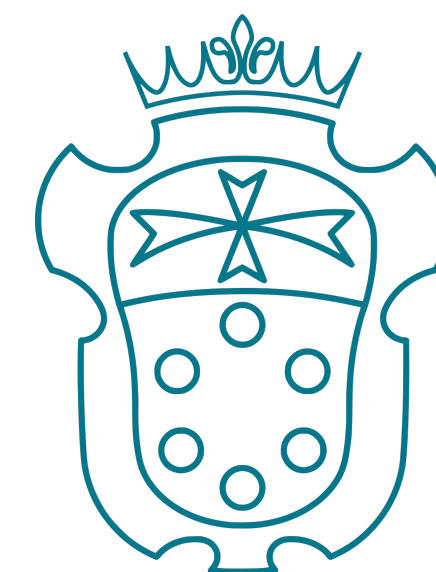


Charm physics: experimental status and perspectives

Fourth Italian Workshop on Physics at High Intensity (WIFAI)

Michael J. Morello

Bari, November 11, 2025



SCUOLA
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Istituto Nazionale di Fisica Nucleare

Quantum oscillations

Phenomenological parametrization

$$\mathbf{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$$

$$\mathbf{M} \equiv (\mathbf{H} + \mathbf{H}^\dagger)/2 \text{ and } \mathbf{\Gamma} \equiv i(\mathbf{H} - \mathbf{H}^\dagger)$$

$\mathbf{M}$ (dispersive) and $\mathbf{\Gamma}$ (absorptive) are 2×2 hermitian matrices

$|M^0\rangle$ and $|\bar{M}^0\rangle$ basis

Normalized eigenstates of $\mathbf{H}$

$$|M_1\rangle \equiv p |M^0\rangle + q |\bar{M}^0\rangle$$

$$|M_2\rangle \equiv p |M^0\rangle - q |\bar{M}^0\rangle$$

Schrödinger equation

$$i \frac{d}{dt} \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

Diagonalization condition

$$\left(\frac{q}{p}\right)^2 = \frac{H_{21}}{H_{12}} = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}.$$

Time evolution

$$\Rightarrow |M_{1,2}(t)\rangle = e^{-i\omega_{1,2}t} |M_{1,2}(0)\rangle$$

$$\omega_{1,2} \equiv M_{1,2} - \frac{i}{2}\Gamma_{1,2}$$

CPV in mixing

$$\left|\frac{q}{p}\right| \neq 1$$

If CP is violated 5 physics observables : $M = \frac{M_1 + M_2}{2}$, $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$, $x = \frac{M_2 - M_1}{2\Gamma}$, $y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$, and $\left|\frac{q}{p}\right|$.
(CPT symmetry assumed)

Note that $\phi = \arg(q/p)$ is not a physics observable. A choice convention needed to solve the ambiguity in the definition of $|M_1\rangle$ and $|M_2\rangle$, usually one assumes $y > 0$. Necessary also to solve another ambiguity due to the relative sign between phases of p and q . This depends on the convention of CP transformation of M^0 and $\bar{M}^0$ mesons.

Quantum oscillations

Theoretical parametrization

$$M = \frac{M_1 + M_2}{2} = M_{11} = M_{22}$$

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2} = \Gamma_{11} = \Gamma_{22}$$

An alternative parametrization which is **convention-independent** and quantifies directly the magnitudes and the phase difference between the dispersive and absorptive transition amplitudes is used. In particular, the theoretical mixing parameters and the mixing phase are defined as

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

They are all observable quantities. While x_{12} and y_{12} are *CP*-even observables, ϕ_{12} is a *CP*-odd weak phase.

The theoretical and phenomenological mixing parameters are related as

$$\begin{aligned} x^2 - y^2 &= x_{12}^2 - y_{12}^2, \\ xy &= x_{12}y_{12} \cos \phi_{12}, \\ \left| \frac{q}{p} \right|^{\pm 2} (x^2 + y^2) &= x_{12}^2 + y_{12}^2 \pm 2x_{12}y_{12} \sin \phi_{12}, \end{aligned} \quad \begin{array}{c} \left| \frac{q}{p} \right| \approx 1 \\ \text{experimentally} \\ \Longrightarrow \end{array} \quad \begin{aligned} x_{12} &\approx |x| \text{ and } y_{12} \approx |y| \\ \left| \frac{q}{p} \right| - 1 &\approx \frac{x_{12}y_{12}}{x_{12}^2 + y_{12}^2} \sin \phi_{12} \end{aligned}$$

Up to quadratic correction in $\sin \phi_{12}$

Phenomenological vs Theoretical

- They are fully equivalent, and choosing one or the other is mostly a matter of personal taste.
- For mixing, the observable parameters are always tree:

$$\lambda_f^\Gamma = \frac{\Gamma_{12}}{|\Gamma_{12}|} \frac{A_f}{\bar{A}_f}$$

$$\lambda_f^M = \frac{M_{12}}{|M_{12}|} \frac{A_f}{\bar{A}_f}$$

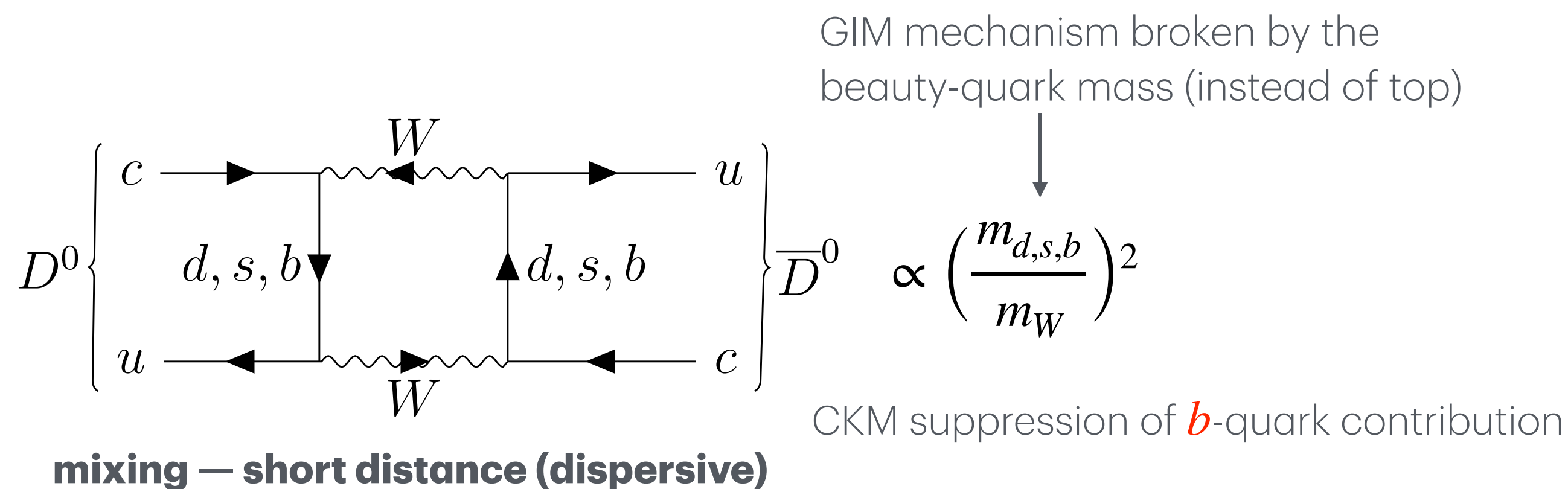
$$|y|, \frac{x}{y}, \left| \frac{q}{p} \right| \quad \text{vs} \quad x_{12}, y_{12}, \phi_{12}$$

- On the contrary $\phi^M \equiv \arg(M_{12})$ and $\phi^\Gamma \equiv \arg(\Gamma_{12})$, and $\arg(q/p)$ are not quark nor meson phasing invariant and thus they are not observable. Please note that $\phi^M - \phi^\Gamma = \phi_{12}$ is observable.
- $\phi_f^M \equiv \arg(\lambda_f^M)$ and $\phi_f^\Gamma \equiv \arg(\lambda_f^\Gamma)$ instead are observable because the phase conventions cancel out in the multiplication of M_{12} (or Γ_{12}) with the decay amplitudes, as it happens for $\phi_{\lambda_f} = \arg(q\bar{A}_f/pA_f)$.
- **Final state dependence currently neglected because of still large experimental uncertainties.**
- Note: if CP is conserved $\phi^M = \phi^\Gamma = \arg(q/p) \equiv \phi$ (and of course $\phi_{12} = 0$ and $|q/p| = 1$).

Charm Mixing

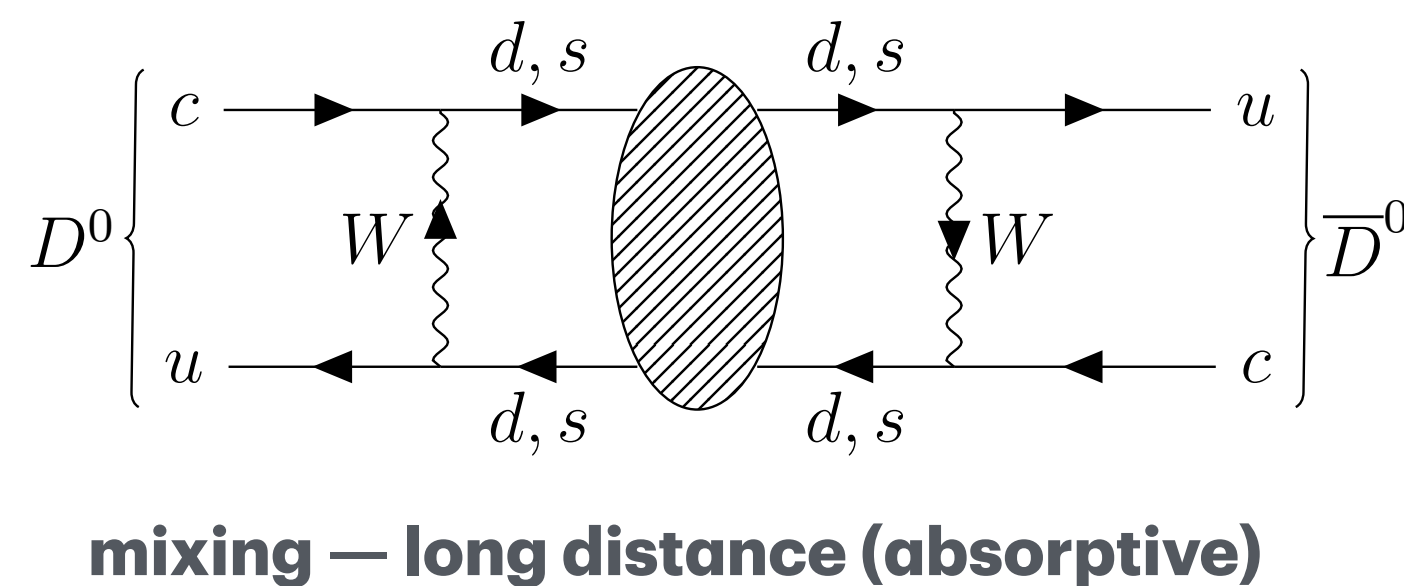
Phenomenology

Complementary to $\mathbf{K}$ and $\mathbf{B}$ mesons. FCNC are extremely suppressed



$$V_{\text{CKM}} = \begin{pmatrix} \text{d} & \text{s} & \text{b} \\ \begin{pmatrix} 1 - \frac{\lambda^2}{2} \\ -\lambda \end{pmatrix} & \begin{pmatrix} \lambda \\ 1 - \frac{\lambda^2}{2} \end{pmatrix} & \begin{pmatrix} A\lambda^3(\rho - i\eta) \\ A\lambda^2 \end{pmatrix} \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} \begin{matrix} u \\ c \\ t \end{matrix} + \mathcal{O}(\lambda^4)$$

$\lambda = \sin \theta_C \approx 0.23$



The 3rd quark generation nearly decouples from the first two, while the contributions from d and s quarks cancel out in the limit of U -spin symmetry ($m_d = m_s$)

$$x_{12} \simeq |x| = (0.4 \pm 0.05) \% \text{ (off-shell)}, y_{12} \simeq |y| \approx (0.621 \pm 0.022) \% \text{ (on-shell)}$$

Main contributions come from low-energy QCD interactions through on-shell resonances. **Theory predictions are very challenging.**

CP Violation in Charm Sector

Mixing and Interference

Only transitions of c quark to lighter quarks involved in charm meson decays, mixing and relevant amplitudes are therefore described, to an excellent approximation, by the physics of the first two generations only.

$$\Lambda_b \sim \mathcal{O}(\lambda^5) \quad \begin{array}{c} \Lambda_s \sim \mathcal{O}(\lambda) \\ \Lambda_d \sim \mathcal{O}(\lambda) \end{array}$$

$$V_{cd}^* V_{ud} + V_{cs}^* V_{us} + V_{cb}^* V_{ub} = 0$$

$$\Lambda_d = -\lambda + \frac{\lambda^3}{2} + \frac{\lambda^5}{8}(1 + 4A^2) - \lambda^5 A^2(\rho + i\eta) + \mathcal{O}(\lambda^7),$$

$$\Lambda_s = \lambda - \frac{\lambda^3}{2} - \frac{\lambda^5}{8}(1 + 4A^2) + \mathcal{O}(\lambda^7),$$

$$\Lambda_b = \lambda^5 A^2(\rho - i\eta) + \mathcal{O}(\lambda^{11}), \quad \Lambda_q = V_{cq}^* V_{uq} \quad (q \in d, s, b)$$

$$\lambda_{cu}^q \equiv \Lambda_q$$

SM expectations are naively of the order of

$$\text{Im}\left(\frac{\lambda_{cu}^b}{\lambda}\right) = \text{Im}\left(\frac{V_{ub} V_{cb}^*}{V_{us} V_{cs}^*}\right) \approx \lambda^4 A^2 \eta \approx 6 \times 10^{-4}$$

In terms of CKM elements Γ_{12}^{SM} and M_{12}^{SM} can be decomposed in their U-spin transitions ($\Delta U = 0, 1, 2$, with $\Delta U_3 = 0$). The dominant are those with $\Delta U = 2$, therefore one can derive the SM phases:

$$\phi_2^M \equiv \arg \left[\frac{M_{12}}{\frac{1}{4}(\lambda_{cu}^s - \lambda_{cu}^d)^2 M_2} \right], \quad \phi_2^\Gamma \equiv \arg \left[\frac{\Gamma_{12}}{\frac{1}{4}(\lambda_{cu}^s - \lambda_{cu}^d)^2 \Gamma_2} \right]$$

$$|\phi_2^\Gamma| \approx \left| 2 \text{Im} \left(\frac{\lambda_{cu}^b}{\lambda_{cu}^s - \lambda_{cu}^d} \right) \frac{\Gamma_1}{\Gamma_2} \right| \approx \left| \frac{\lambda_{cu}^b}{\lambda} \right| \sin \gamma \frac{1}{\epsilon} \approx (2.2 \times 10^{-3}) \times \frac{0.3}{\epsilon}$$

where $\epsilon \approx 0.4$ is the U-spin suppression factor. The phase ϕ_2^M is expected to be of the same order of ϕ_2^Γ .

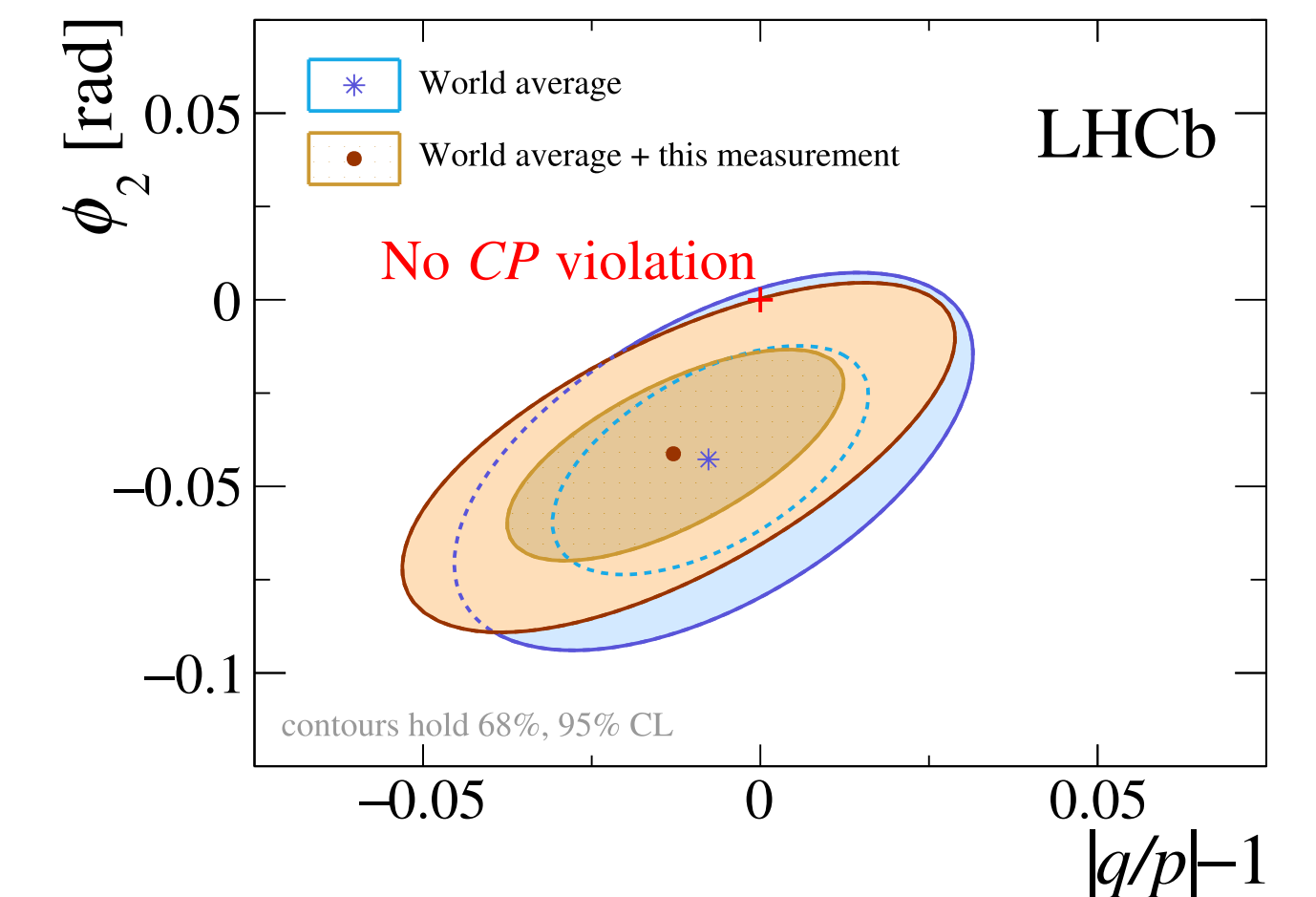
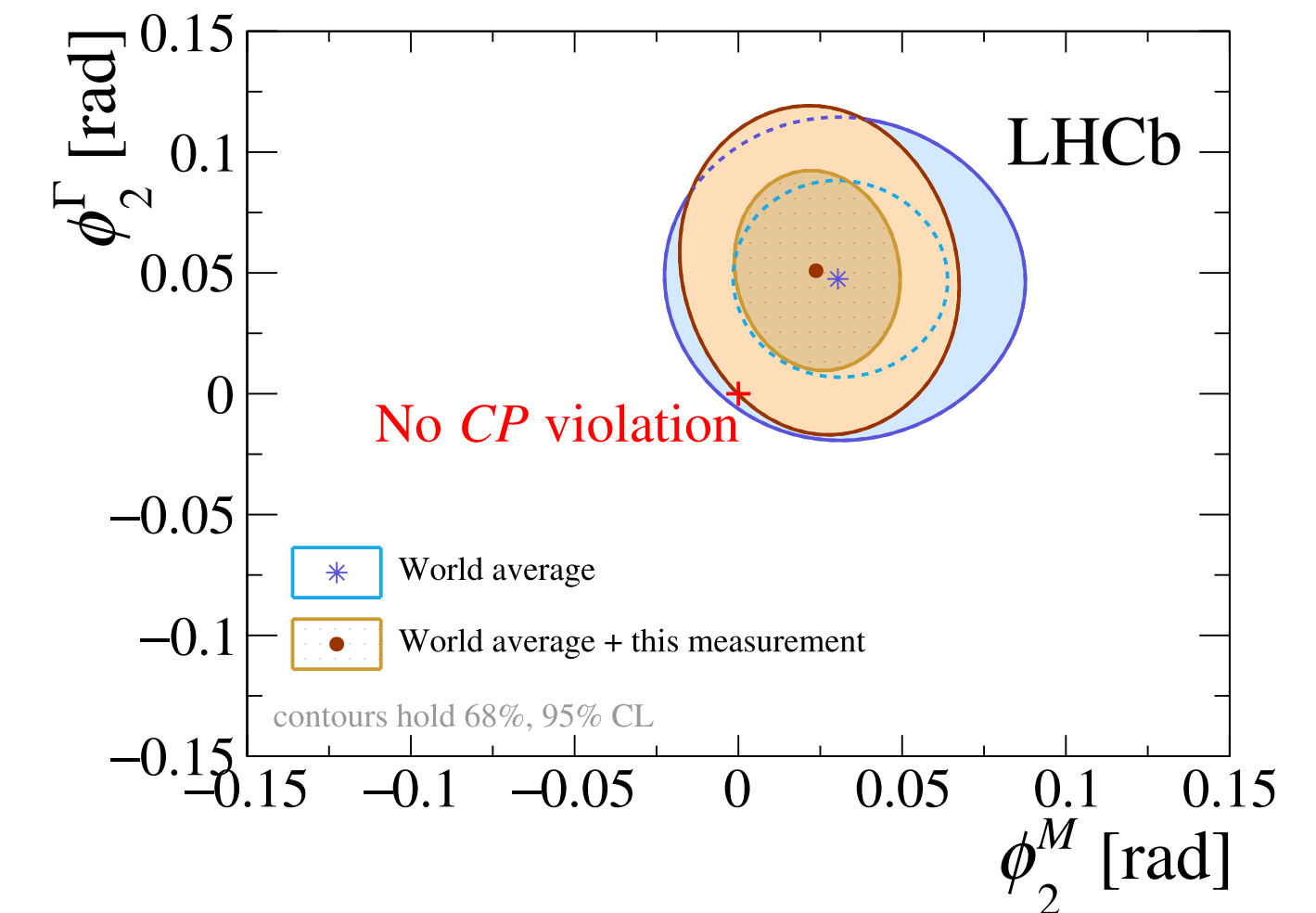
CP Violation in Charm Sector

Mixing and Interference

- Dispersive and absorptive phases, ϕ_2^Γ and ϕ_2^M are estimated to be of the order of 2mrad [Kagan& Silvestrini, [PRD 103, 053008 \(2021\)](#)].
- Enhancements up to one of order of magnitude cannot be excluded**
([1103.5785],[1002.4794],[2001.04079])
- An upper bound of 5mrad has recently been argued for ϕ_2^Γ
[[PRD 103, 053008 \(2021\)](#)]
- The current experimental limits are less precise by one order of magnitude, as the weak phases are currently measured to be $\phi_2^M = (0.030 \pm 0.021)$ rad and $\phi_2^\Gamma = (0.044 \pm 0.027)$ rad.
- Mixing phases can be observed only because contributions from final state f under consideration, neglected at the current experimental precision.

