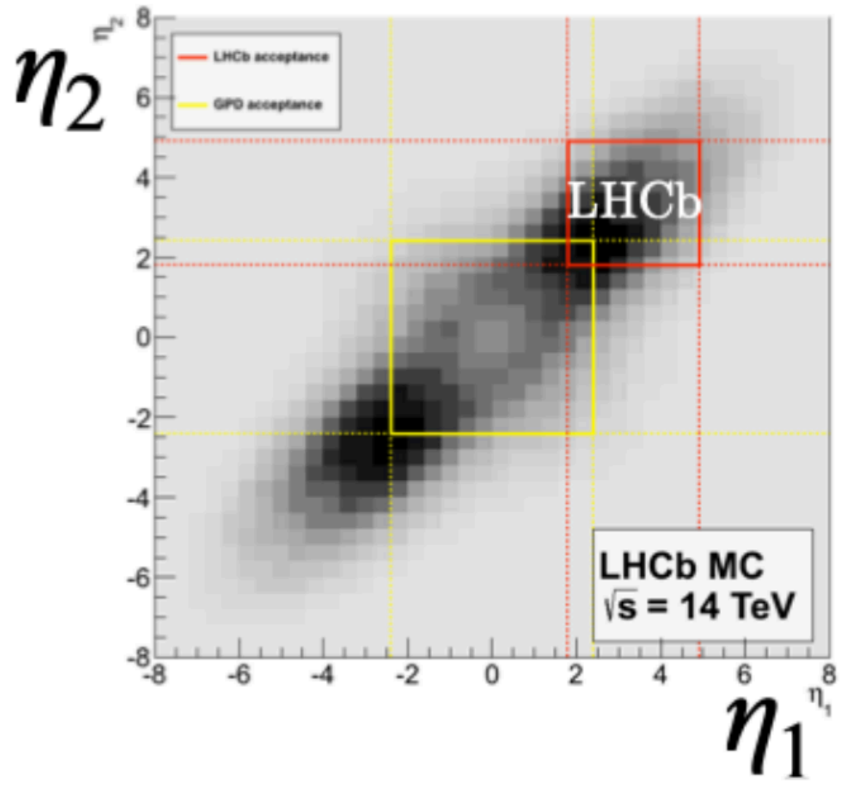

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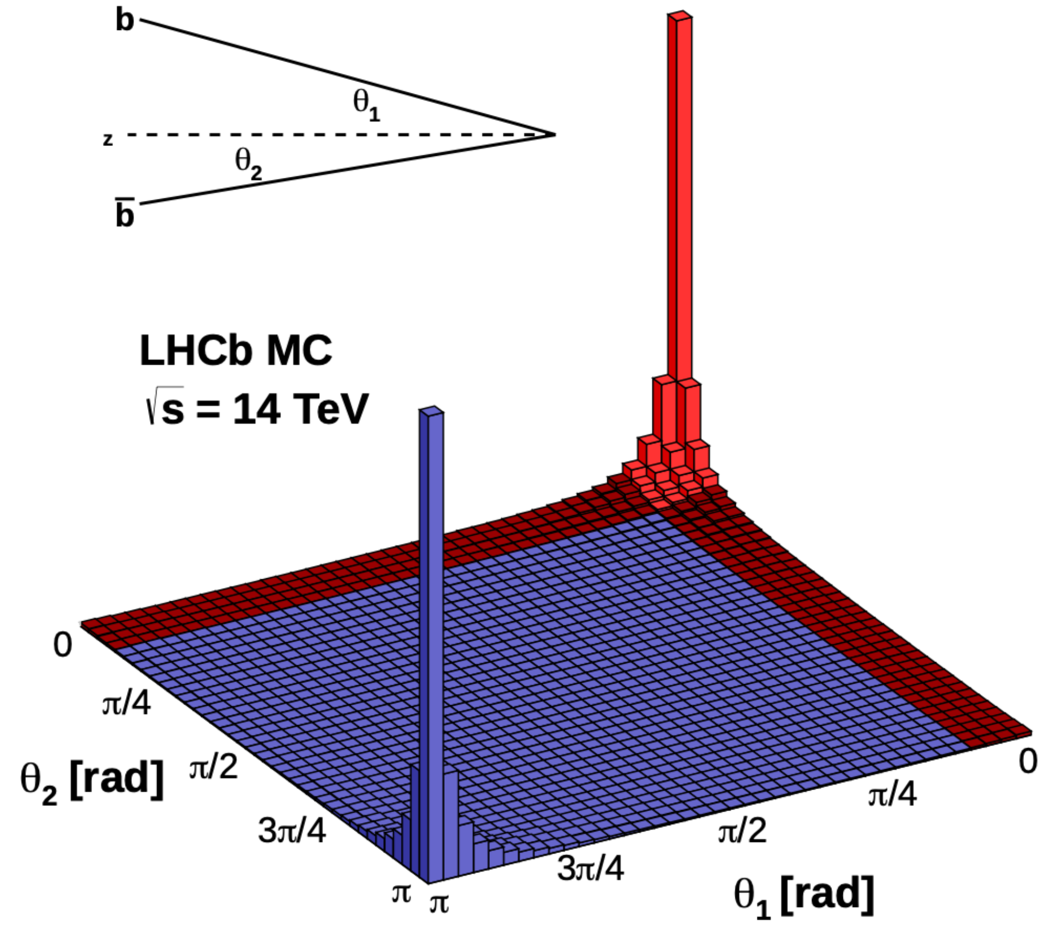
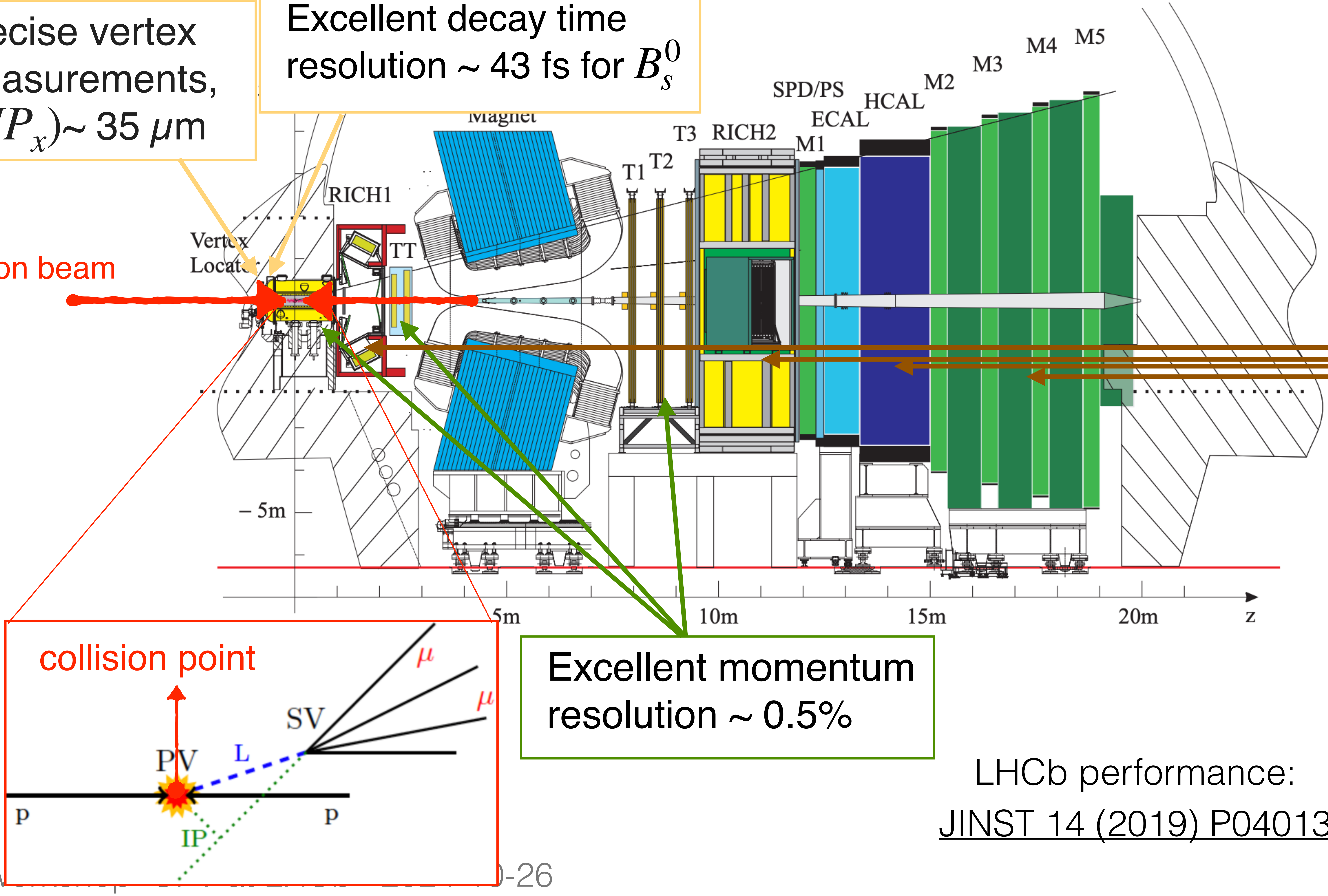