LHCb-PAPER-2024-008

PRD 111 (2025) 012001



CP Violation in Charm Sector

In the decay (or direct)

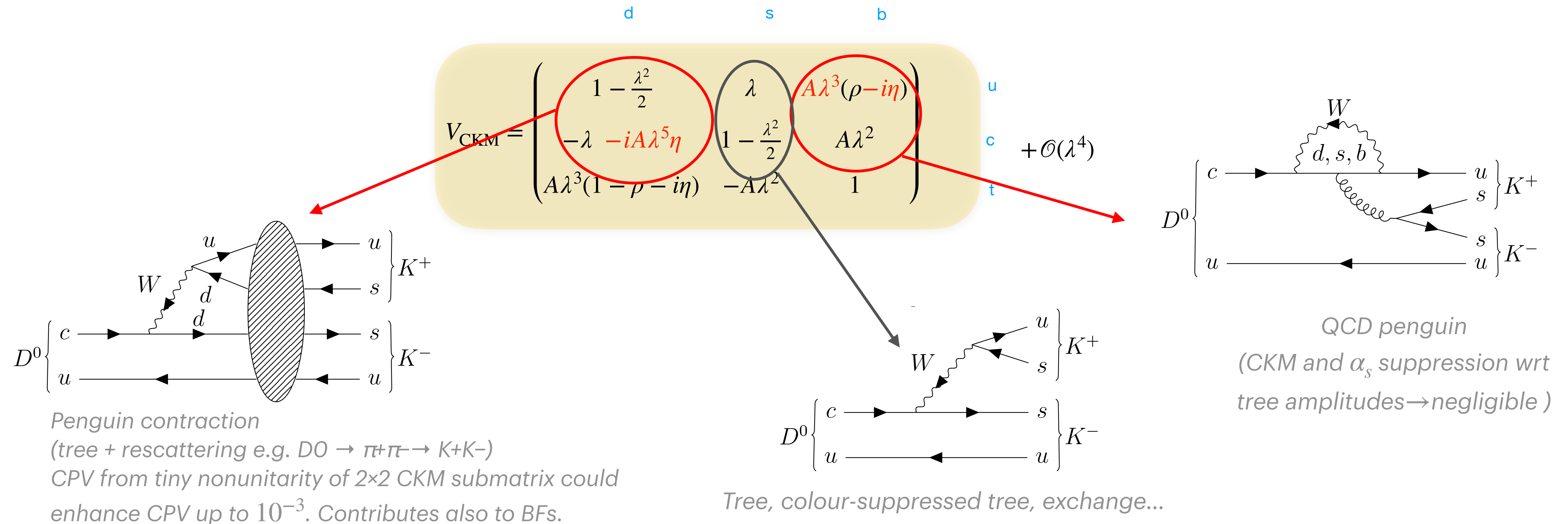
Detectable in Cabibbo-suppressed (CS) decays only.

Cabibbo favoured (CF) and doubly Cabibbo suppressed (DCS): no QCD penguin/chromomagnetic dipole operators.

$$\lambda_i \equiv V_{ci}^* V_{ui}$$

$$A(D^0 \rightarrow K^- K^+) \equiv \lambda_s T + \lambda_b P$$

$$a_{K^+ K^-}^d \approx \underbrace{-2 \operatorname{Im}\left(\frac{\lambda_b}{\lambda_s}\right)}_{1.3 \times 10^{-3}} \left| \frac{P}{T} \right| \sin(\delta_P - \delta_T)$$



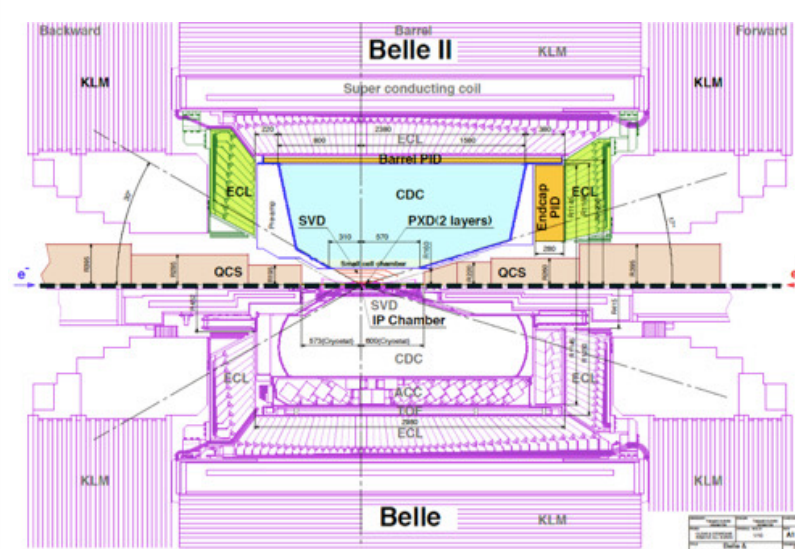
Experimental environment

LHCb Run1	2011-2012, 3fb ⁻¹
LHCb Run2,	2015-2018, 6fb ⁻¹
LHCb-U1, Run3	2024, 9fb ⁻¹
LHCb-U1, Run3	2025, 12fb ⁻¹
LHCb-U1, Run3	2026, ...

From S. Prell and F. Blanc talks at the CKM workshop 2025 in Cagliari

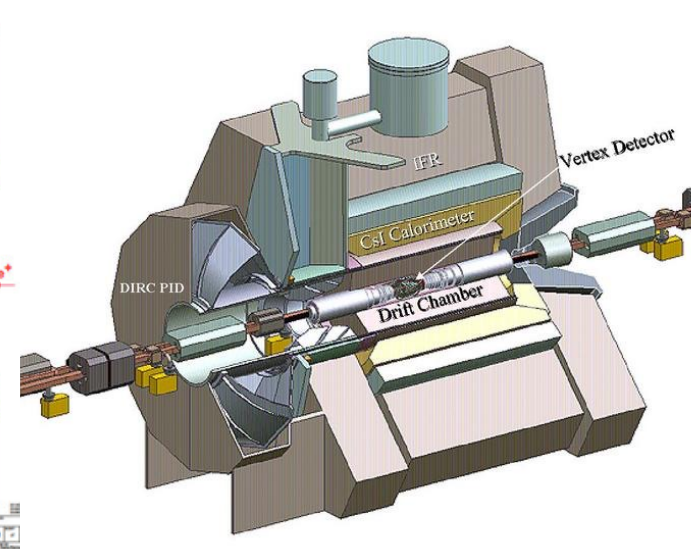
The e^+e^- experiments

Belle & Belle II



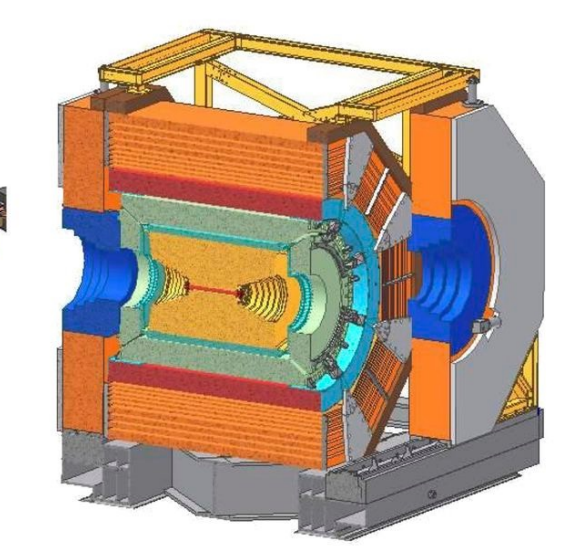
KEK, Japan

BABAR



SLAC, USA

BES III



IHEP, China

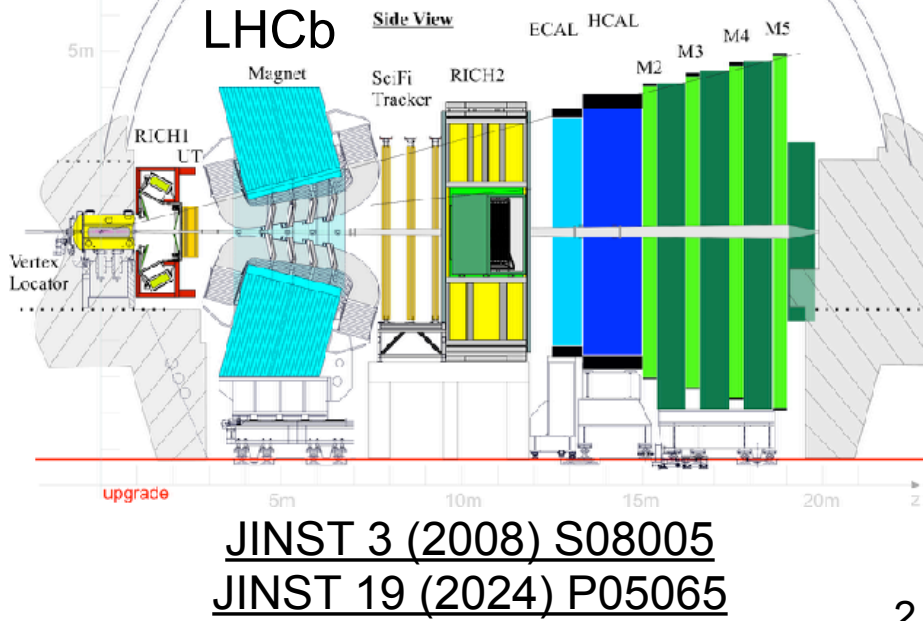
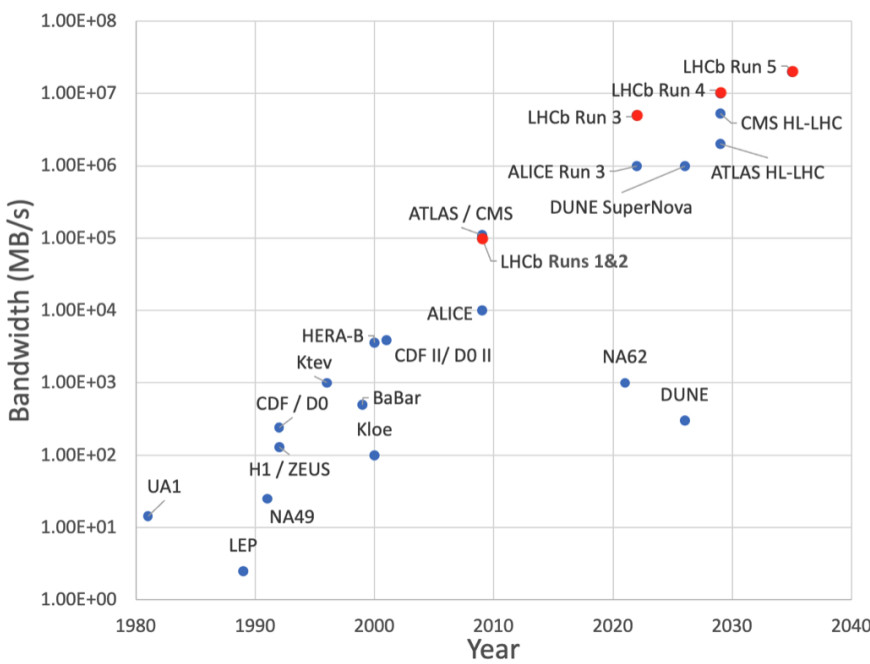
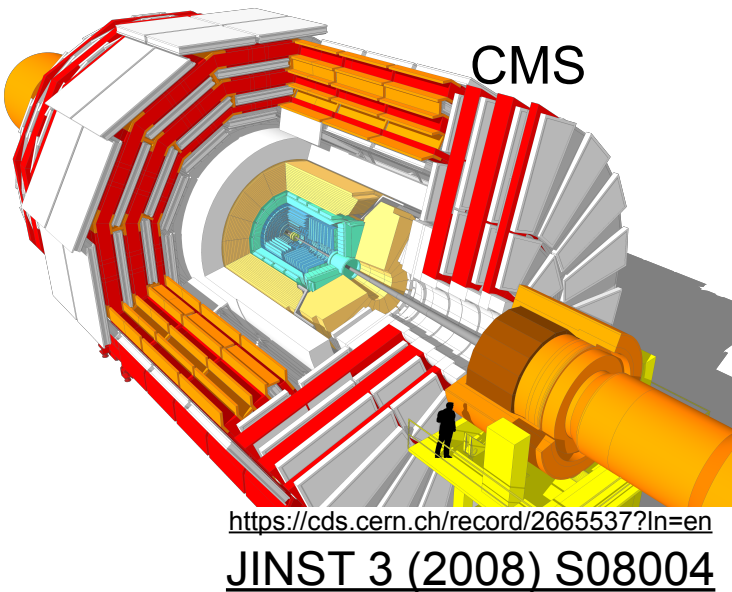
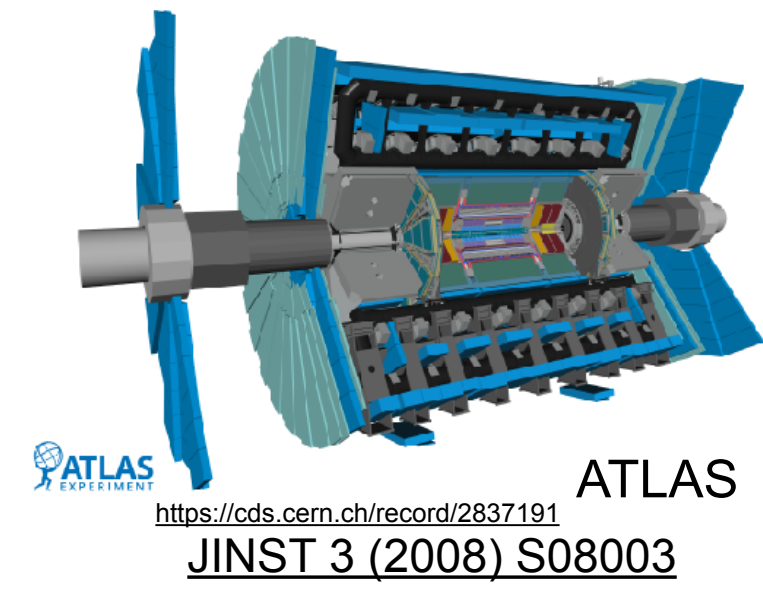
Most data at $\sqrt{s} = m(Y(4S)) = 10.58 \text{ GeV}$, also on $Y(1,2,3,5S)$ and selected energy ranges

- Belle II (2019 -)*
 - 505 fb⁻¹ @ $Y(4S)$
- Belle (2000-2010)*
 - 711 fb⁻¹ @ $Y(4S)$
- BABAR (2000 - 2008)*
 - 431 fb⁻¹ @ $Y(4S)$
- BESIII (2009 -)*
 - Open charm data: 20 fb⁻¹ at $\psi(3770)$, 7.3 fb⁻¹ $D^{(*)0}\bar{D}^{(*)0}$ at 4.13 – 4.23 GeV

Flavour physics at hadron colliders (LHC)



- At the LHC, high $b\bar{b}$ and $c\bar{c}$ cross sections $\Rightarrow$ high rate, large statistics
 - but have to deal with large background $\Rightarrow$ trigger strategies
- LHCb** detector was designed and optimised for flavour physics
 - forward spectrometer, running at limited pileup
 - excellent PID capabilities (e, μ , π , K, p)
 - full software trigger ($\geq$ Run3)
- ATLAS** and **CMS**
 - high pileup + 4π geometry $\Rightarrow$ highest statistics
 - excellent muon identification
 - dedicated trigger strategies for flavour physics



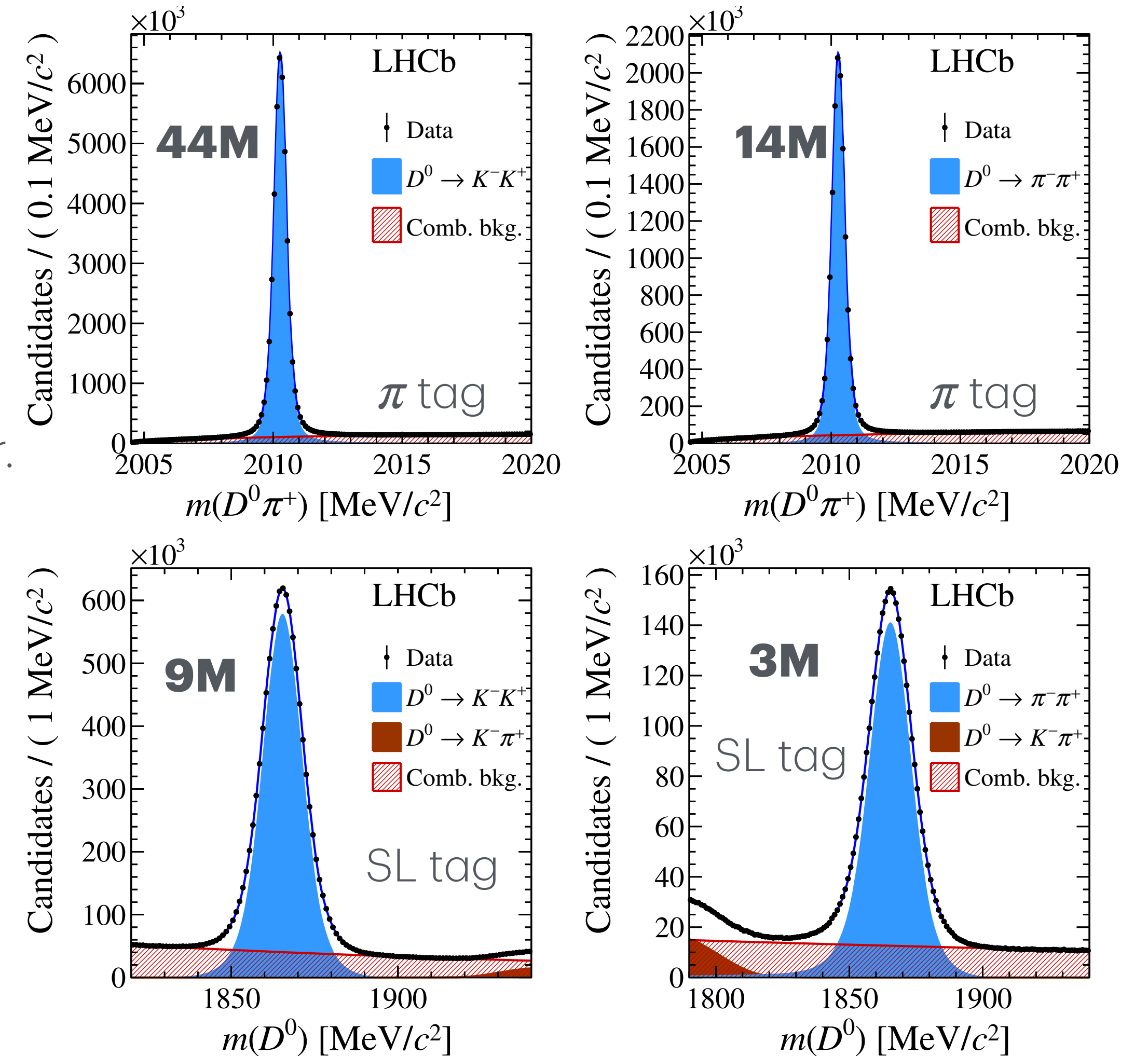
The golden observable $\Delta A_{CP}(D^0 \rightarrow h^+ h^-)$

PRL122 (2019) 211803

- Nuisance asymmetries cancel out in the difference.
- Strict U-spin expectation: $a_{K^+K^-}^d = -a_{\pi^+\pi^-}^d$
- LHCb Run 2, 2015-2018, 6 fb^{-1}
- First observation ever of CP violation in the charm sector.
A clear manifestation of CP violation in the decay.

$$\begin{aligned}\Delta A_{CP} &= A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-) \\ &= (-1.54 \pm 0.29) \times 10^{-3} \\ &\approx a_{KK}^d - a_{\pi\pi}^d \quad (> 5.3\sigma)\end{aligned}$$

- Very robust and efficient cancellation mechanism.
Uncertainty driven by size of the of $D^0 \rightarrow \pi^+\pi^-$.



Individual CP asymmetries ($D^0 \rightarrow h^+ h^-$)

The challenge of measuring a_{KK}^d and $a_{\pi\pi}^d$

PRL131 (2023)091802

Measure raw asymmetries from multiple decays modes:

$$A(K^- \pi^+) \approx A_P(D^{*+}) - A_D(K^+) + A_D(\pi^+) + A_D(\pi_{\text{tag}}^+),$$

$$A(K^- \pi^+ \pi^+) \approx A_P(D^+) - A_D(K^+) + A_D(\pi_1^+) + A_D(\pi_2^+),$$

$$A(\bar{K}^0 \pi^+) \approx A_P(D^+) + A(\bar{K}^0) + A_D(\pi^+),$$

$$A(\phi \pi^+) \approx A_P(D_s^+) + A_D(\pi^+),$$

$$A(\bar{K}^0 K^+) \approx A_P(D_s^+) + A(\bar{K}^0) + A_D(K^+).$$

Two different chains with D^+ and D_s^+ CF/DCS modes:

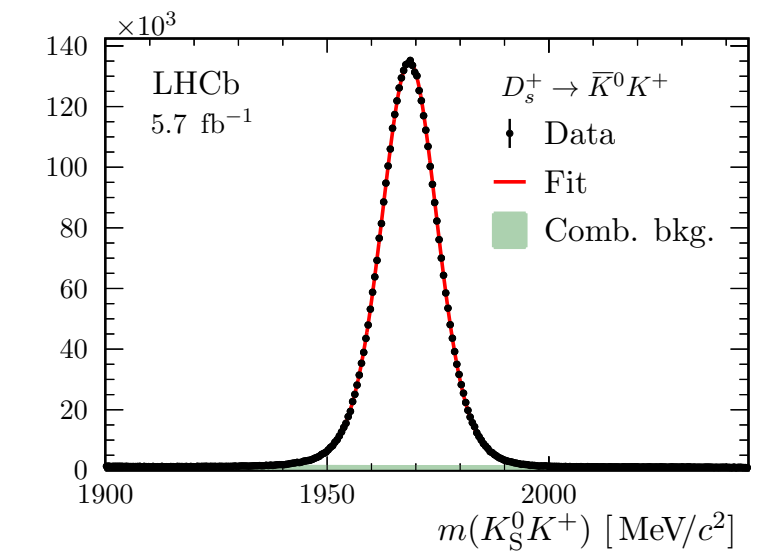
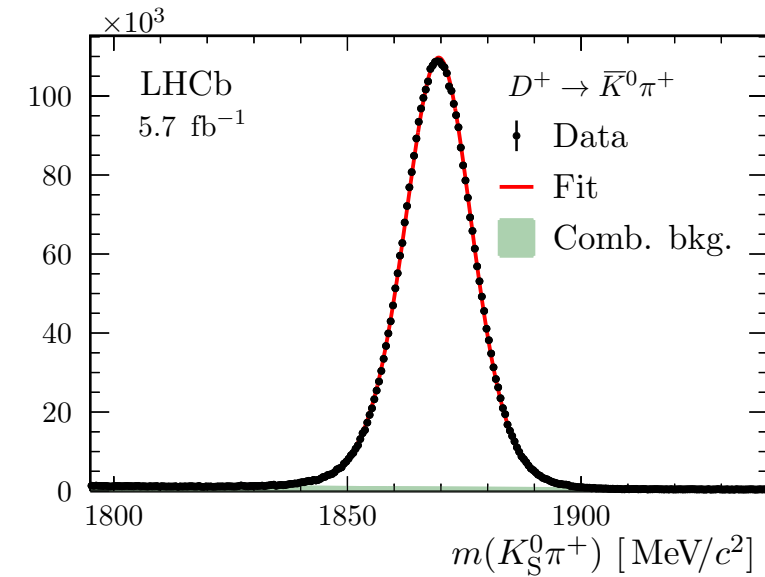
$$C_{D^+} : \mathcal{A}_{CP}(K^- K^+) = A(K^- K^+) - A(K^- \pi^+) \\ + A(K^- \pi^+ \pi^+) - A(\bar{K}^0 \pi^+) + A(\bar{K}^0),$$

$$C_{D_s^+} : \mathcal{A}_{CP}(K^- K^+) = A(K^- K^+) - A(K^- \pi^+) \\ + A(\phi \pi^+) - A(\bar{K}^0 K^+) + A(\bar{K}^0).$$

Uncertainties dominated by the size of independent calibration decay modes. Results can be combined.