$2 < \eta < 5$

Precise vertex measurements, $\sigma(IP_x)$~ 35 μm

Excellent decay time resolution ~ 43 fs for B_s^0



Excellent particle identification

$\epsilon(K) \approx 95\,\%$

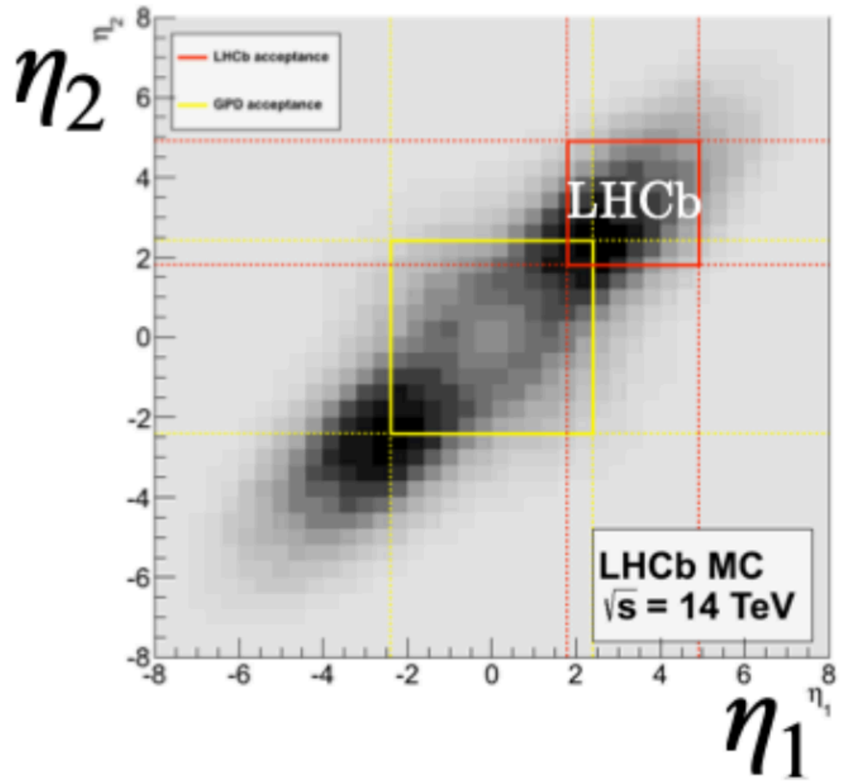
misID $p(\pi \to K) \approx 5\,\%$

$\epsilon(\mu) \approx 97\,\%$

Excellent momentum resolution ~ 0.5%

LHCb performance:

JINST 14 (2019) P04013

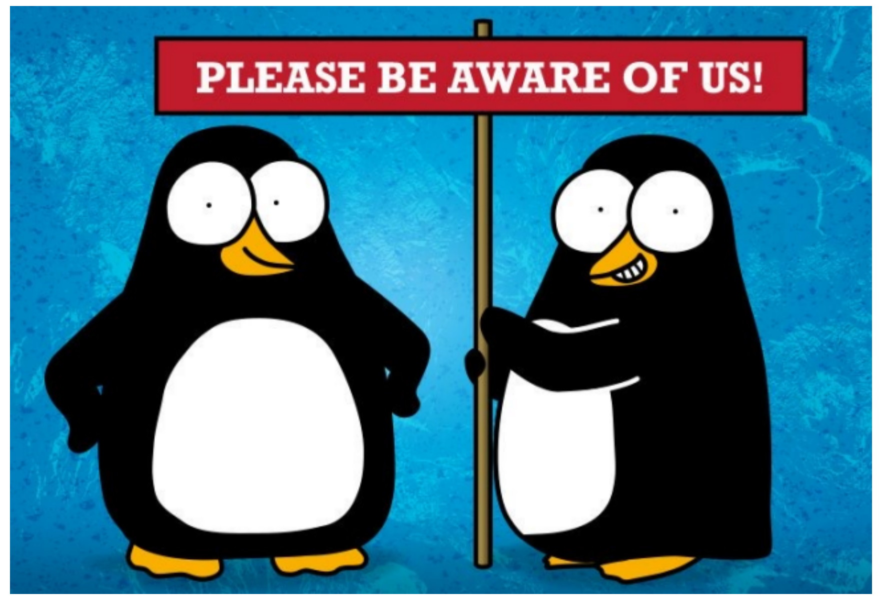


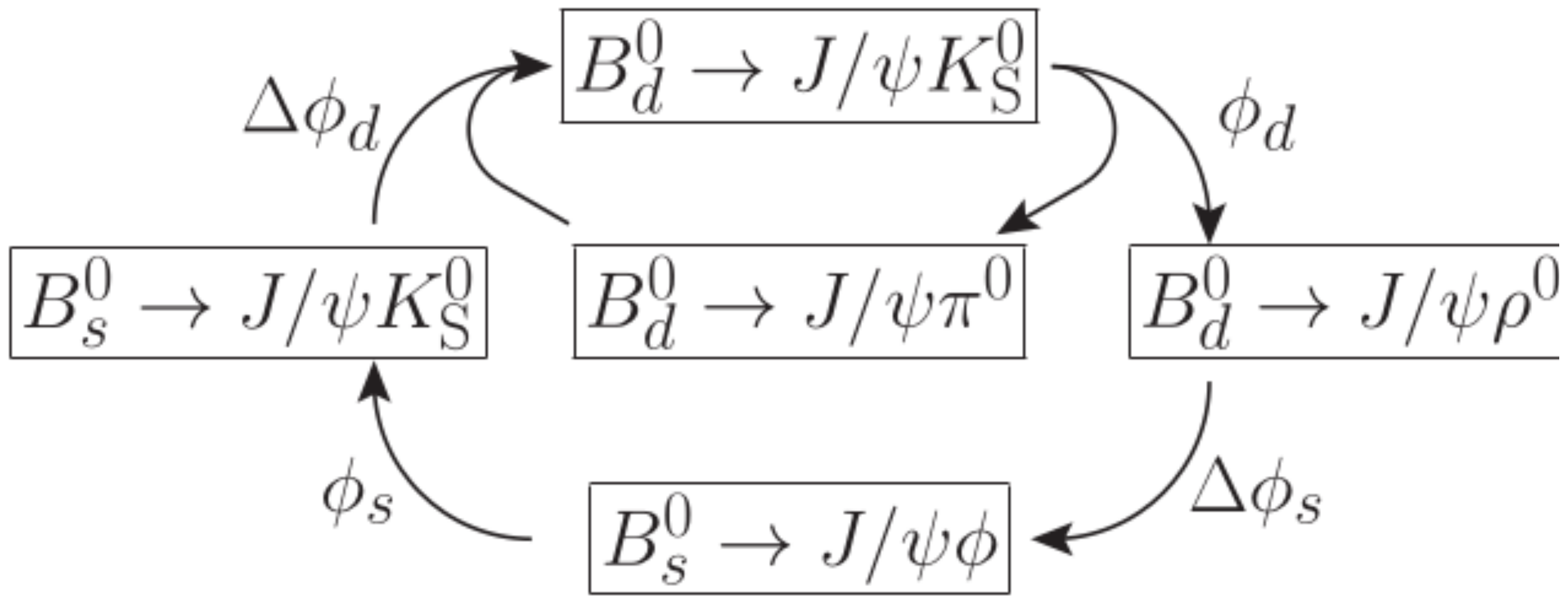
Control of penguin contribution

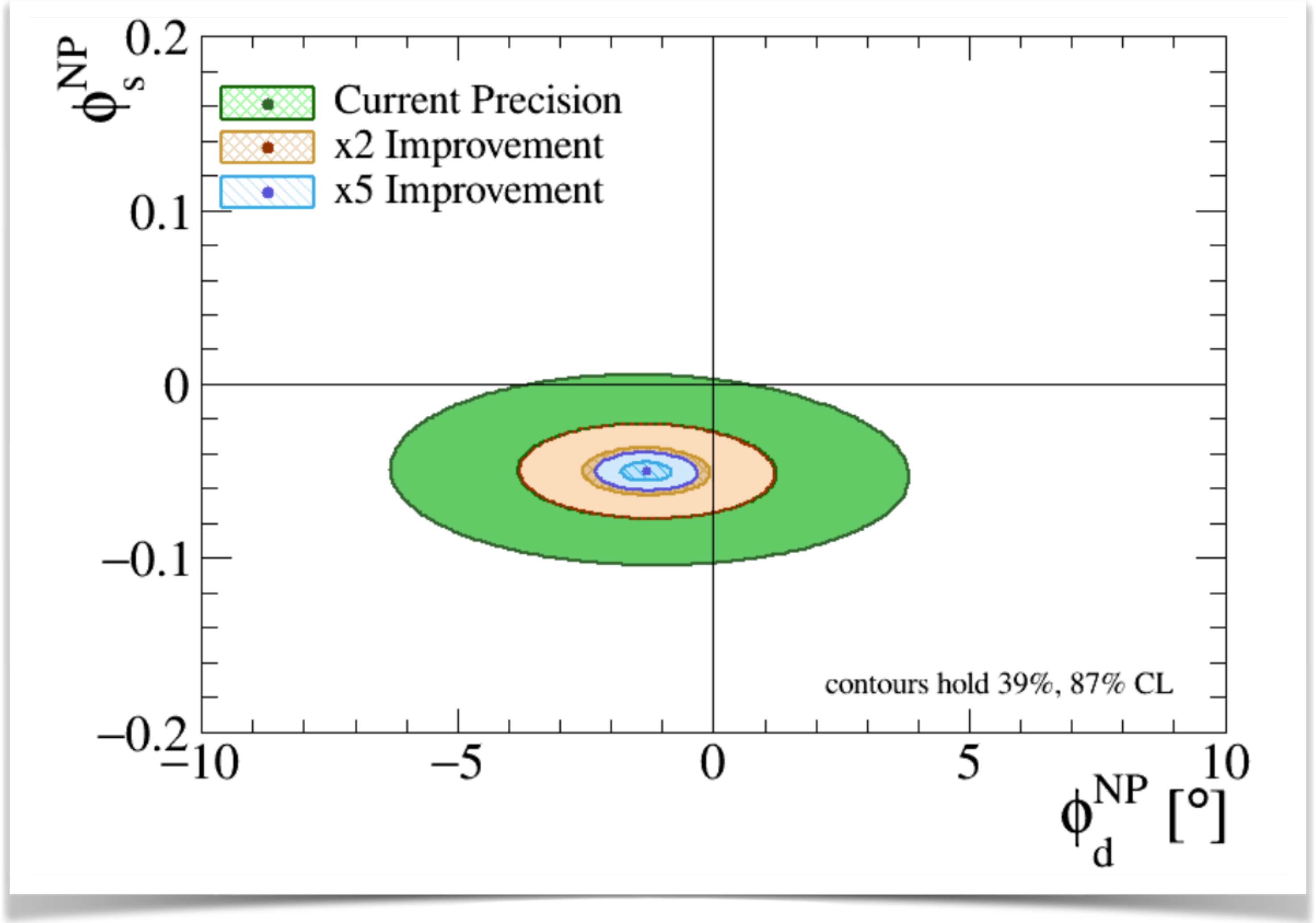
- $\sigma(\phi_s) \sim 0.016$ comparable with the theoretical estimation of $\Delta\phi_s^{penguin} \sim 1^\circ \approx 0.017$, better control of penguin effect necessary
- Combined analysis of penguin contributions in ϕ_s and ϕ_d $(\sin 2\beta)$, using SU(3) flavour symmetry