TABLE I. 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]		Reduction factor	
	C_{D^+}	$C_{D_s^+}$	C_{D^+}	$C_{D_s^+}$
$D^0 \rightarrow K^- K^+$	37	37	0.72	0.76
$D^0 \rightarrow K^- \pi^+$	58	56	0.33	0.76
$D^+ \rightarrow K^- \pi^+ \pi^+$	188	...	0.23	...
$D^+ \rightarrow \bar{K}^0 \pi^+$	6	...	0.25	...
$D_s^+ \rightarrow \phi \pi^+$	...	43	...	0.55
$D_s^+ \rightarrow \bar{K}^0 K^+$	...	5	...	0.70



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

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

[with a total correlation of 6%]

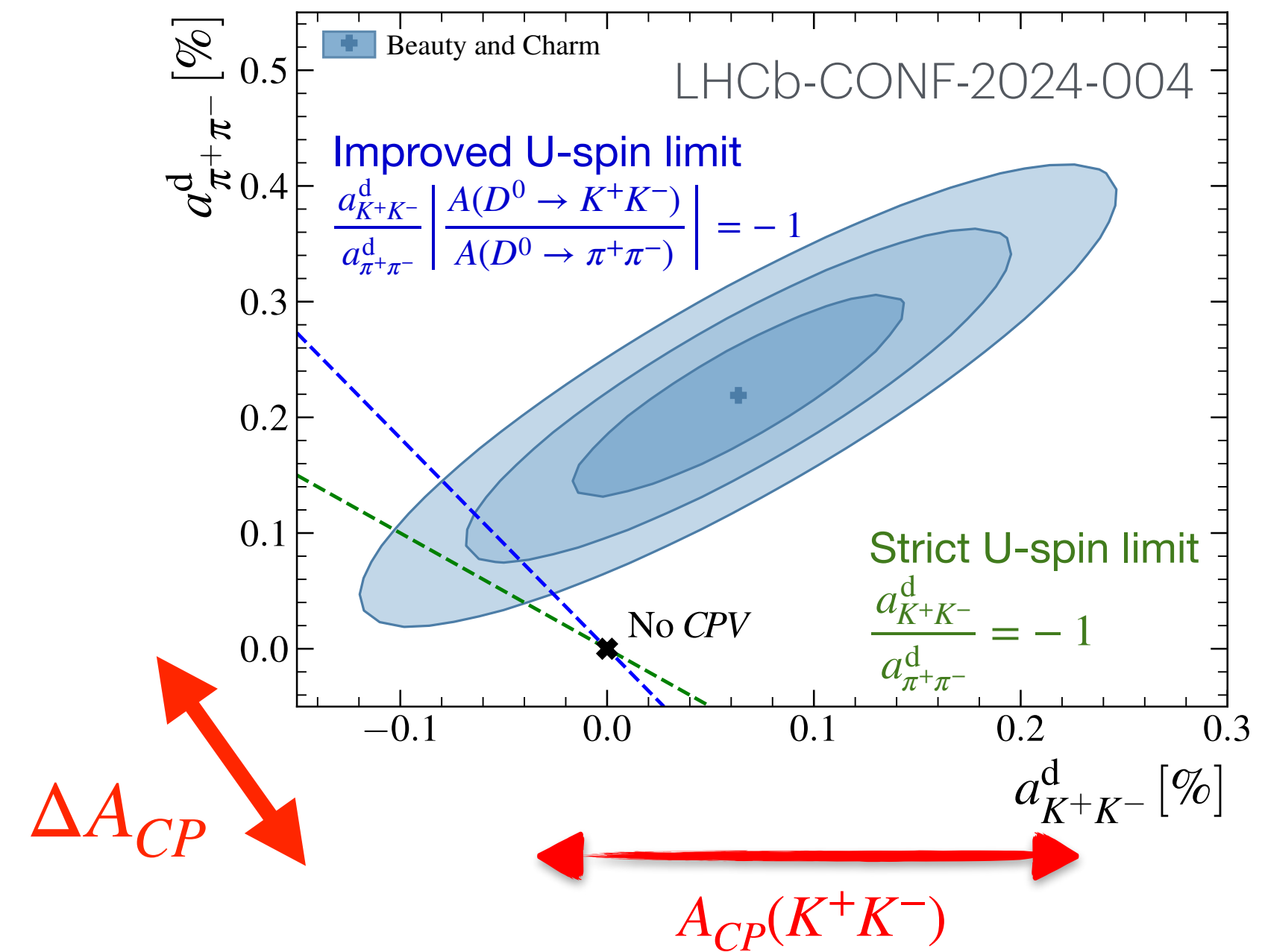
$$\mathcal{A}_{CP}(K^- K^+) = [6.8 \pm 5.4(\text{stat}) \pm 1.6(\text{syst})] \times 10^{-4}$$

Individual CP asymmetries ($D^0 \rightarrow h^+h^-$)

The challenge of measuring a_{KK}^d and $a_{\pi\pi}^d$

By combining with ΔA_{CP} and ΔY to measure direct CP asymmetry in both decays

$$\begin{aligned} a_{KK}^d &= (6.4 \pm 5.3) \times 10^{-4} \\ a_{\pi\pi}^d &= (21.9 \pm 5.8) \times 10^{-4} \end{aligned} \quad (3.8\sigma)$$



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$$\lambda_i \equiv V_{ci}^* V_{ui}$$

$$A(D^0 \rightarrow K^- K^+) \equiv \lambda_s T + \lambda_b P$$

$$a_{K^+ K^-}^d \approx -2 \underbrace{\text{Im}\left(\frac{\lambda_b}{\lambda_s}\right)}_{1.3 \times 10^{-3}} \left| \frac{P}{T} \right| \sin(\delta_P - \delta_T)$$

It must be of the order of unit. NP or SM?
Very important to access $|P/T|$ and strong phase difference.

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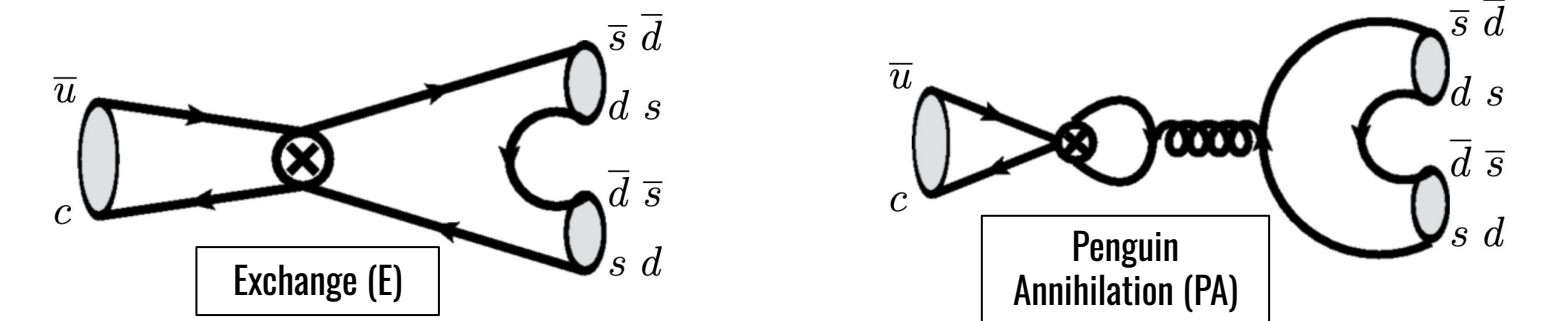
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Very important to access $|P/T|$ and strong phase difference.

Final precision given by $D_{(s)}^+ \rightarrow K_S^0 h^+$ decays.

- Long-living K^0 meson has a limited acceptance in LHCb $\Rightarrow$ different trigger selections mainly based on single track
- Kaon regeneration and CPV in mixing explicitly calculated CERN-THESIS-2014-274. **In the future also need to account for interference between CF and DCS decay amplitude.**

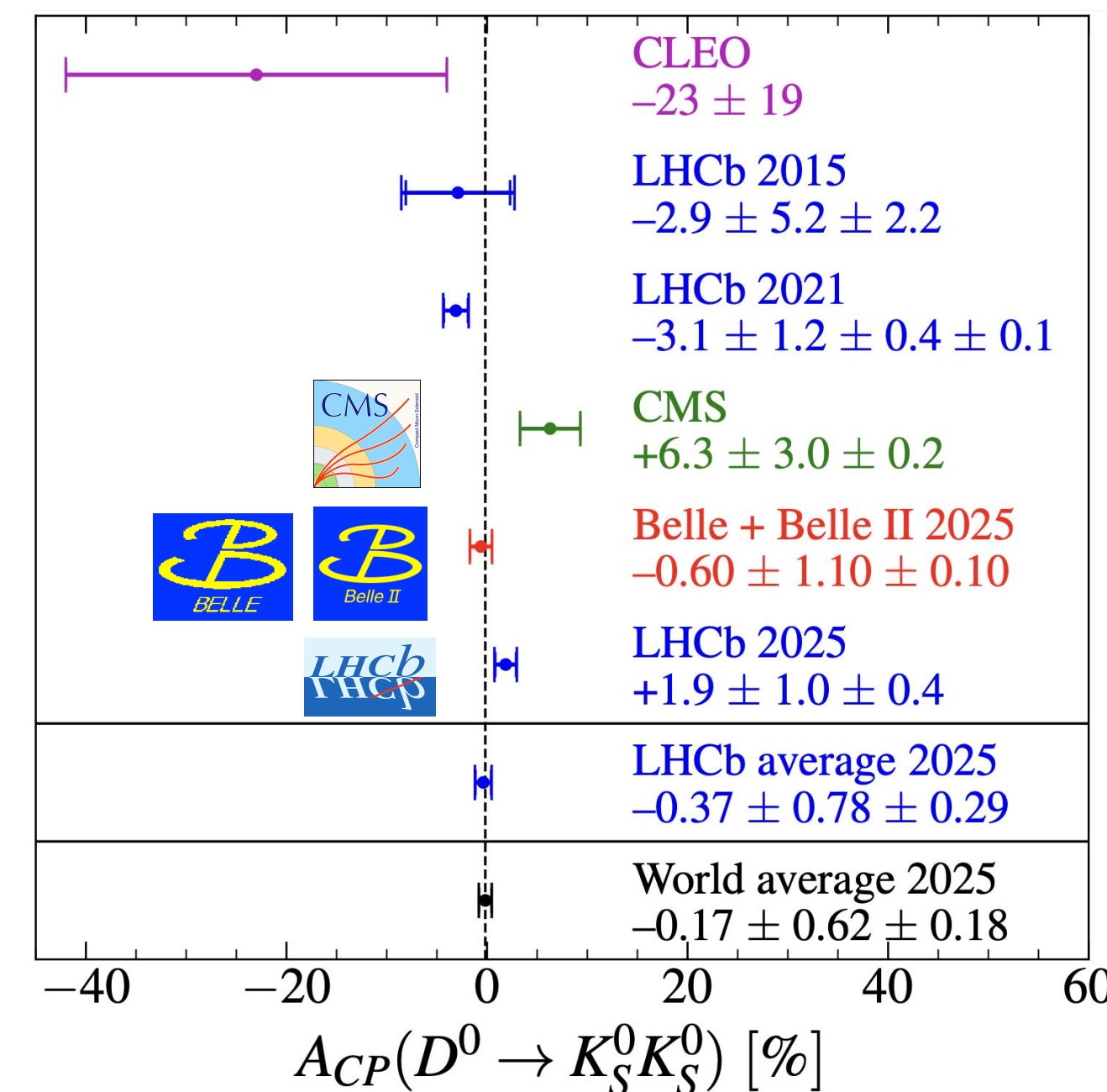
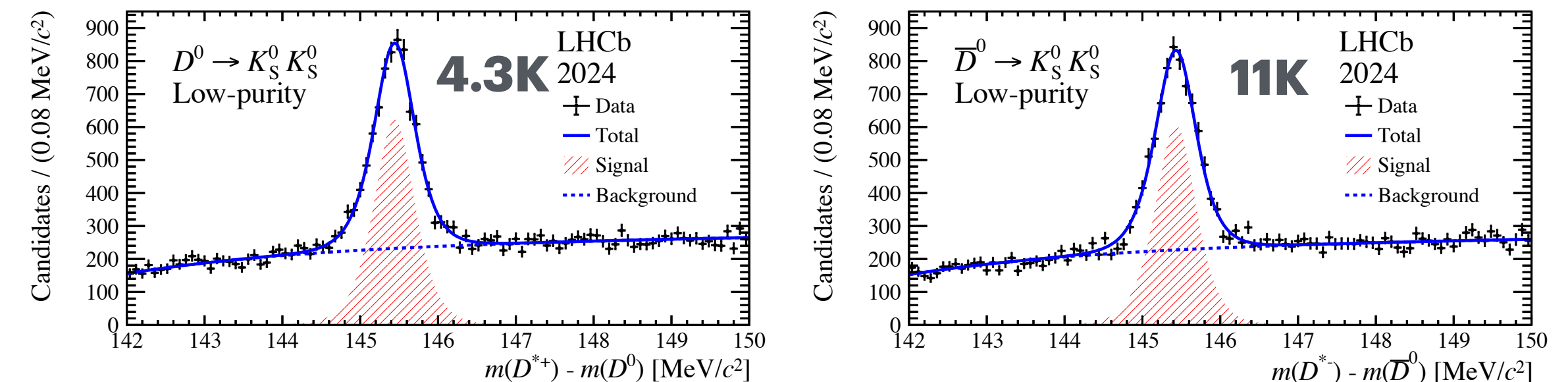
The special role of $D^0 \rightarrow K_S^0 K_S^0$

Direct CP violation



- Excellent candidate for charm CPV confirmation.
 - Penguin diagram suppressed due to CKM.
 - Tree diagram vanishes in the SU(3) limit.
 - Sensitive to different amplitude mix w.r.t. $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^- \rightarrow$ complementarity with ΔA_{CP} .
- Theoretical predictions upper end is $A_{CP}(K_S^0 K_S^0) \approx 1\%$. However no clear picture. Other predictions $\approx 10^{-4}$ based on certain parameter assumptions.
- **An accuracy of $\approx 3 \times 10^{-3}$ might be no longer a dream with the entire dataset from LHCb Run3.** Note both LHCb and CMS use $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ as calibration channel.

First LHCb measurement with 2024 data, 6.2 fb⁻¹.



Confirmed x3 efficiency gain wrt LHCb Run 2 at analysis level.

EPJC 84 (2024) 1264

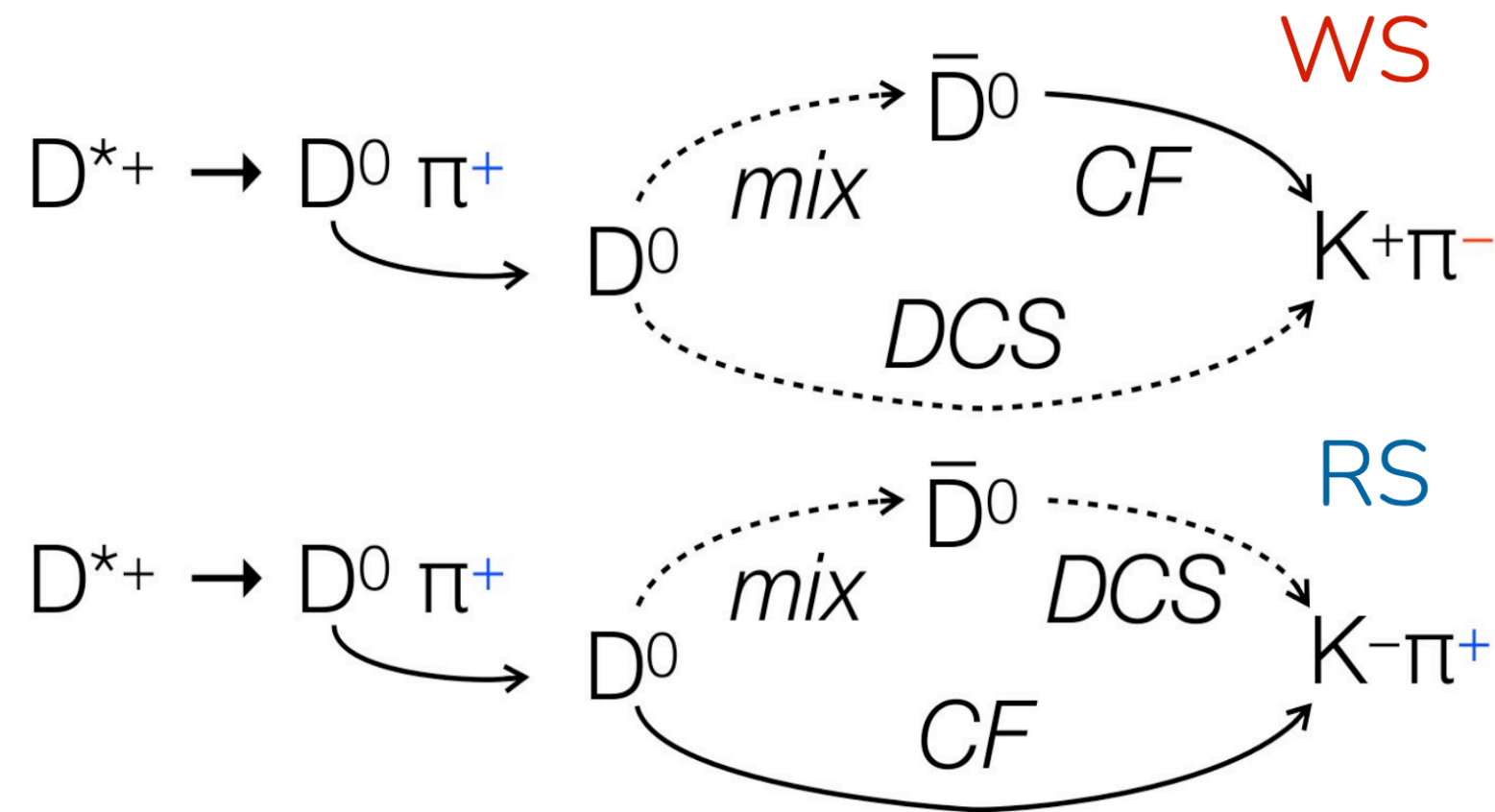
PRD 112 (2025) 012017

[2510.14732]. Submitted to JHEP.

Mixing and CPV with $D^0 \rightarrow K\pi$

PRD 111 (2025) 012001

Right-Sign and Wrong-Sign $D^0 \rightarrow K\pi$ decays



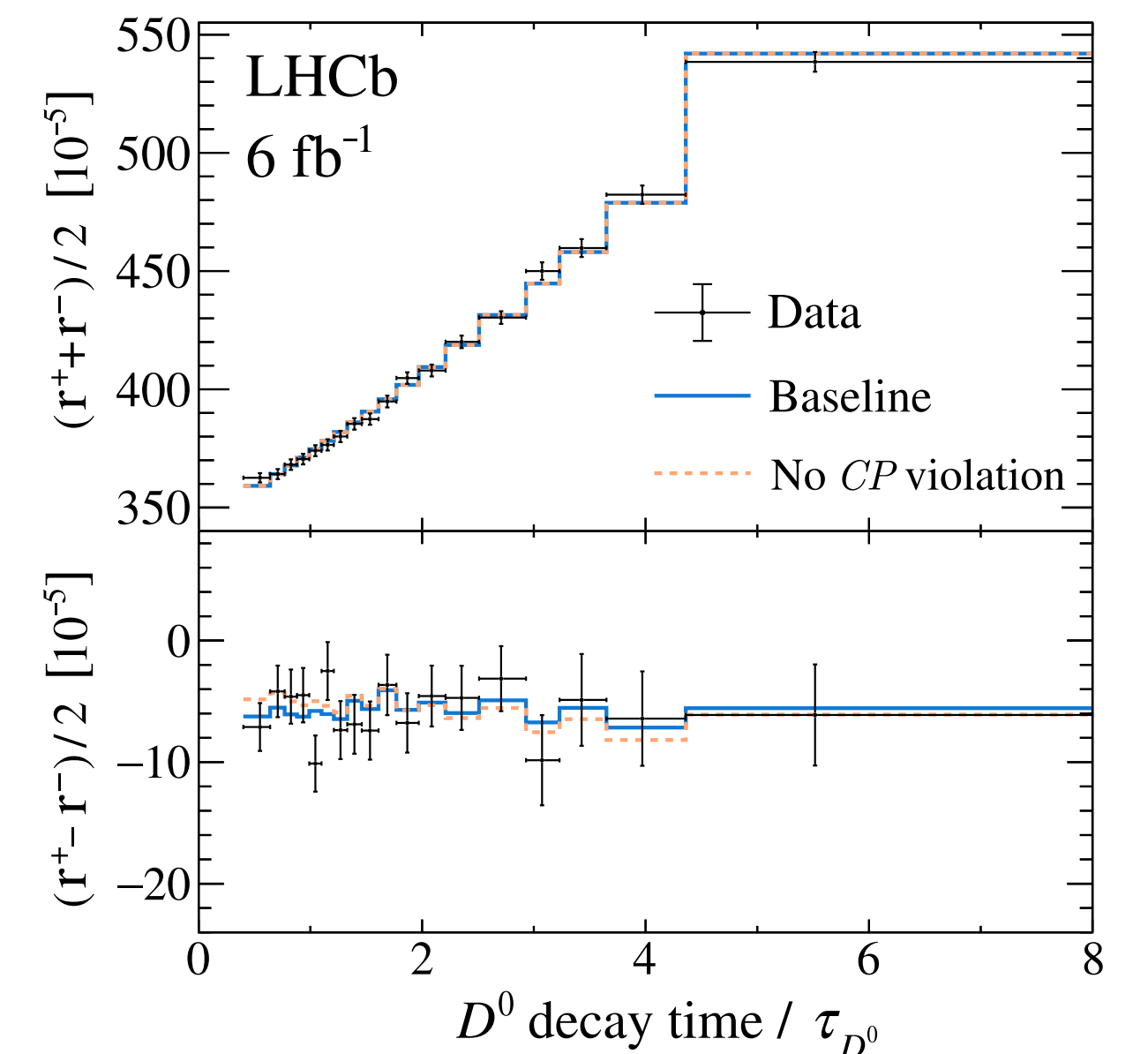
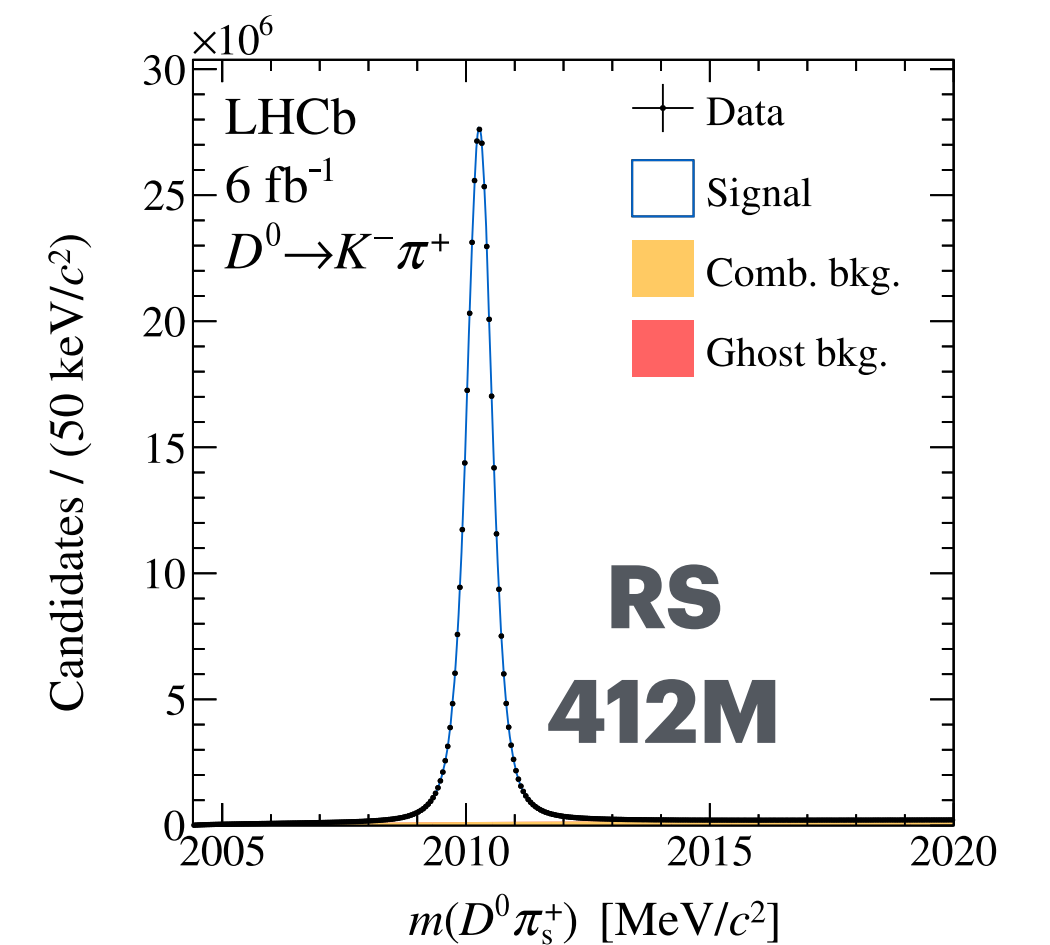
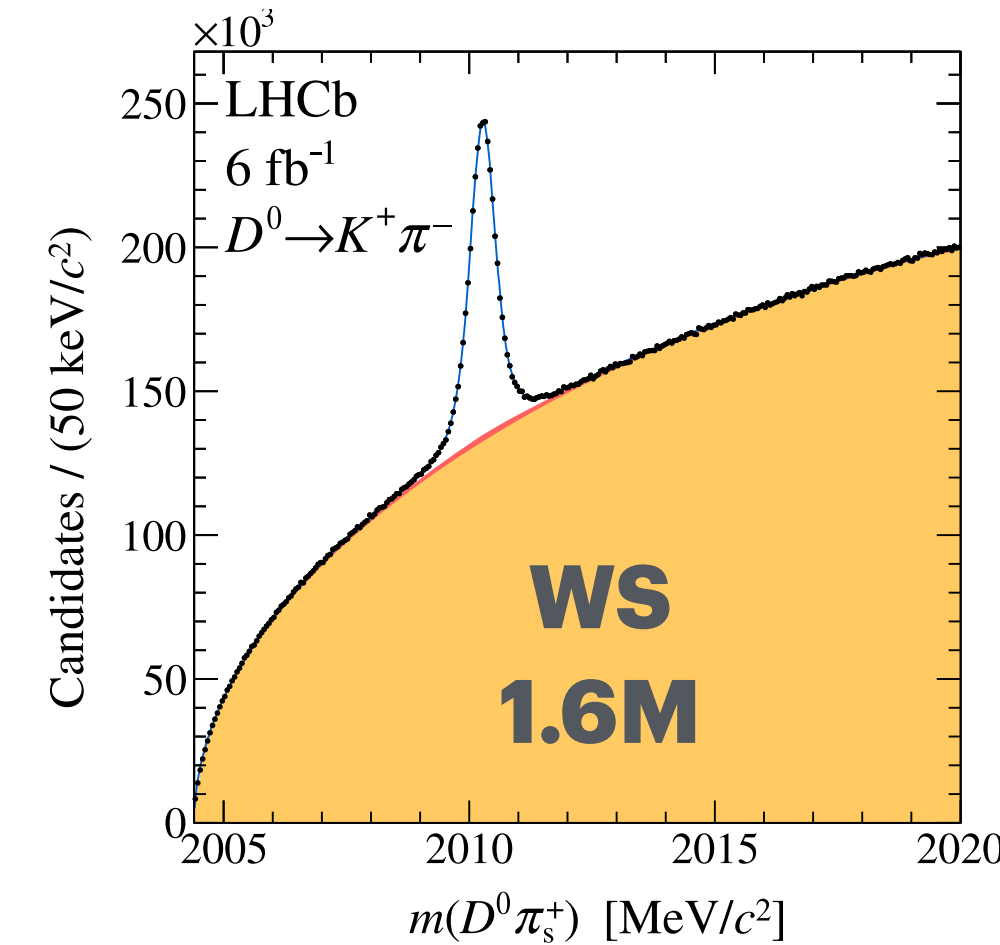
Time-dependence of the WS-to-RS yield ratios

$$R_{K\pi}^+(t) = \frac{\Gamma(D^0 \rightarrow K^+ \pi^-)}{\Gamma(\bar{D}^0 \rightarrow K^+ \pi^-)}$$

$$R_{K\pi}^-(t) = \frac{\Gamma(\bar{D}^0 \rightarrow K^- \pi^+)}{\Gamma(D^0 \rightarrow K^- \pi^+)}$$

$$\text{Mixing} \rightarrow \frac{R_{K\pi}^+ + R_{K\pi}^-}{2}$$

$$\text{CP Violation} \rightarrow \frac{R_{K\pi}^+ - R_{K\pi}^-}{2}$$



Mixing and CPV with $D^0 \rightarrow K\pi$

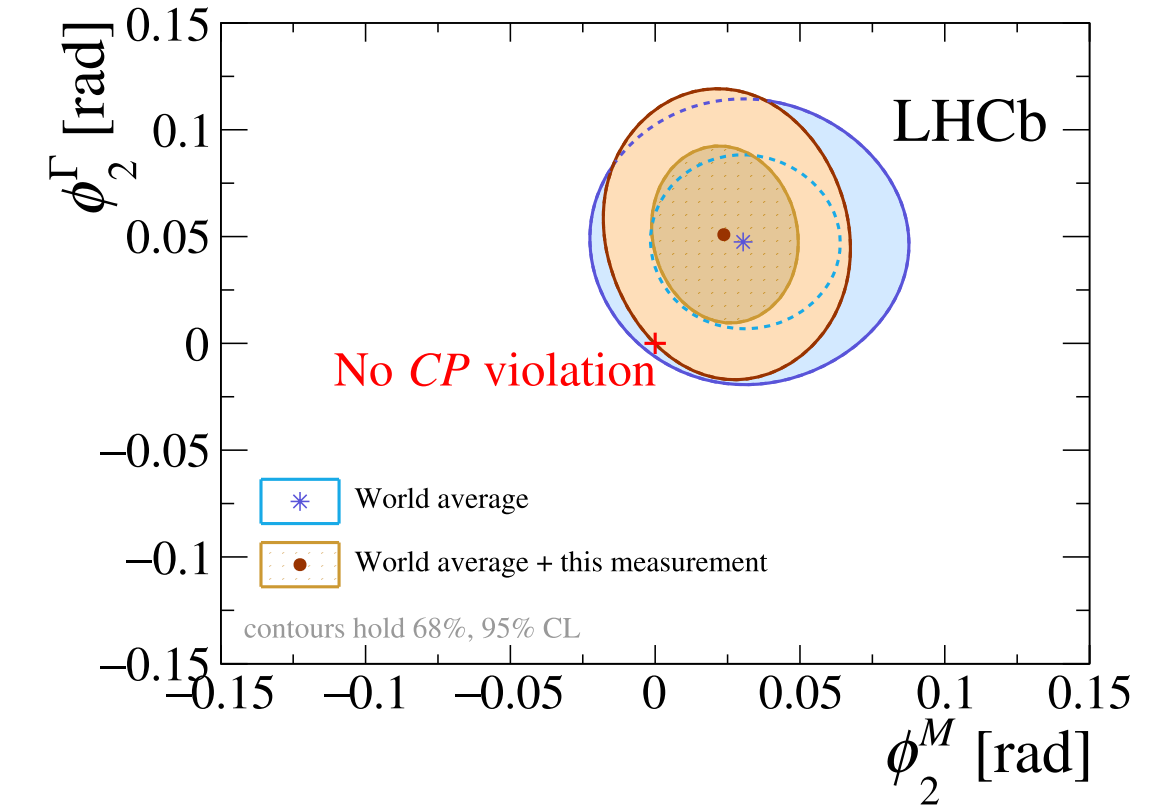
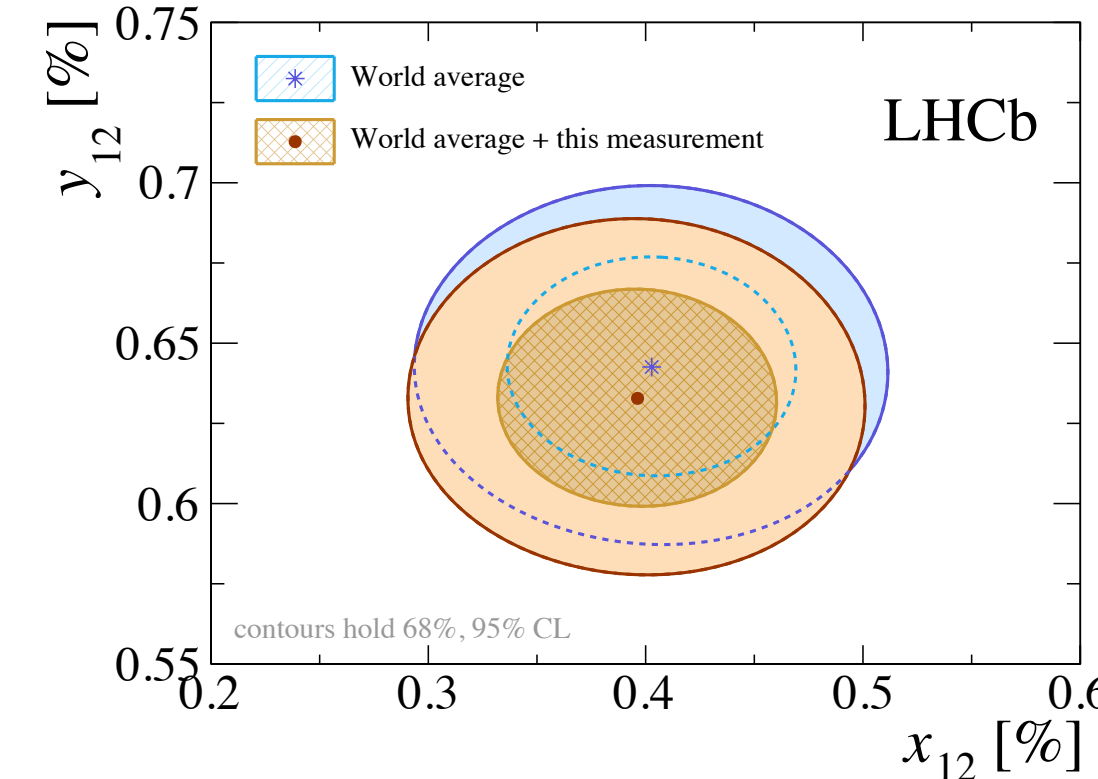
Parameters	Correlations [%]				
	$c_{K\pi}$	$c'_{K\pi}$	$A_{K\pi}$	$\Delta c_{K\pi}$	$\Delta c'_{K\pi}$
$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$	-92.4	80.0	0.9	-0.8
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$	-94.1	-1.4	1.4	-0.7
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$		0.7	-0.7	0.1
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$			-91.5	79.4
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$				-94.1
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$				

Mixing observables

$$\frac{R_{K\pi}^+ + R_{K\pi}^-}{2} = R_{K\pi} \left(1 + \frac{c_{K\pi}}{\sqrt{R_{K\pi}}} t + \frac{c'_{K\pi}}{R_{K\pi}} t^2 \right) \approx \frac{x_{12}^2 + y_{12}^2}{4}$$

$$\approx y_{12} \cos \Delta_{K\pi} + x_{12} \sin \Delta_{K\pi}$$

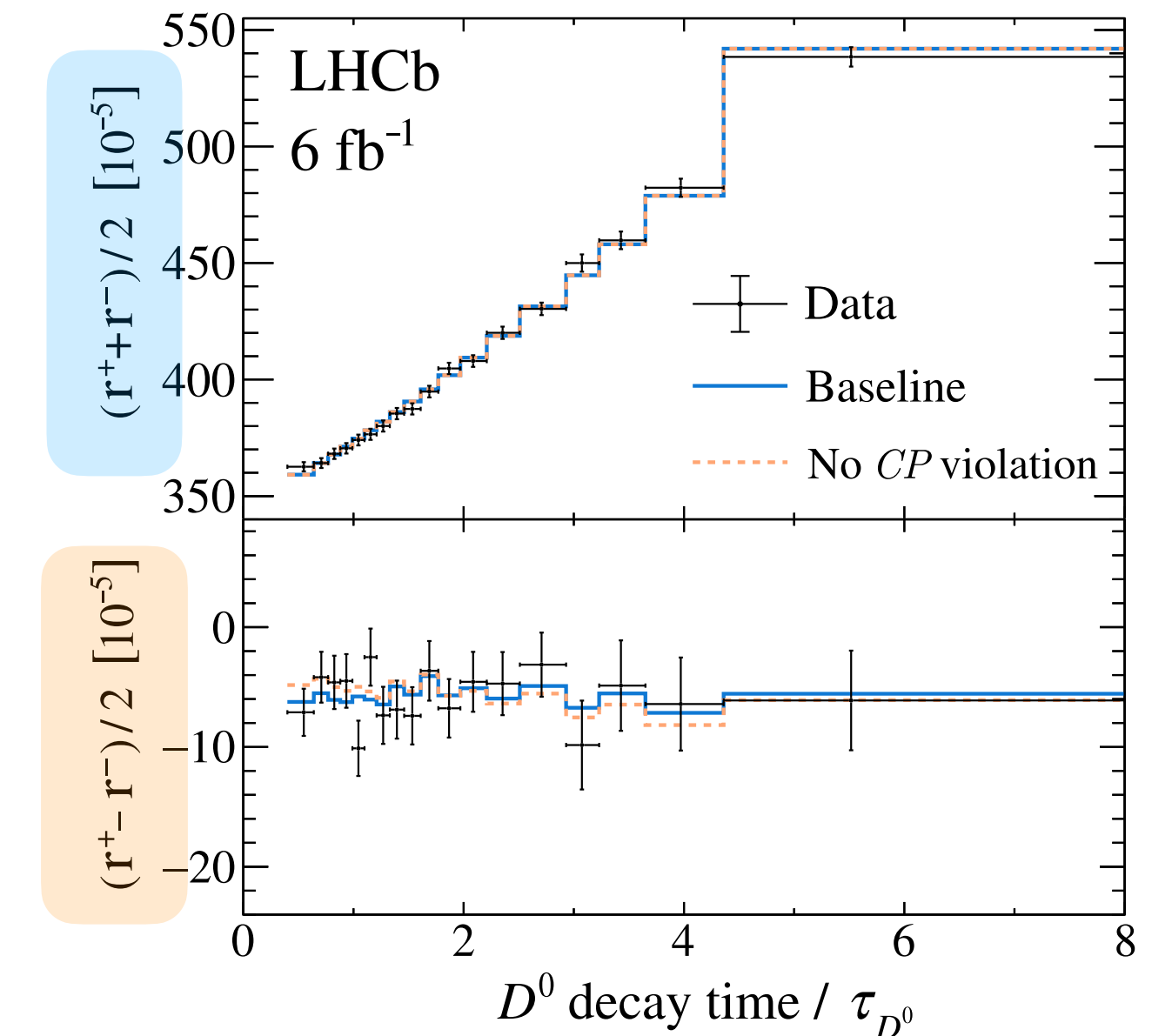
DCS/CF ratio
 $R_{K\pi} \approx 3.4 \times 10^{-3}$
 Strong phase diff.
 $\Delta_{K\pi} = (-12.7 \pm 2.3)^\circ$



CP violation observables: all compatible with no CPV

$$\frac{R_{K\pi}^+ - R_{K\pi}^-}{2} = R_{K\pi} \left(A_{K\pi} + \frac{\Delta c_{K\pi}}{\sqrt{R_{K\pi}}} t + \frac{\Delta c'_{K\pi}}{R_{K\pi}} t^2 \right) \approx (\phi_2^M - \phi_2^\Gamma) \frac{x_{12} y_{12}}{2}$$

$\approx a_{K^+\pi^-}^d$ (direct)
 $\approx \phi_2^M x_{12}$ (interference)
 $\approx (\phi_2^M - \phi_2^\Gamma) \frac{x_{12} y_{12}}{2}$ (mixing)



LHCb-PAPER-2024-008
 PRD 111 (2025) 012001

Strong phase differences

$D\bar{D}$ quantum correlations

- Strong phase between $D/\bar{D}$ decays are essential input for γ angle extraction, as well as for mixing and CPV in charm. CLEO-c and BESIII already exploit QC or $D\bar{D}$ pair ($C = -1$) produced at $\psi(3770)$ resonance in many decay modes.
- QC should exist also at energies above $\psi(3770)$ mass from $e^+e^- \rightarrow XD^0\bar{D}^0$ with $C = (-1)^{n_\gamma+1}$ where $X = n_\gamma$ photons.
- First observation of QC with $C = +1$.** From rates of different combinations of D decays to flavor and CP eigenstates:

$$r_{K\pi}^D e^{-i\delta_{K\pi}^D} = \frac{A(\bar{D}^0 \rightarrow K^- \pi^+)}{A(D^0 \rightarrow K^- \pi^+)},$$