$$\phi_d = \sin(2\beta^{\text{tree}}) + \Delta\phi_d{}^{\text{penguin}} + \phi_d{}^{\text{NP}}$$

$$\phi_s = \phi_s^{\text{tree}} + \Delta\phi_s^{\text{penguin}} + \phi_s^{NP}$$







J.Phys.G 48 (2021) 6, 065002

Method to measure ΔA^{CP}

- CP asymmetries

$$A^{CP}(B^{\mp} \to J/\psi\pi^{\mp}) = a^{\rm raw}(B^{\mp} \to J/\psi\pi^{\mp}) - a^{\rm prod}(B^{\mp}) - a^{\rm det}(\pi^{\mp}) - a^{\rm PID}(\pi^{\mp})$$
$$A^{CP}(B^{\mp} \to J/\psi K^{\mp}) = a^{\rm raw}(B^{\mp} \to J/\psi K^{\mp}) - a^{\rm prod}(B^{\mp}) - a^{Det}(K^{\mp}) - a^{\rm PID}(K^{\mp})$$

Raw asymmetries from mass fit

Production asymmetries largely cancelled

Detection asymmetries from D^+ control data

PID asymmetries from PIDCorr

- CP asymmetry difference

$$\Delta A^{CP} \equiv A^{CP}(B^{\mp} \to J/\psi\pi^{\mp}) - A^{CP}(B^{\mp} \to J/\psi K^{\mp})$$
$$= \Delta a^{\rm raw} - \Delta a^{\rm prod} - \Delta a^{\rm det} - \Delta a^{\rm PID}$$