$$\delta_{K\pi}^D = (192^{+11.0+1.9}_{-12.4-2.4})^\circ$$

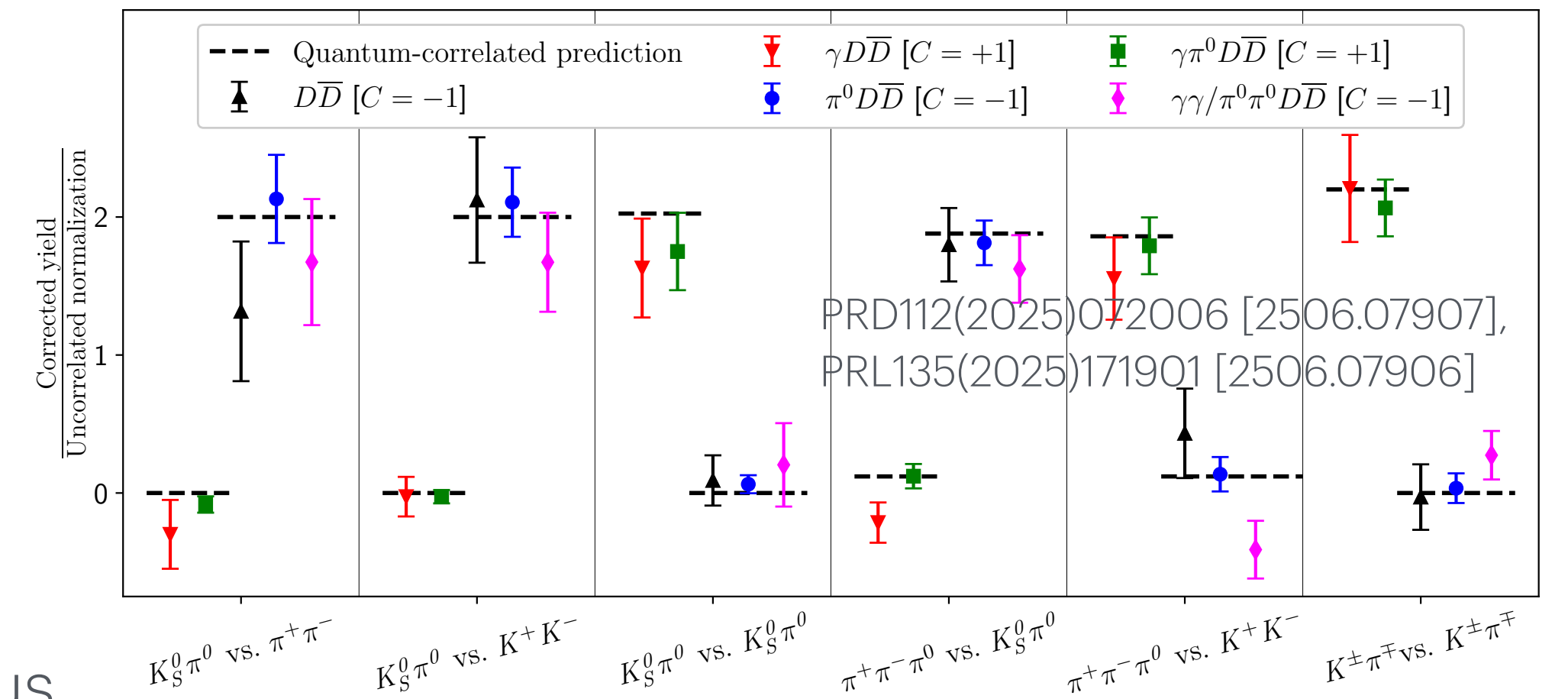
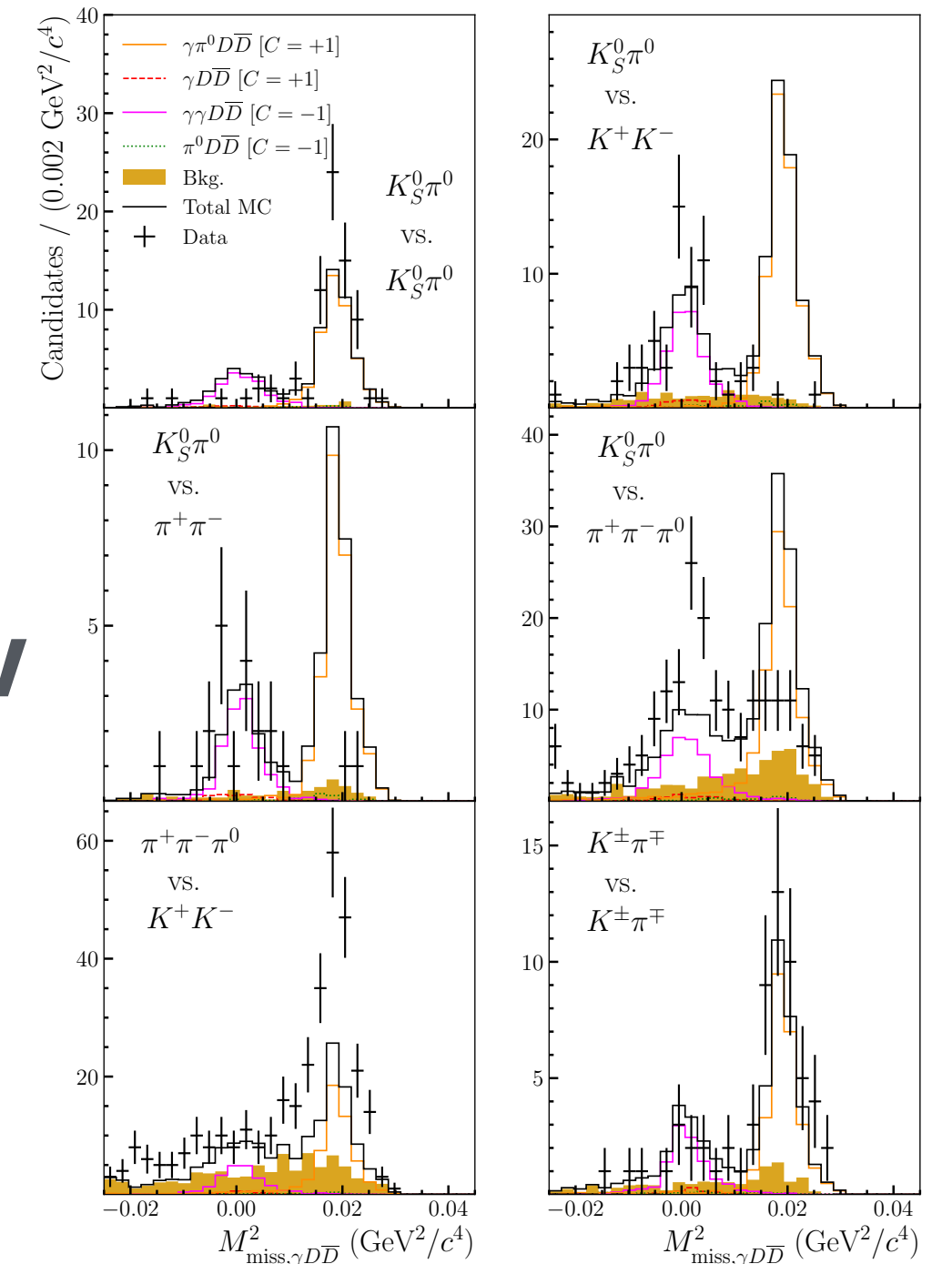
In agreement with LHCb global average (see next) and with previous BESIII measurement $\delta_{K\pi}^D = (187^{+8.9+5.4}_{-9.8-6.4})^\circ$ at $\psi(3770)$ with 2.9fb-1.

BESIII

**7.3 fb⁻¹ of data @
E_{CM} = 4.13 – 4.23 GeV**

TABLE I. Mechanisms by which quantum-correlated $D\bar{D}$ pairs with eigenvalue C are produced through the $e^+e^- \rightarrow D\bar{D}$, $D^*\bar{D}$ and $D^*\bar{D}^*$ processes.

Production mechanism	C
$e^+e^- \rightarrow D\bar{D}$	-1
$e^+e^- \rightarrow D^*\bar{D} \rightarrow D\bar{D}\gamma$	+1
$e^+e^- \rightarrow D^*\bar{D} \rightarrow D\bar{D}\pi^0$	-1
$e^+e^- \rightarrow D^*\bar{D}^* \rightarrow D\bar{D}\gamma\gamma$	-1
$e^+e^- \rightarrow D^*\bar{D}^* \rightarrow D\bar{D}\pi^0\gamma$	+1
$e^+e^- \rightarrow D^*\bar{D}^* \rightarrow D\bar{D}\pi^0\pi^0$	-1



$$\Delta_{K\pi} = -\delta_{K\pi}(\text{HFLAV}) = \pi - \delta_{K\pi}^D$$

Mixing and CPV with $D^0 \rightarrow K\pi\pi\pi$

Phase-space bin	$\kappa_{(i)}$	$\delta_{(i)} [^\circ]$
Inclusive	$0.43^{+0.07}_{-0.06}$	162^{+20}_{-18}
1	$0.56^{+0.19}_{-0.20}$	127^{+31}_{-14}
2	$0.89^{+0.11}_{-0.22}$	134^{+20}_{-12}
3	$0.71^{+0.11}_{-0.10}$	167^{+24}_{-19}
4	$0.41^{+0.25}_{-0.25}$	292^{+42}_{-18}

LHCb-PAPER-2025-029, [2510.04963] (Submitted to JHEP)

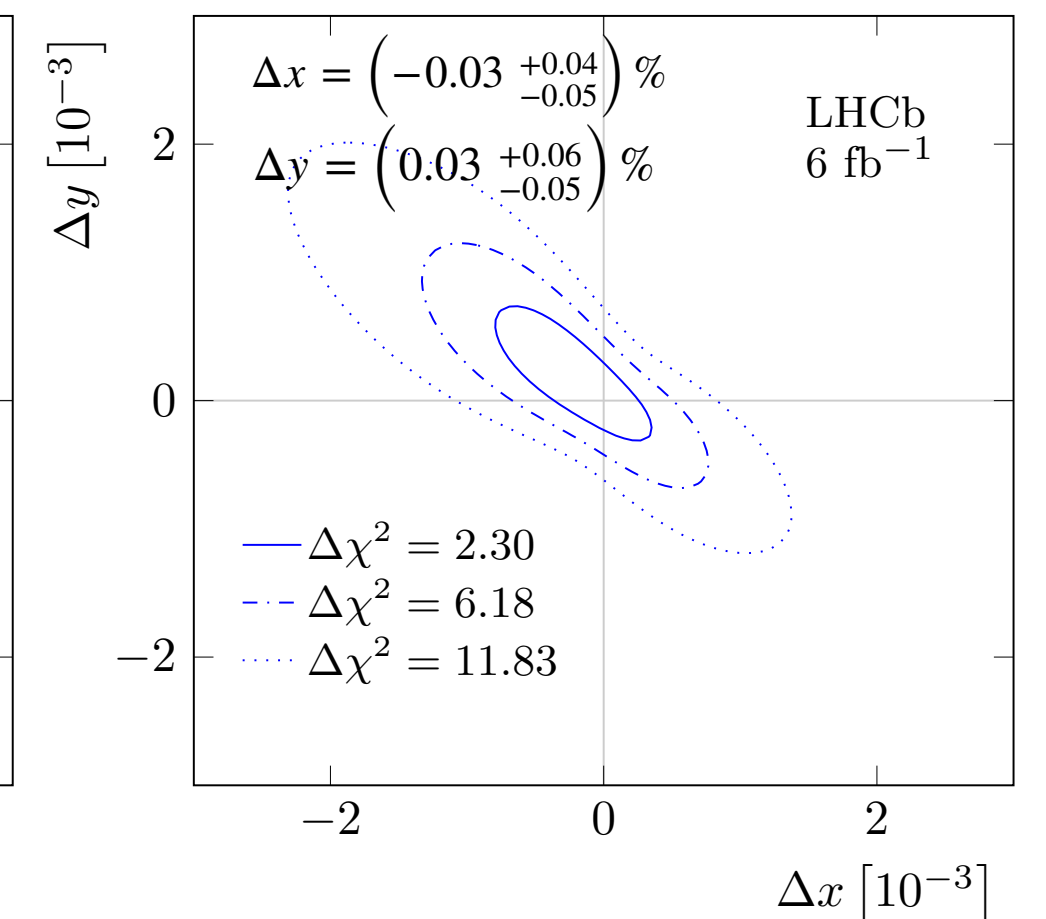
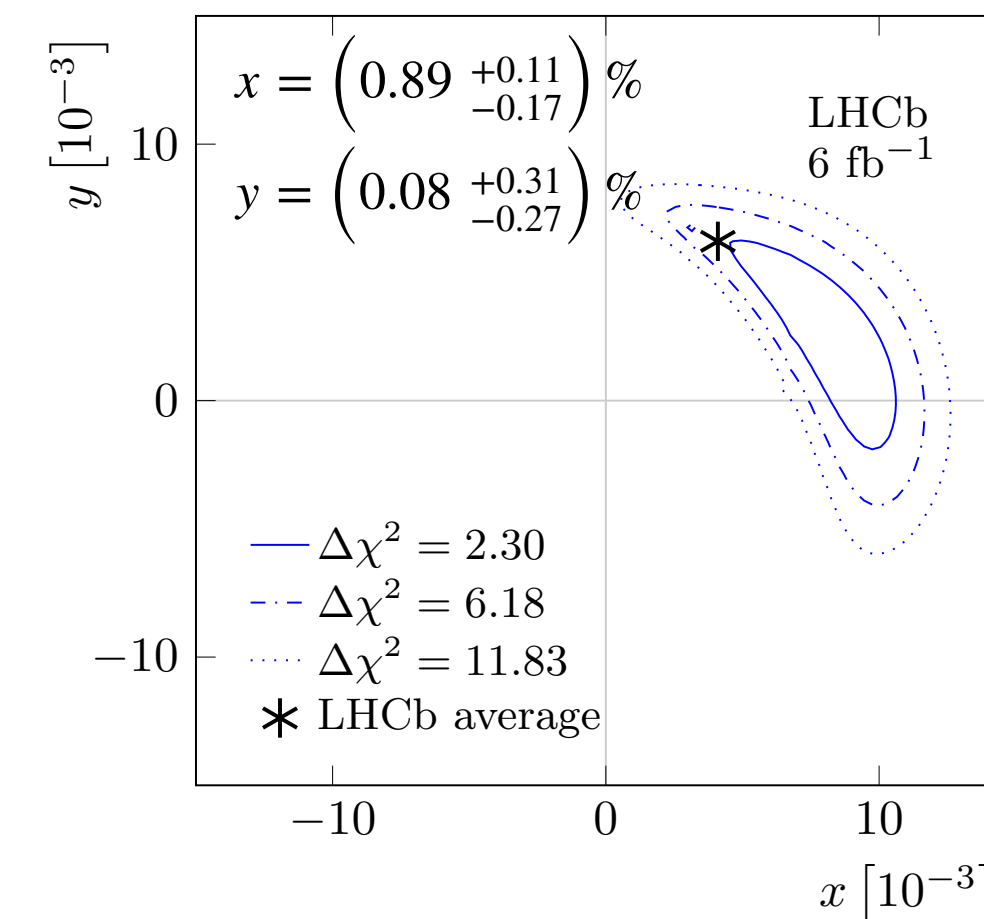
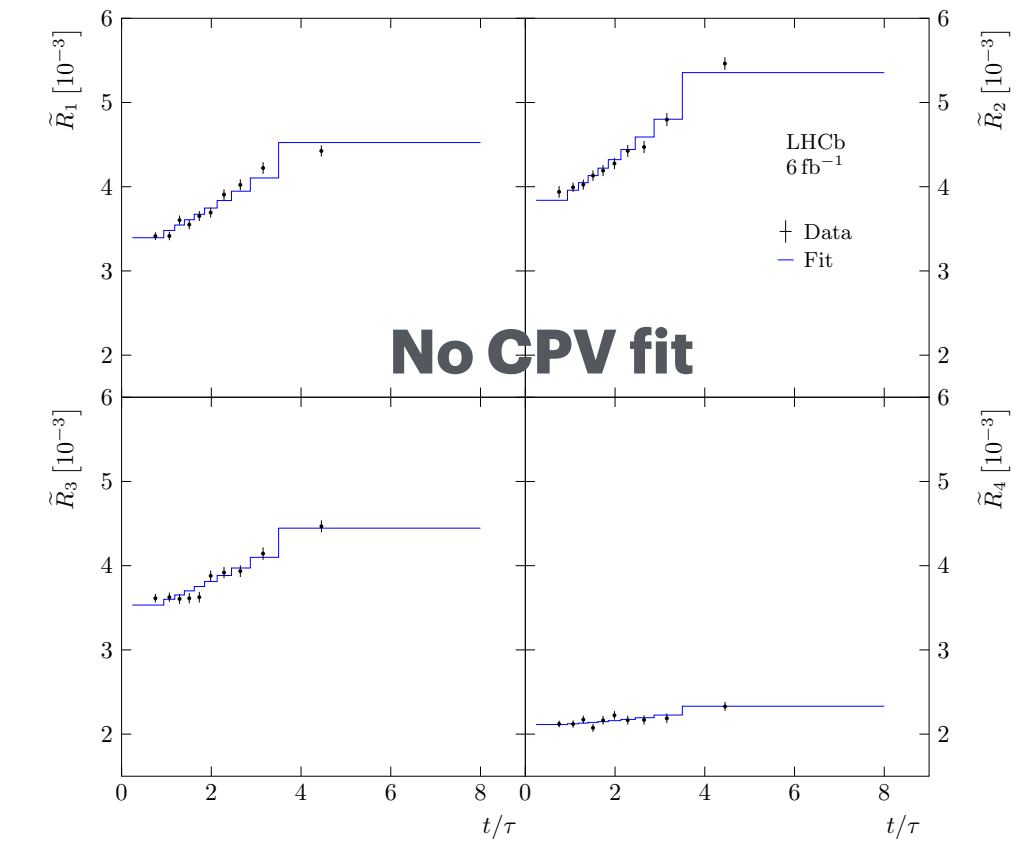
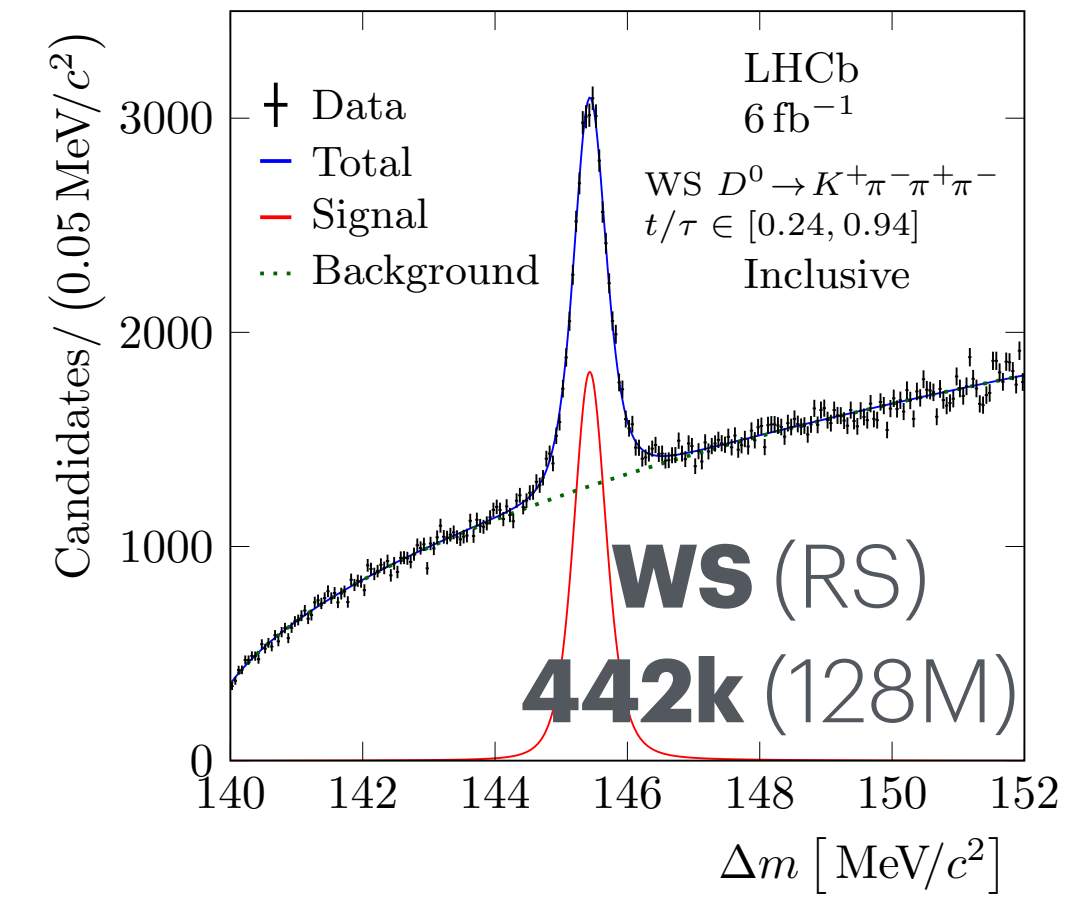
- Similar analysis approach of $D^0 \rightarrow K\pi$ decays by studying the WS-to-RS ratio a function of decay time.
- Time-dependence (index j) measured in **4 space bins (index i)**

$$R_{ij}^+ \equiv \frac{\Gamma[D^0 \rightarrow K^+\pi^-\pi^+\pi^-]}{\Gamma[\bar{D}^0 \rightarrow K^+\pi^-\pi^+\pi^-]} \approx r_i^+ - r_i^+(\kappa y'^+)_i \left\langle \frac{t_{ij}}{\tau} \right\rangle + \frac{(x^{+2} + y^{+2})}{4} \left\langle \frac{t_{ij}^2}{\tau} \right\rangle,$$

$$R_{ij}^- \equiv \frac{\Gamma[\bar{D}^0 \rightarrow K^-\pi^+\pi^-\pi^+]}{\Gamma[D^0 \rightarrow K^-\pi^+\pi^-\pi^+]} \approx r_i^- - r_i^-(\kappa y'^-)_i \left\langle \frac{t_{ij}}{\tau} \right\rangle + \frac{(x^{-2} + y^{-2})}{4} \left\langle \frac{t_{ij}^2}{\tau} \right\rangle,$$

- Strong parameters, k_i and δ_i constrained with results from CLEO-c, BESIII, LHCb.

- CP-violating parameters: $\Delta x = \frac{x^+ - x^-}{2}$, $\Delta y = \frac{y^+ - y^-}{2}$



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

The king of charm

- Phenomenology very rich. Probe Mixing and CPV with different sensitivity to physic observables depending on the DP position. Multiple interfering amplitudes (CF,DCS, CP-eigenstates).
- Two approaches:
 - Model dependent (full time-dependent amplitude analysis) - see next slide.
 - Model-independent (bin-flip) using strong phases differences in bins of Dalitz plot from Charm Factories (BES-III, CLEO-c)
- Particular sensitive to $x = (M_1 - M_2)/2\Gamma$. First observation in 2021!!!



LHCb, PRL (2021)127.111801

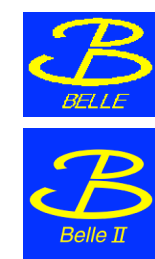
LHCb, PRD108(2023) 052005

$$x_{CP} \approx x_{12} \approx x = (4.01 \pm 0.45 \pm 0.20) \times 10^{-3} \quad (7.5\sigma)$$

$$y_{CP} \approx y_{12} \approx y = (5.51 \pm 1.16 \pm 0.59) \times 10^{-3}$$

$$\Delta x \approx -y_{12} \sin \phi_2^\Gamma = (-0.29 \pm 0.18 \pm 0.01) \times 10^{-3}$$

$$\Delta y \approx +x_{12} \sin \phi_2^M = (+0.31 \pm 0.35 \pm 0.13) \times 10^{-3}$$



Recent results

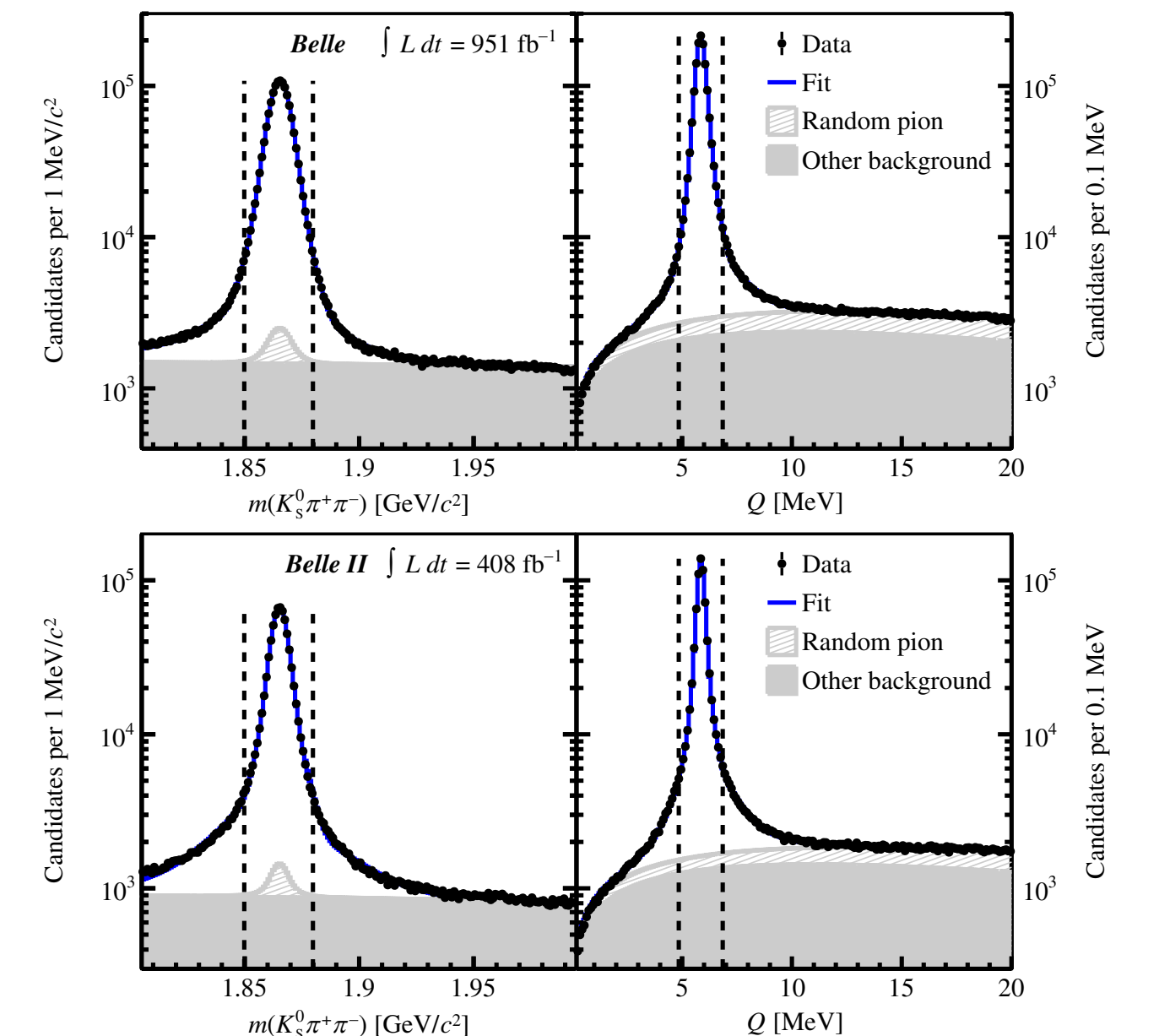
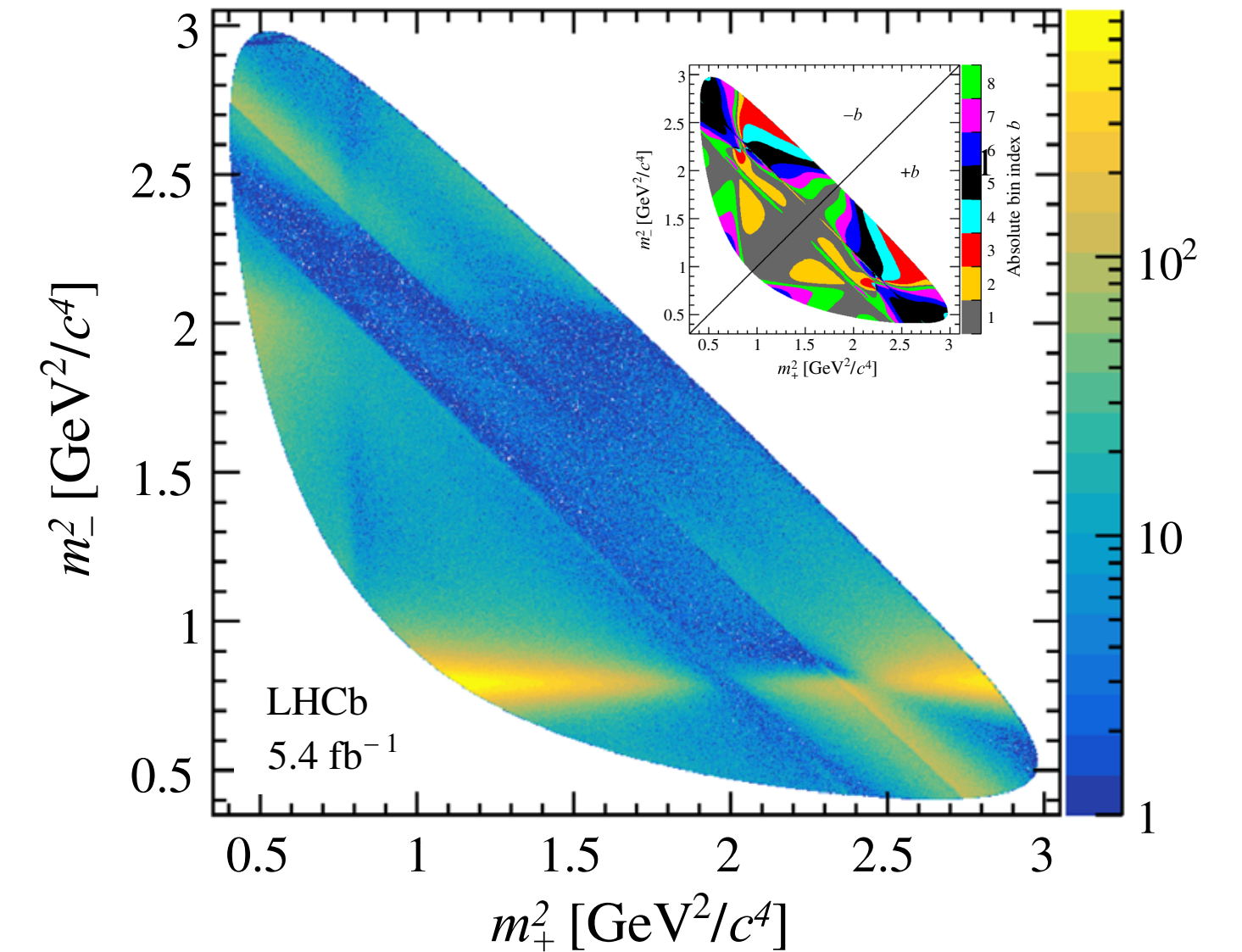
(model-independent)

PRD 111(2025)112011

$$x = (4.0 \pm 1.7 \pm 0.4) \times 10^{-3}$$

$$y = (2.9 \pm 1.4 \times 0.3) \times 10^{-3}$$

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



$$D^0 \rightarrow K_S^0 \pi^+ \pi^-$$

The king of charm

- Model-independent approach very powerful, particularly in hadronic environment, **however also important amplitudes structure**.

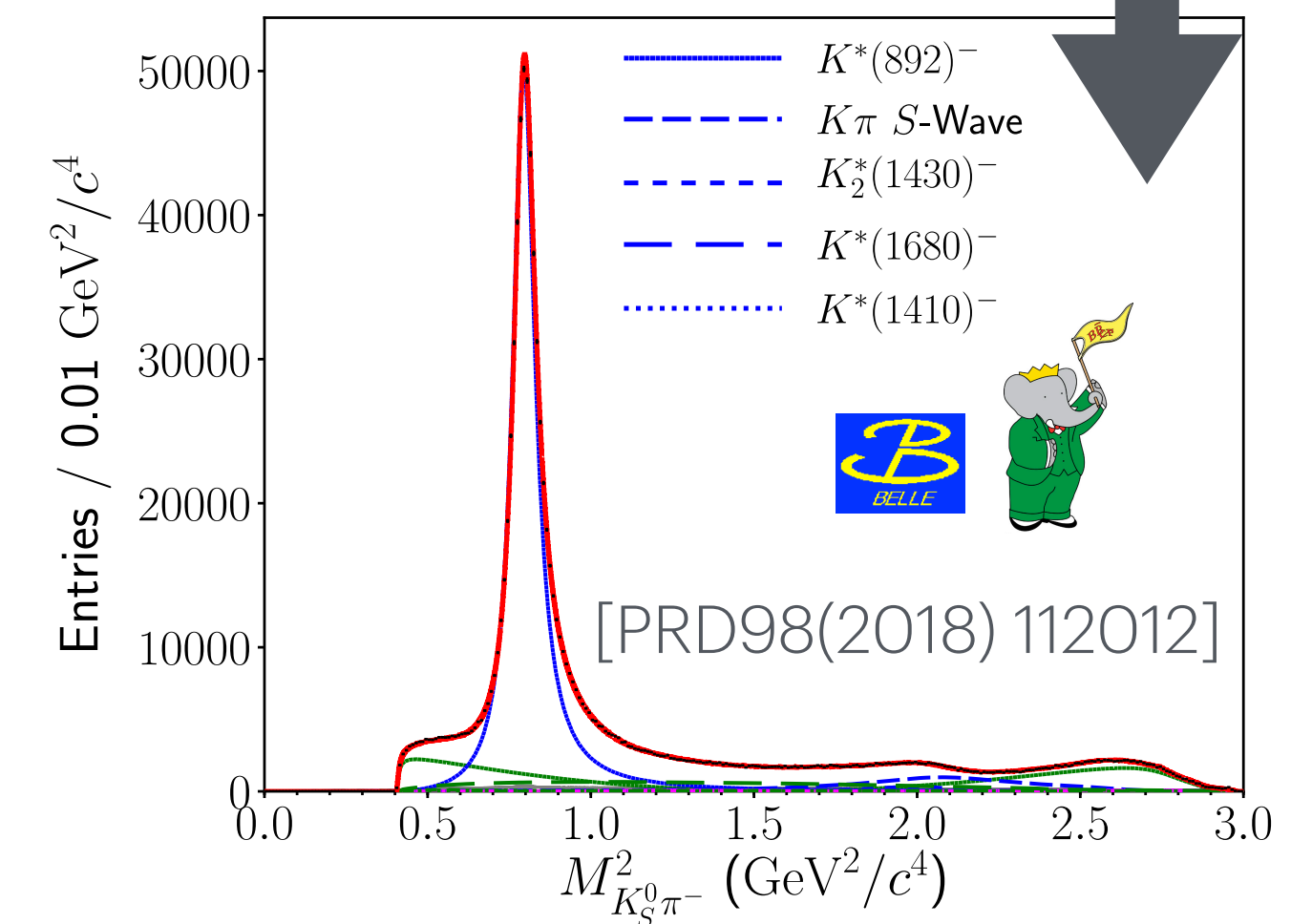
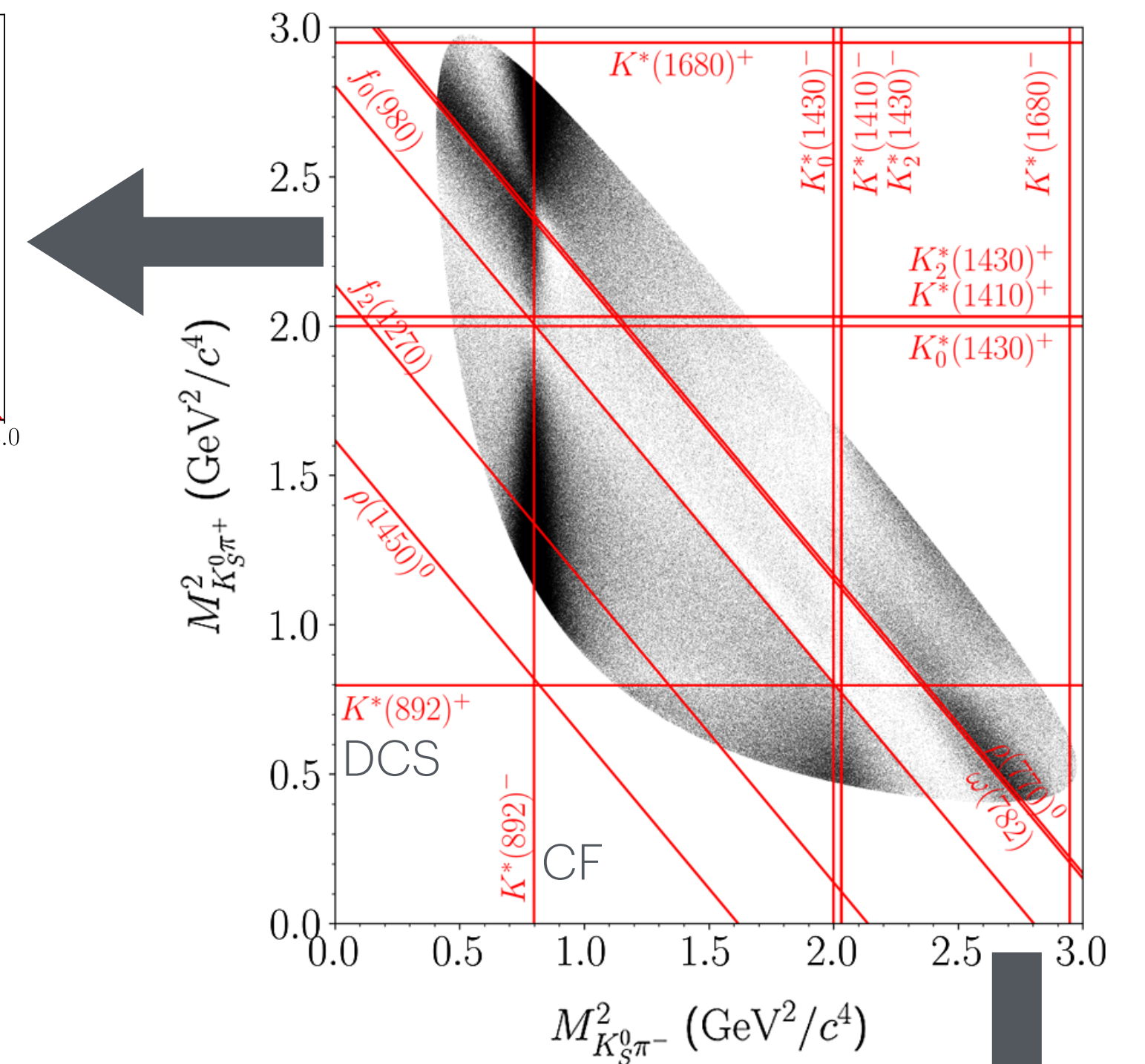
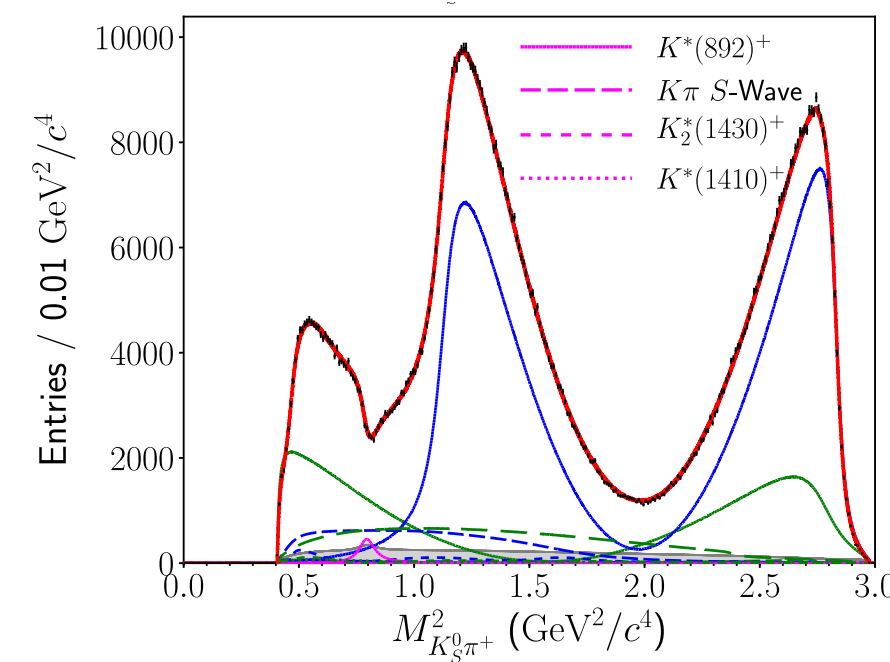
- Mixing and CPV from B-Factories — Belle PRD 89(2014) 091103(R), BaBar PRL105(2010)081803 — Hoping for BelleII updates soon.
- More difficult at LHCb but doable. Still waiting for results.

- More sensitive to mixing and CPV than bin-flip.**

- Becoming more and more important as calibration channel.**

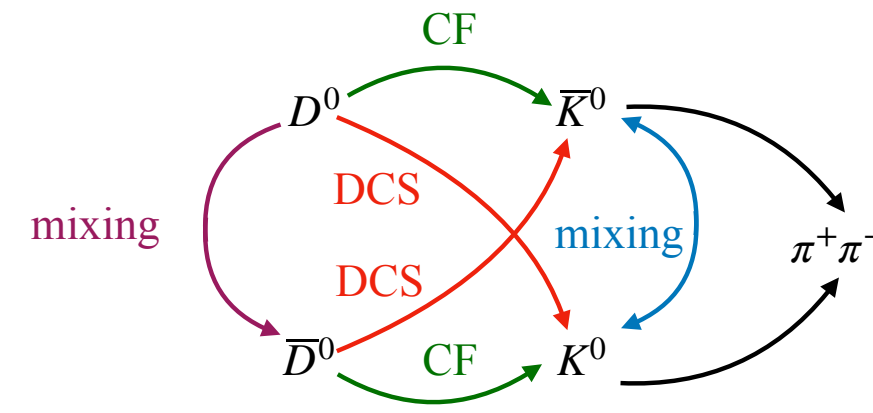
For instance for time-integrated $A_{CP}(D^0 \rightarrow K^+ K^-)$, $A_{CP}(D^+ \rightarrow \phi \pi^+)$, $A_{CP}(D^0 \rightarrow K_S^0 K_S^0)$, ...

- Particularly relevant for future measurements. Key role of mixing and CPV in neutral kaon system and regeneration effect in matter.



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

Approaching extreme precision



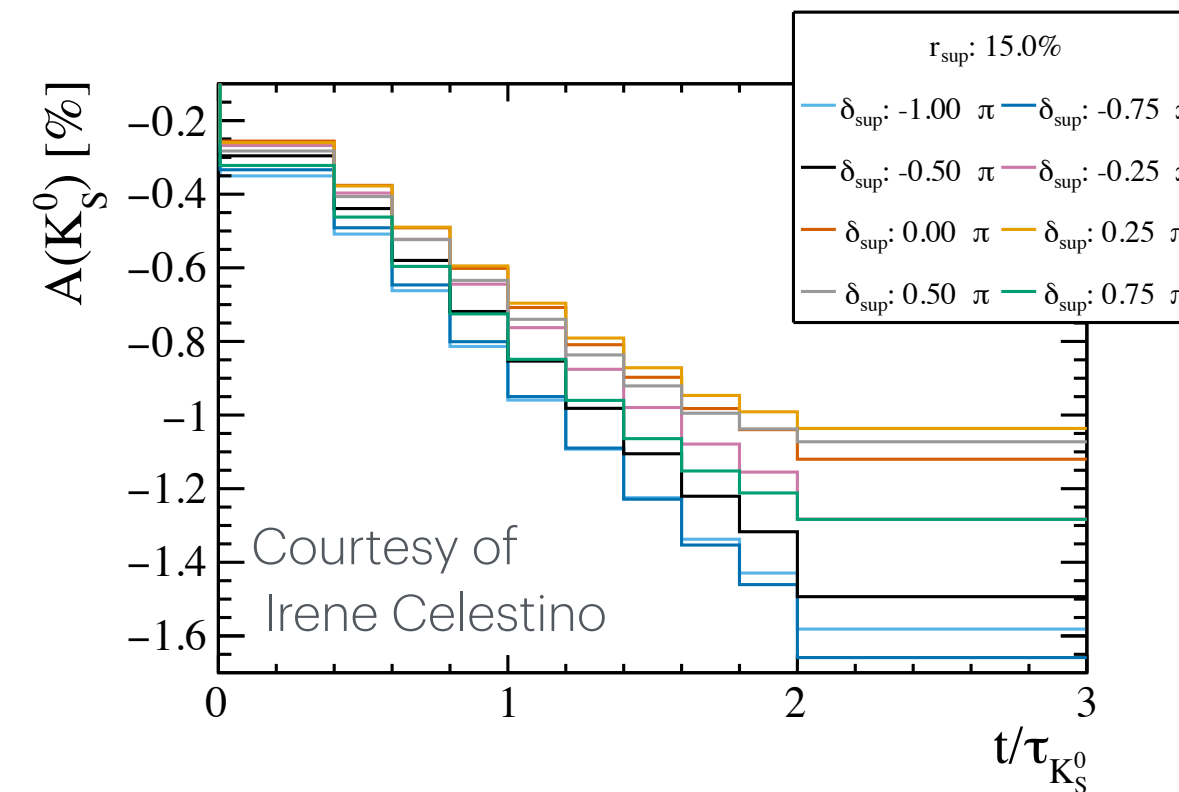
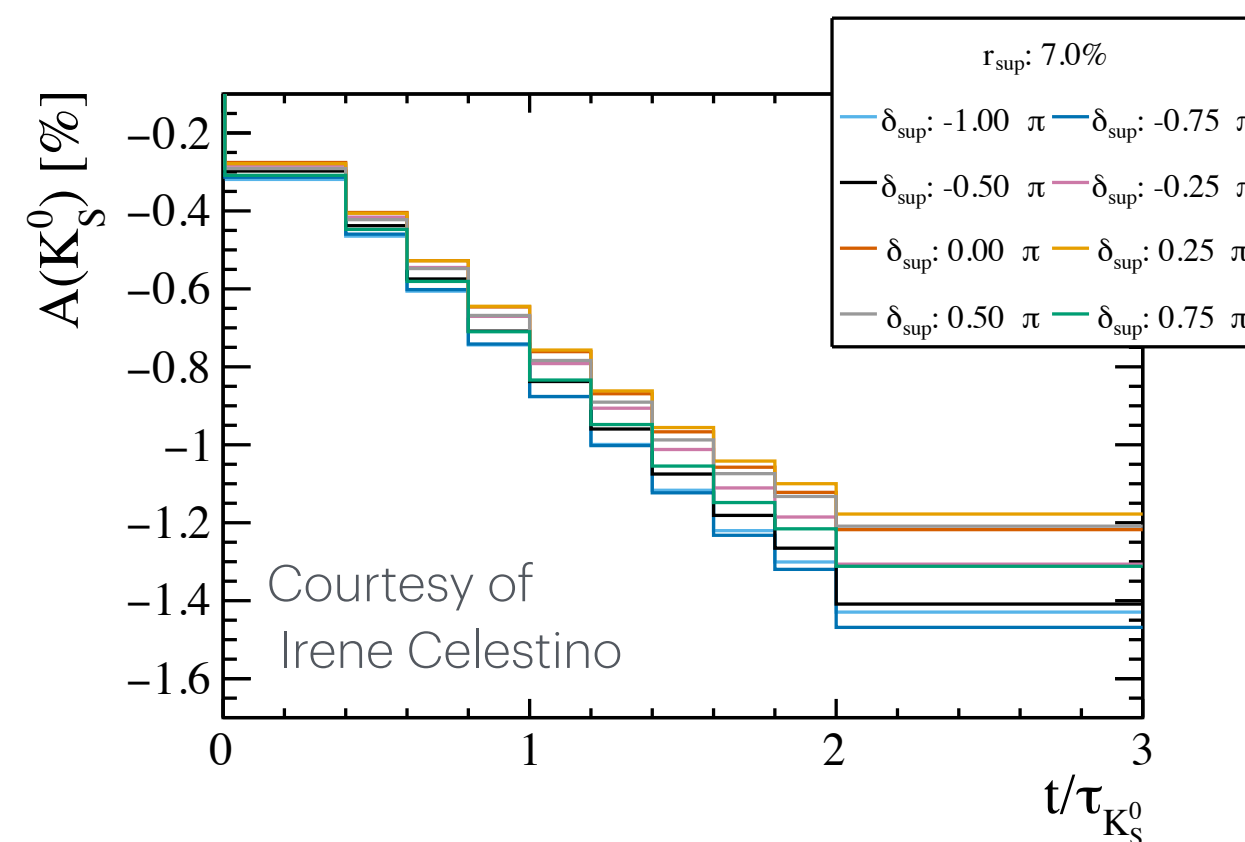
$$\begin{aligned} |\psi_K(0)\rangle &\propto \mathcal{A}(D^0 \rightarrow \bar{K}^0 \pi^+ \pi^-) |\bar{K}^0\rangle + \mathcal{A}(D^0 \rightarrow K^0 \pi^+ \pi^-) |K^0\rangle \\ &\equiv \mathcal{A}_{CF}^{tot} |\bar{K}^0\rangle + \mathcal{A}_{DCS}^{tot} e^{i\phi_{DCS}} |K^0\rangle \\ &\equiv \mathcal{A}_{CF}^{tot} [|\bar{K}^0\rangle + r_{tot} e^{i\delta_{tot} + \phi_{DCS}} |K^0\rangle], \end{aligned}$$

$$\begin{aligned} |\bar{\psi}_K(0)\rangle &\propto \mathcal{A}(\bar{D}^0 \rightarrow K^0 \pi^+ \pi^-) |K^0\rangle + \mathcal{A}(\bar{D}^0 \rightarrow \bar{K}^0 \pi^+ \pi^-) |\bar{K}^0\rangle \\ &= \mathcal{A}_{CF}^{tot} |K^0\rangle + \mathcal{A}_{DCS}^{tot} e^{-i\phi_{DCS}} |\bar{K}^0\rangle \\ &= \mathcal{A}_{CF}^{tot} [|\bar{K}^0\rangle + r_{tot} e^{i\delta_{tot} - \phi_{DCS}} |K^0\rangle]. \end{aligned}$$