credit: Manshu Li

γ measurements

B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^{\pm} \to Dh^{\pm}$	$D \to h^{\pm}h'^{\mp}$	[35]	Run 1&2	*As before*
$B^{\pm} \to Dh^{\pm}$	$D \to h^{+}h^{-}\pi^{+}\pi^{-}$	[19]	Run 1&2	**New**
$B^{\pm} \to Dh^{\pm}$	$D \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$	[36]	Run 1&2	*As before*
$B^{\pm} \to Dh^{\pm}$	$D \to h^{\pm}h'^{\mp}\pi^{0}$	[37]	Run 1&2	*As before*
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S h^{+}h^{-}$	[38]	Run 1&2	*As before*
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S K^{\pm}\pi^{\mp}$	[39]	Run 1&2	*As before*
$B^{\pm} \to D^{*}h^{\pm}$	$D \to h^{\pm}h'^{\mp}$ (PR)	[35]	Run 1&2	*As before*
$B^{\pm} \to D^{*}h^{\pm}$	$D \to K^0_S h^{+}h^{-}$ (PR)	[20]	Run 1&2	**New**
$B^{\pm} \to D^{*}h^{\pm}$	$D \to K^0_S h^{+}h^{-}$ (FR)	[21]	Run 1&2	**New**
$B^{\pm} \to DK^{*\pm}$	$D \to h^{\pm}h'^{\mp}$	[22]†	Run 1&2	**Updated**
$B^{\pm} \to DK^{*\pm}$	$D \to h^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$	[22]†	Run 1&2	**Updated**
$B^{\pm} \to DK^{*\pm}$	$D \to K^0_S h^{+}h^{-}$	[22]†	Run 1&2	**New**
$B^{\pm} \to Dh^{\pm}\pi^{+}\pi^{-}$	$D \to h^{\pm}h'^{\mp}$	[40]	Run 1	*As before*
$B^{0} \to DK^{*0}$	$D \to h^{\pm}h'^{\mp}$	[23]	Run 1&2	**Updated**
$B^{0} \to DK^{*0}$	$D \to h^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$	[23]	Run 1&2	**Updated**
$B^{0} \to DK^{*0}$	$D \to K^0_S h^{+}h^{-}$	[24]	Run 1&2	**Updated**
$B^{0} \to D^{\mp}\pi^{\pm}$	$D^{+} \to K^{-}\pi^{+}\pi^{+}$	[41]	Run 1	*As before*
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^{+} \to h^{+}h^{-}\pi^{+}$	[25, 42]†	Run 1&2	**Updated**
$B^0_s \to D_s^{\mp}K^{\pm}\pi^{+}\pi^{-}$	$D_s^{+} \to h^{+}h^{-}\pi^{+}$	[43]	Run 1&2	*As before*

D decay	Observable(s)	Ref.	Dataset	Status since Ref. [14]
$D^0 \to h^{+}h^{-}$	ΔA_{CP}	[44–46]	Run 1&2	*As before*
$D^0 \to K^{+}K^{-}$	$A_{CP}(K^{+}K^{-})$	[46–48]	Run 2	*As before*
$D^0 \to h^{+}h^{-}$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[49, 50]	Run 1&2	*As before*
$D^0 \to h^{+}h^{-}$	ΔY	[51–54]	Run 1&2	*As before*
$D^0 \to K^{+}\pi^{-}$ (double tag)	$R^{\pm}$, $(x'^{\pm})^2$, $y'^{\pm}$	[55]	Run 1	*As before*
$D^0 \to K^{+}\pi^{-}$ (single tag)	$R_{K\pi}$, $A_{K\pi}$, $c_{K\pi}^{(\prime)}$, $\Delta c_{K\pi}^{(\prime)}$	[27, 56]	Run 1&2	**Updated**
$D^0 \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$	$(x^2+y^2)/4$	[57]	Run 1	*As before*
$D^0 \to K^0_S\pi^{+}\pi^{-}$	x, y	[58]	Run 1	*As before*
$D^0 \to K^0_S\pi^{+}\pi^{-}$	x_{CP}, y_{CP}, Δx, Δy	[59]	Run 1	*As before*
$D^0 \to K^0_S\pi^{+}\pi^{-}$	x_{CP}, y_{CP}, Δx, Δy	[60, 61]	Run 2	*As before*
$D^0 \to \pi^{+}\pi^{-}\pi^{0}$	ΔY^{eff}	[26]	Run 2	**New**