- Neutral kaon time evolution essential.
- Multiple interfering processes including CF, DCS, kaon mixing (and D^0 mixing at some point) give mixture of $K^0/\bar{K}^0$ at $t = 0$.
- Necessary a precise knowledge of the detector material.
- “Coherent forward scattering” approximation used for regeneration up to now. [Fortschritte der Physik 21, 57-84 (1973), R. H. Good et al. PhysRev.124 (1961)1223]

[PRD98(2018) 112012]

Group	Resonance	Amplitude	Phase (deg)	Fit fraction (%)
CF	$K^*(892)^- \pi^+$	1.720 ± 0.006	136.8 ± 0.2	59.9
	$K_2^*(1430)^- \pi^+$	1.27 ± 0.02	-44.1 ± 0.8	1.3
	$K^*(1680)^- \pi^+$	3.31 ± 0.20	-118.2 ± 3.1	0.5
	$K^*(1410)^- \pi^+$	0.29 ± 0.03	99.4 ± 5.5	0.1
	$K_0^*(1430)^- \pi^+$	2.36 ± 0.06	99.4 ± 1.7	7.0
DCS	$K^*(892)^+ \pi^-$	0.164 ± 0.003	-42.2 ± 0.9	0.6
	$K_2^*(1430)^+ \pi^-$	0.10 ± 0.01	-89.6 ± 7.6	< 0.1
	$K^*(1410)^+ \pi^-$	0.21 ± 0.02	150.2 ± 5.3	< 0.1
	$K_0^*(1430)^+ \pi^-$	0.11 ± 0.01	162.3 ± 6.6	< 0.1
Neutrals	$K_1^0 \rho(770)^0$	1 (fixed)	0 (fixed)	20.4
	$K_1^0 \omega(782)$	0.0388 ± 0.0005	120.7 ± 0.7	0.5
	$K_1^0 f_2(1270)$	1.43 ± 0.03	-36.3 ± 1.1	0.8
	$K_1^0 \rho(1450)^0$	2.85 ± 0.10	102.1 ± 1.9	0.6
S-wave	β_1	8.5 ± 0.5	68.5 ± 3.4	10.0
	β_2	12.2 ± 0.3	24.0 ± 1.4	
	β_3	29.2 ± 1.6	-0.1 ± 2.5	
	β_4	10.8 ± 0.5	-51.9 ± 2.4	
	f_{11}^{prod}	8.0 ± 0.4	-126.0 ± 2.5	
	f_{12}^{prod}	26.3 ± 1.6	-152.3 ± 3.0	
	f_{13}^{prod}	33.0 ± 1.8	-93.2 ± 3.1	
	f_{14}^{prod}	26.2 ± 1.3	-121.4 ± 2.7	
	s_0^{prod}	-0.07 (fixed)		



Effective parametrization
(r_{sup}, δ_{sup})

Unknown mixture of CF/DCS ($K^0/\bar{K}^0$).

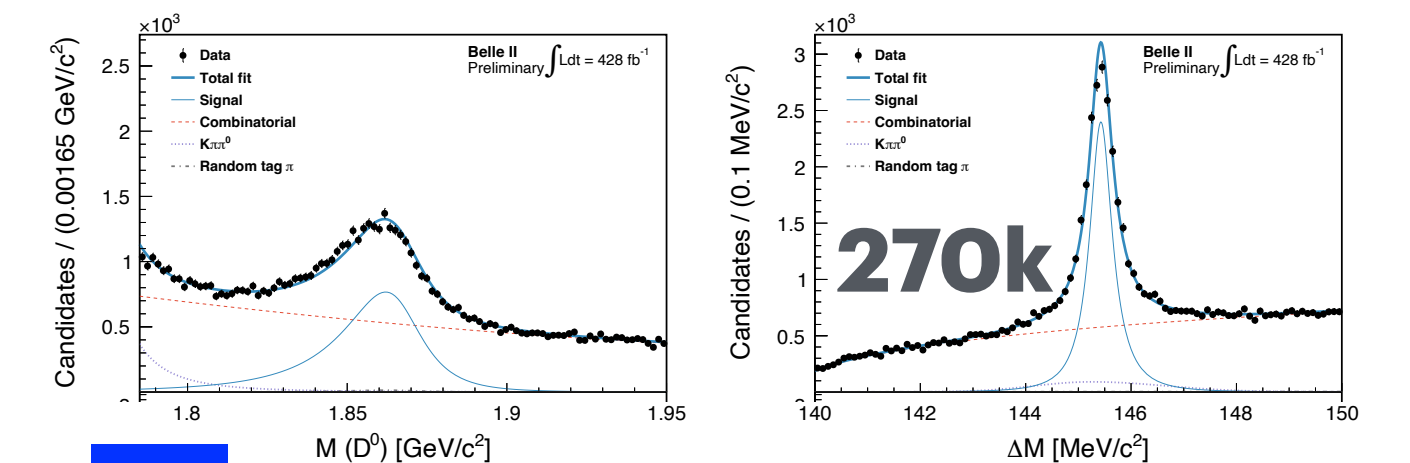
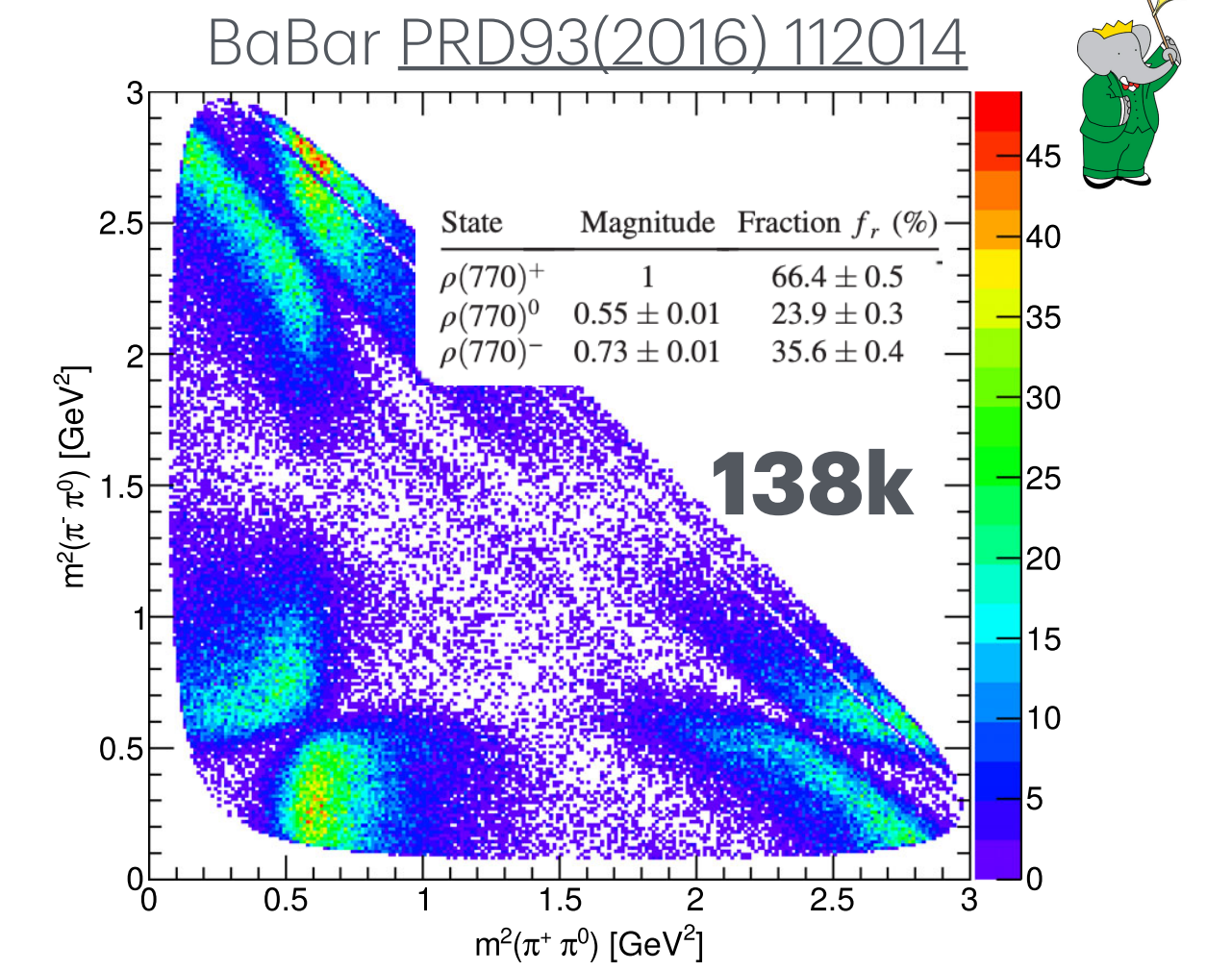
$$D^0 \rightarrow \pi^+ \pi^- \pi^0$$

An interesting opportunity

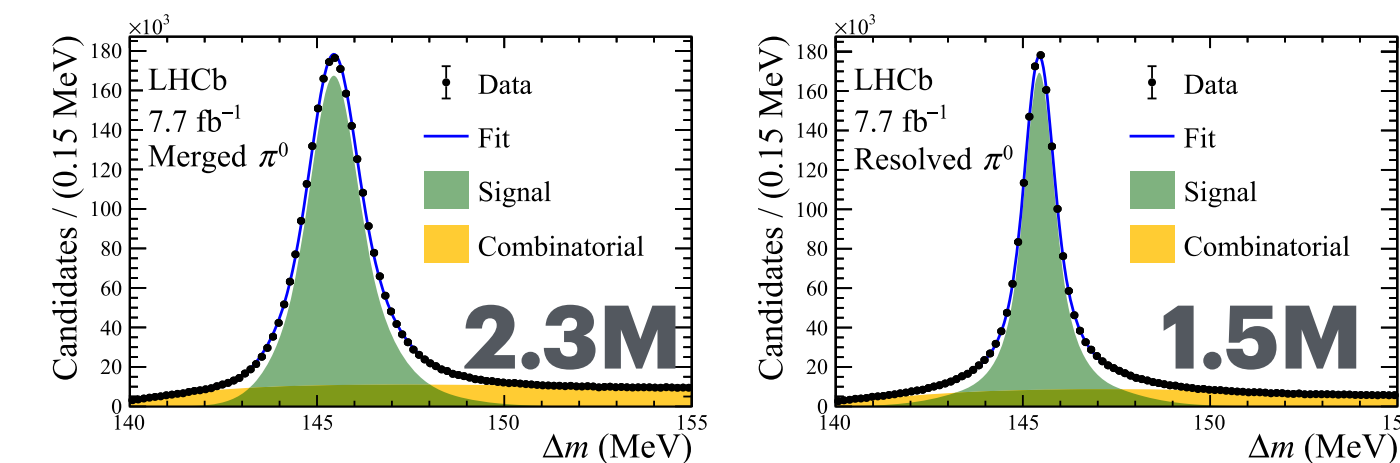
- Pseudo two-body decay have similarities with $D^0 \rightarrow \pi^+ \pi^-$. Interference of two-body decays leading to a common three-body final state can be used to extract penguin amplitude phase $\arg(P/T)$.

[Dery, Grossman, Schacht, Soffer [JHEP05\(2021\)179](#) and references therein].

- Search for CPV based on a model-independent method (Energy Test) with LHCb Run 2 data consistent with CP conservation (p-value: 62%) [[JHEP09\(2023\)129](#)].
- Time- and phase-space-integrated CP asymmetry by the Belle II experiment from 2019 to 2022, 428 fb⁻¹. Submitted to PRD [[2510.21224](#)].
- Time dependent CPV measured by LHCb [[PRL 133 \(2024\)101803](#)] with Run1+2 data. The CP-even fraction measured using CLEO-c data is $F_+^{\pi\pi\pi^0} = 0.973 \pm 0.017$ providing almost undiluted sensitivity.



$$\mathcal{A}_{CP} = (0.29 \pm 0.27 \pm 0.13)\%$$



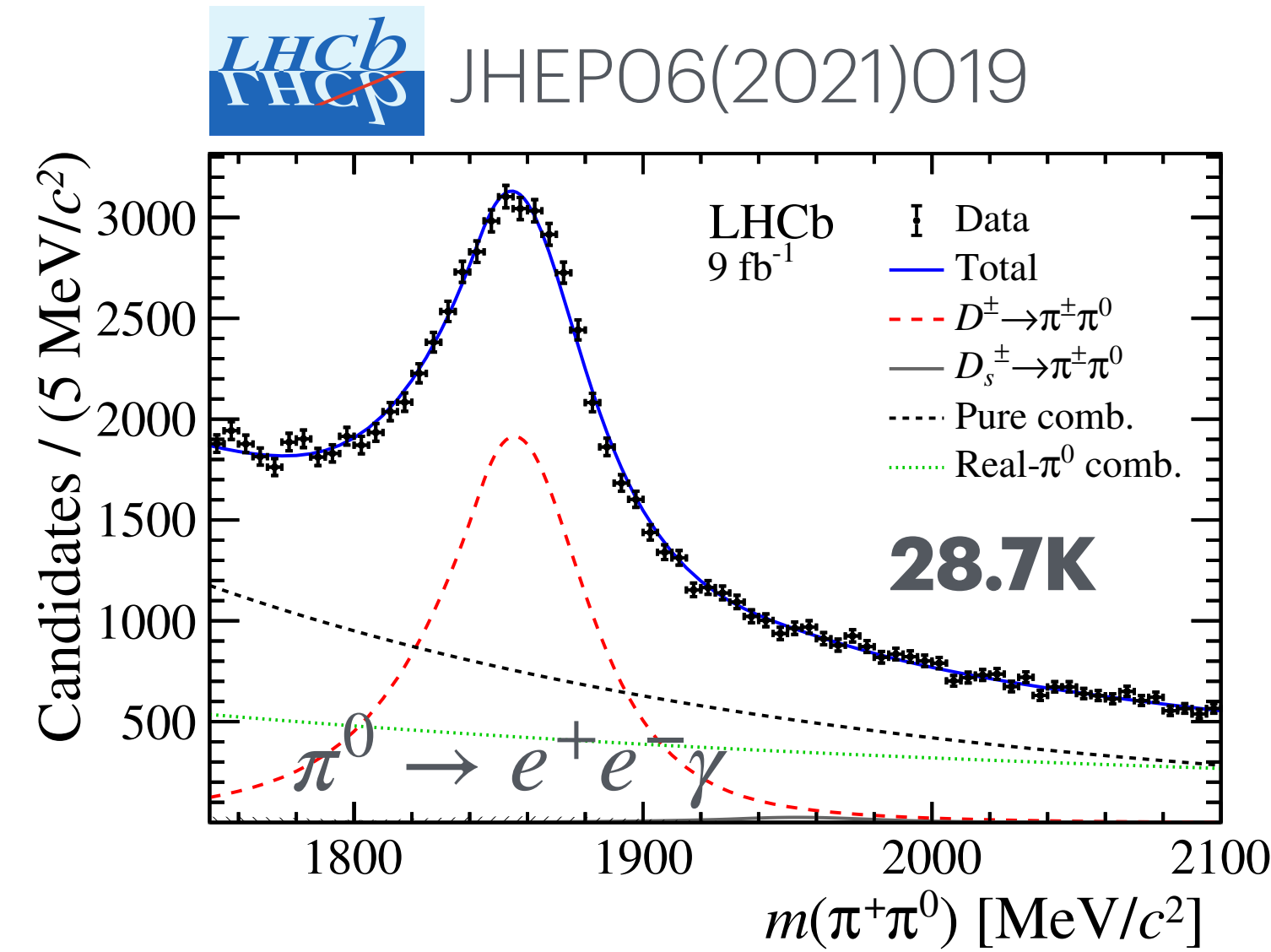
$$\Delta Y = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$$

$$\Delta Y_f^{\text{eff}} = (2F_+^f - 1)\Delta Y$$

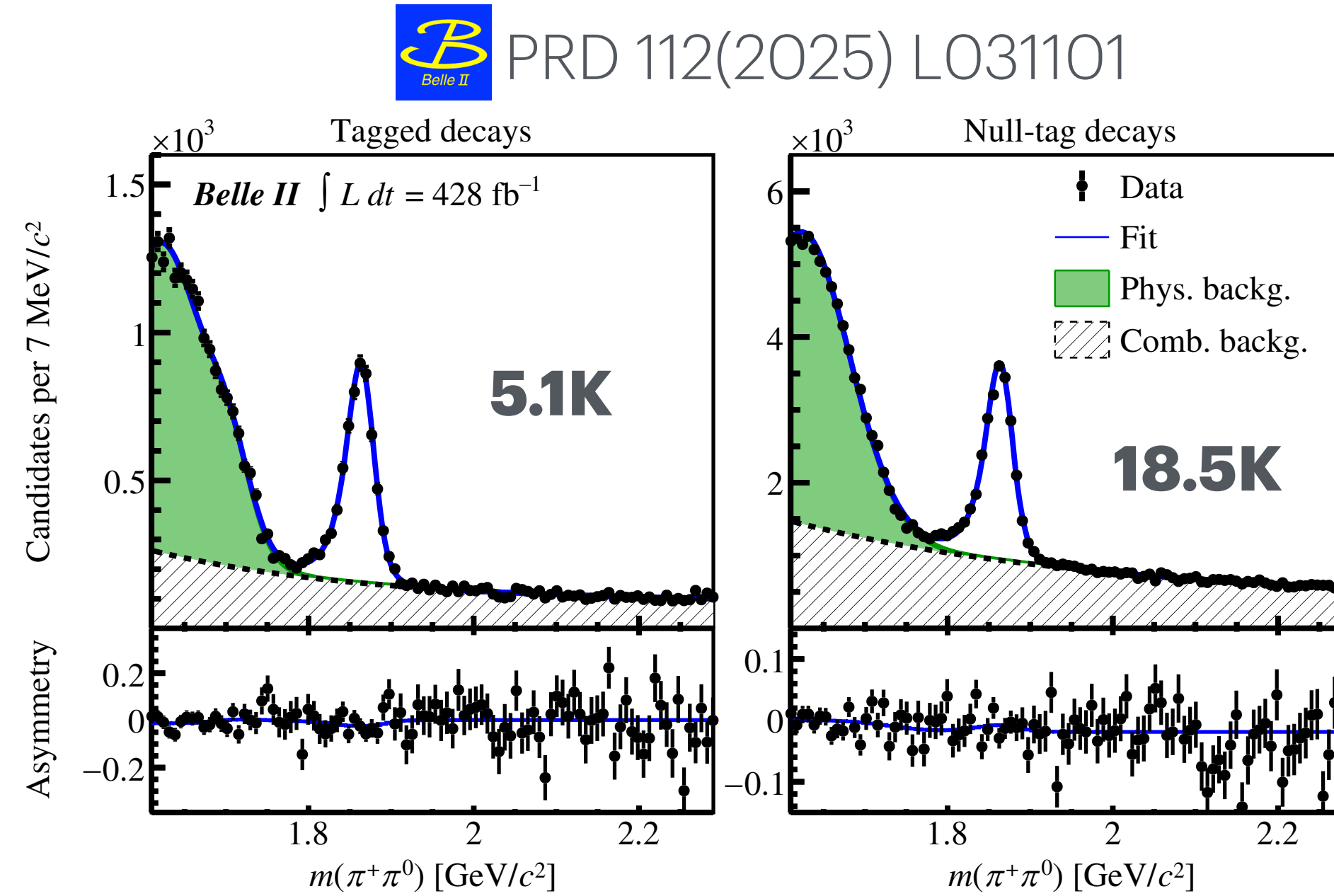
Two-body decays with π^0

Note that for isospin symmetry
 $A_{CP}^{dir}(D^+ \rightarrow \pi^+ \pi^0) = 0$ in SM.

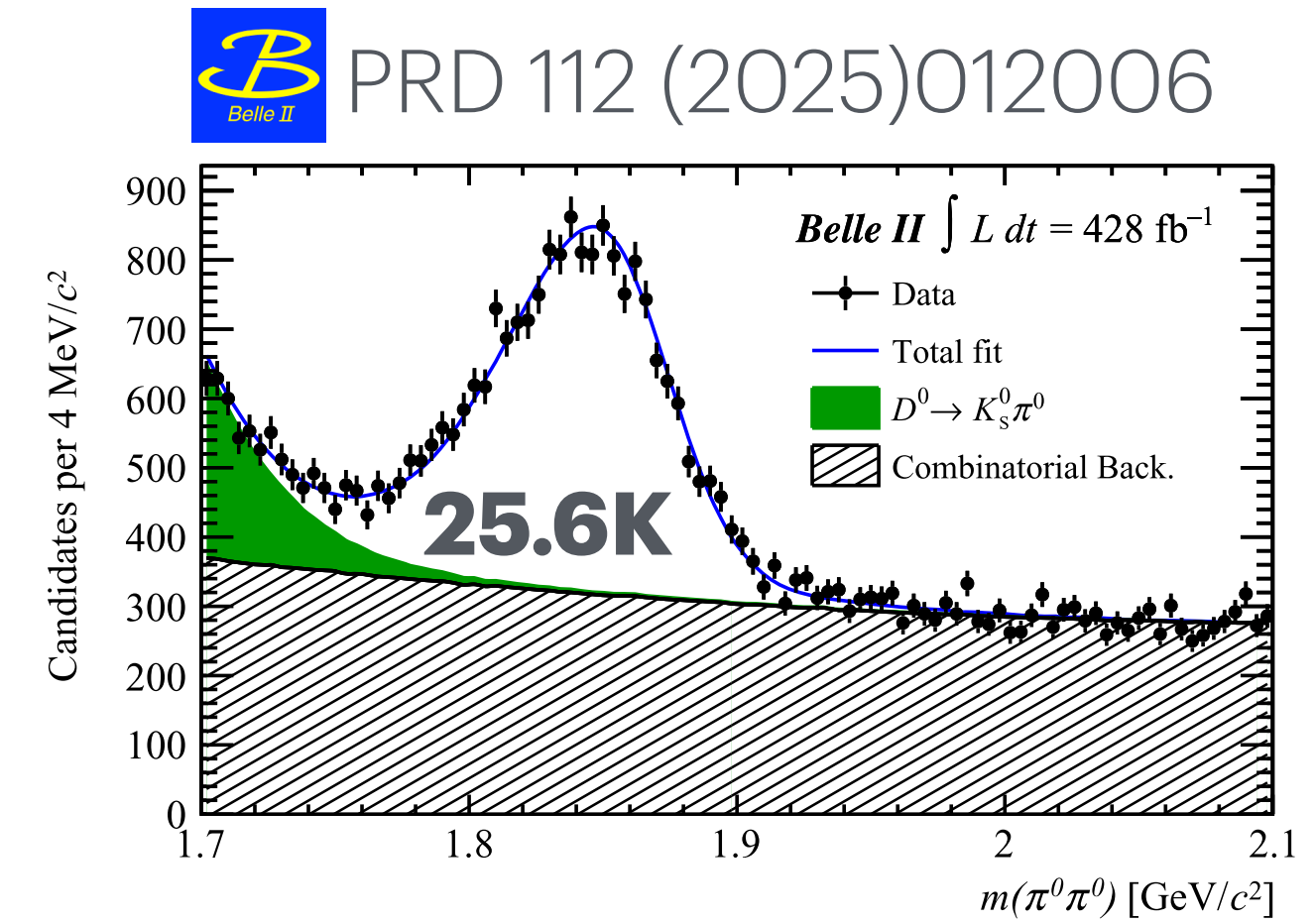
[only at B-factories]



$$A_{CP}(D^+ \rightarrow \pi^+ \pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%$$



$$A_{CP}(D^+ \rightarrow \pi^+ \pi^0) = (-1.8 \pm 0.9 \pm 0.1)\%$$



$$A_{CP}(D^0 \rightarrow \pi^0 \pi^0) = (0.30 \pm 0.72 \pm 0.20)\%$$

$$R = \frac{A_{CP}^{dir}(D^0 \rightarrow \pi^+ \pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}} \left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} - \frac{2}{3} \frac{\mathcal{B}_{+0}}{\tau_{D^+}} \right)} + \frac{A_{CP}^{dir}(D^0 \rightarrow \pi^0 \pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}} \left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} - \frac{2}{3} \frac{\mathcal{B}_{+0}}{\tau_{D^+}} \right)} + \frac{A_{CP}^{dir}(D^+ \rightarrow \pi^+ \pi^0)}{1 - \frac{3}{2} \frac{\tau_{D^+}}{\mathcal{B}_{+0}} \left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}} \right)}$$

$R = (1.5 \pm 2.5) \times 10^{-3}$, precision of the sum rule improved by approximately 20% with latest measurement of $A_{CP}(D^0 \rightarrow \pi^0 \pi^0)$. Still limited by the precision on it.

Putting it all together [LHCb-CONF-2025-003]

CKM angle γ and charm mixing

The world averages for direct measurements of γ are $(66.4^{+2.7}_{-2.8})^\circ$, based on a frequentist framework from the Heavy Flavour Averaging Group [14], and $(65.7 \pm 2.5)^\circ$, based on a Bayesian framework by the UFit collaboration [15]. Both averages are dominated by LHCb results [16]. The experimental uncertainty on γ is larger than the indirect determination obtained from global CKM fits, $\gamma = (66.3^{+0.7}_{-1.9})^\circ$ using a frequentist framework from the CKMfitter collaboration [17], and $\gamma = (64.9 \pm 1.4)^\circ$ with a Bayesian approach from the UFit collaboration [18].

New inputs since LHCb-CONF-2024-004:

LHCb: $B^\pm \rightarrow D(\rightarrow h^+h^-\pi^+\pi^-)h^\pm$ [2509.1539]

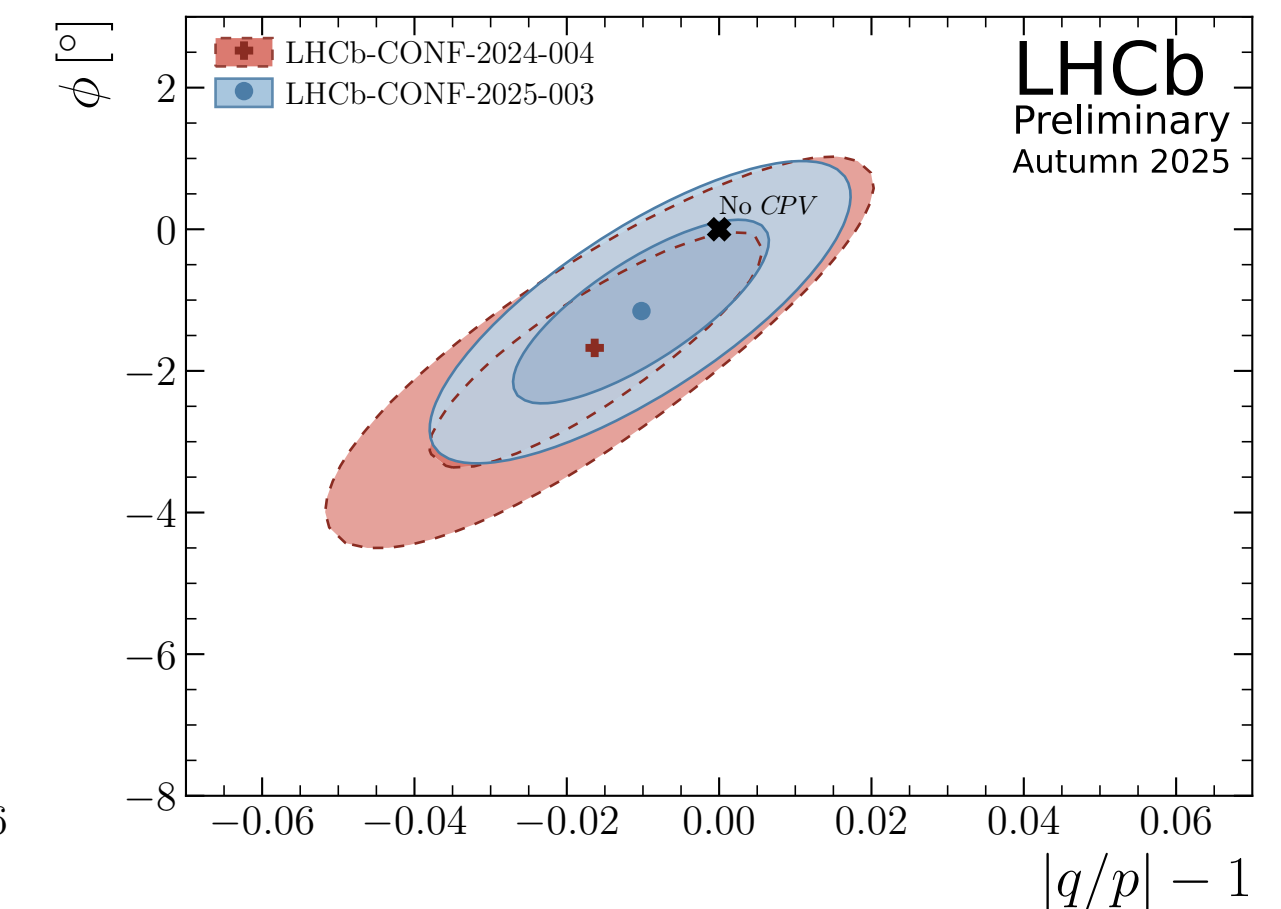
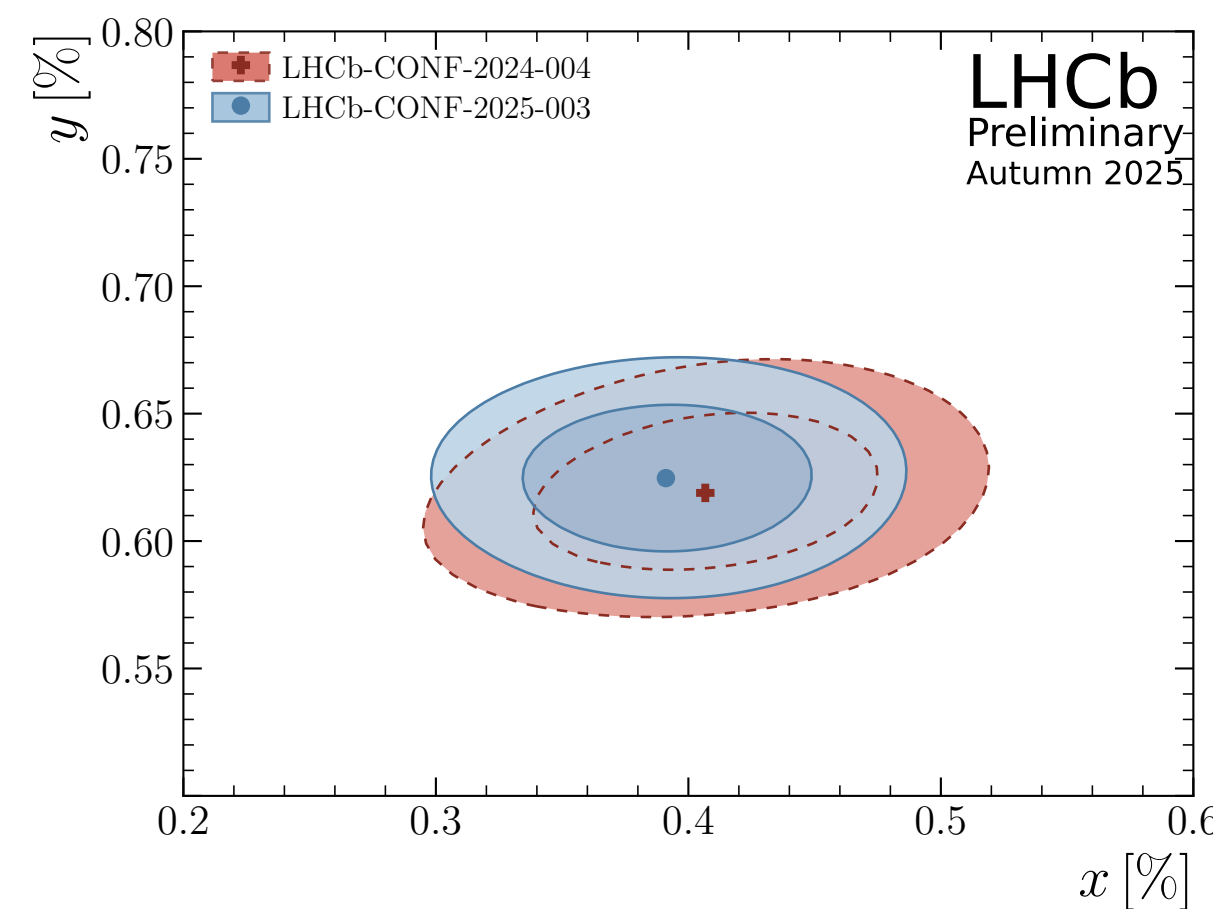
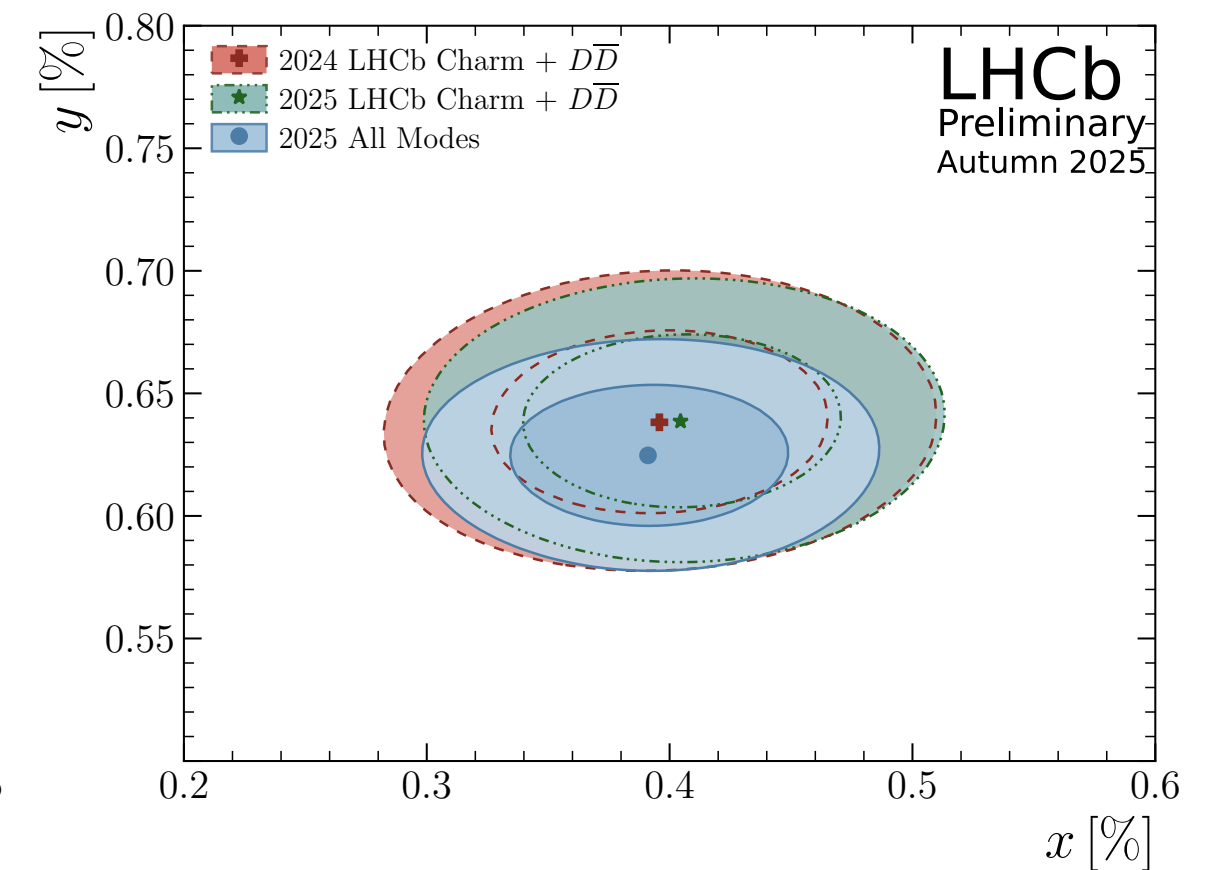
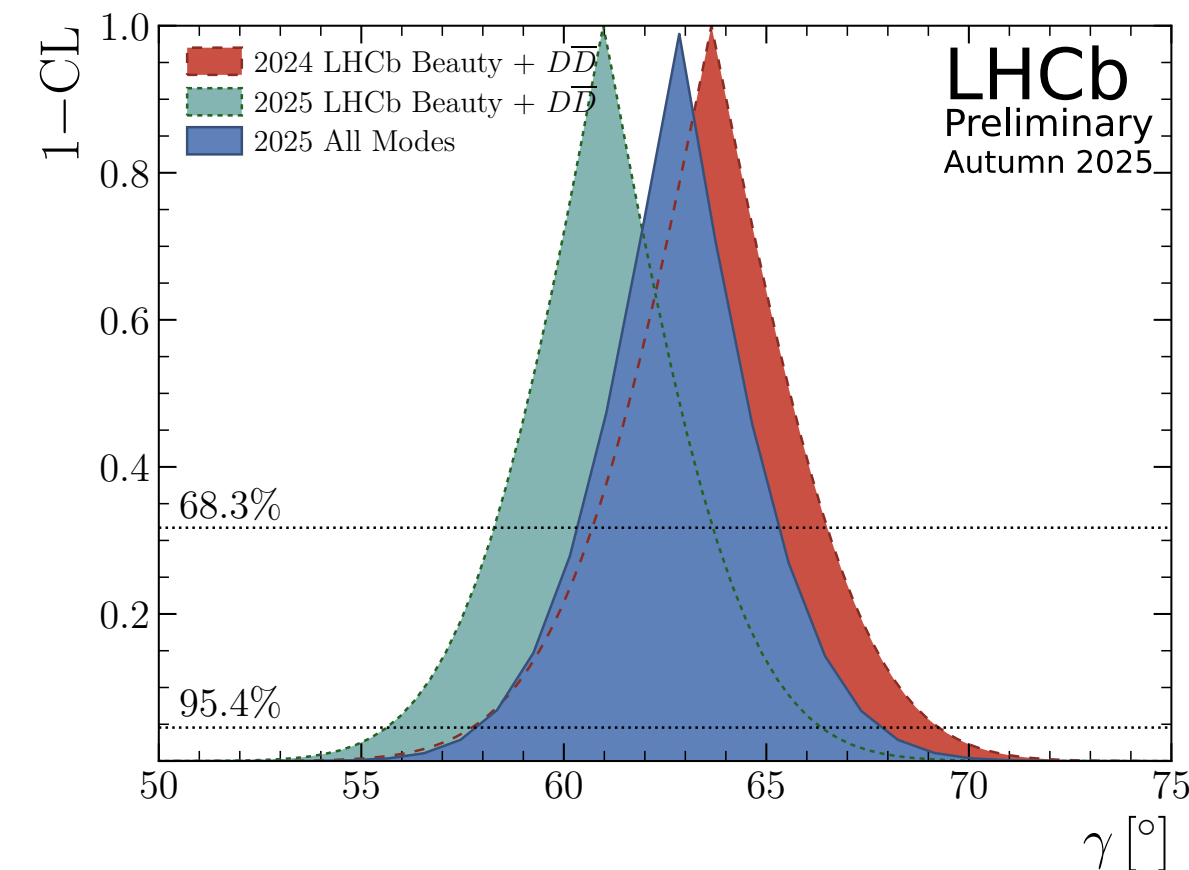
LHCb: $D^0 \rightarrow K\pi\pi\pi$ [2514.04963]

LHCb: $D \rightarrow K^\mp\pi^\pm$ Doble Tag [JHEP03(2025)149]

BESIII: $D \rightarrow K^-\pi^+$ [PRD112(2025)072006]

BESIII: $D \rightarrow h^+h^-\pi^0$ [PRD111(2025)012007]

Parameter	Value
γ [°]	62.8 ± 2.6
$r_{B^\pm}^{DK^\pm}$ [%]	$9.72^{+0.19}_{-0.18}$
$\delta_{B^\pm}^{DK^\pm}$ [°]	$123.3^{+2.8}_{-3.0}$
$r_{B^\pm}^{D\pi^\pm}$ [%]	$0.49^{+0.06}_{-0.05}$
$\delta_{B^\pm}^{D\pi^\pm}$ [°]	$282.9^{+9.8}_{-10.4}$
x [%]	0.391 ± 0.042
y [%]	0.625 ± 0.020
$r_D^{K\pi}$ [%]	5.857 ± 0.009
$\delta_D^{K\pi}$ [°]	192.7 ± 2.3
$ q/p $	$0.990^{+0.011}_{-0.012}$
ϕ [°]	-1.2 ± 0.9



$[1^\circ \approx 1.7 \times 10^{-2} \text{ rad}]$

Putting it all together [LHCb-CONF-2025-003]

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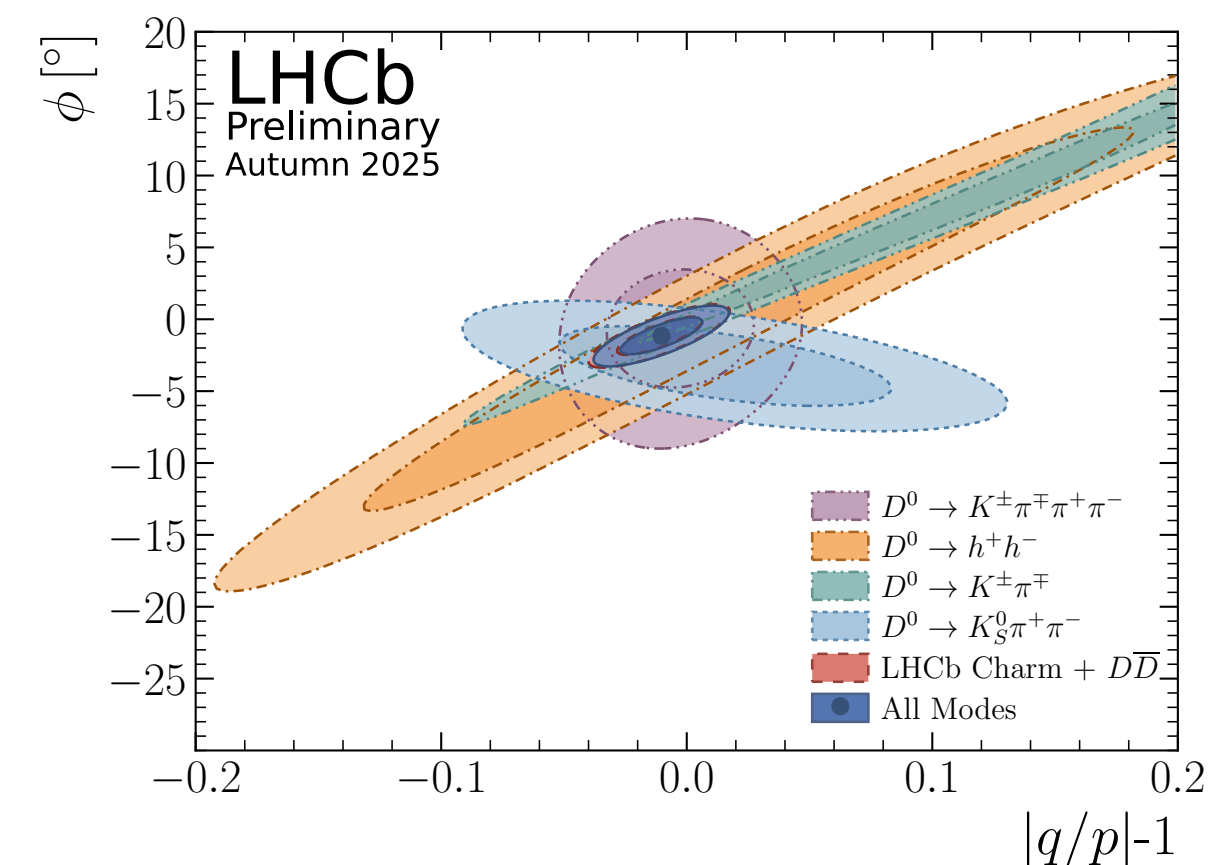
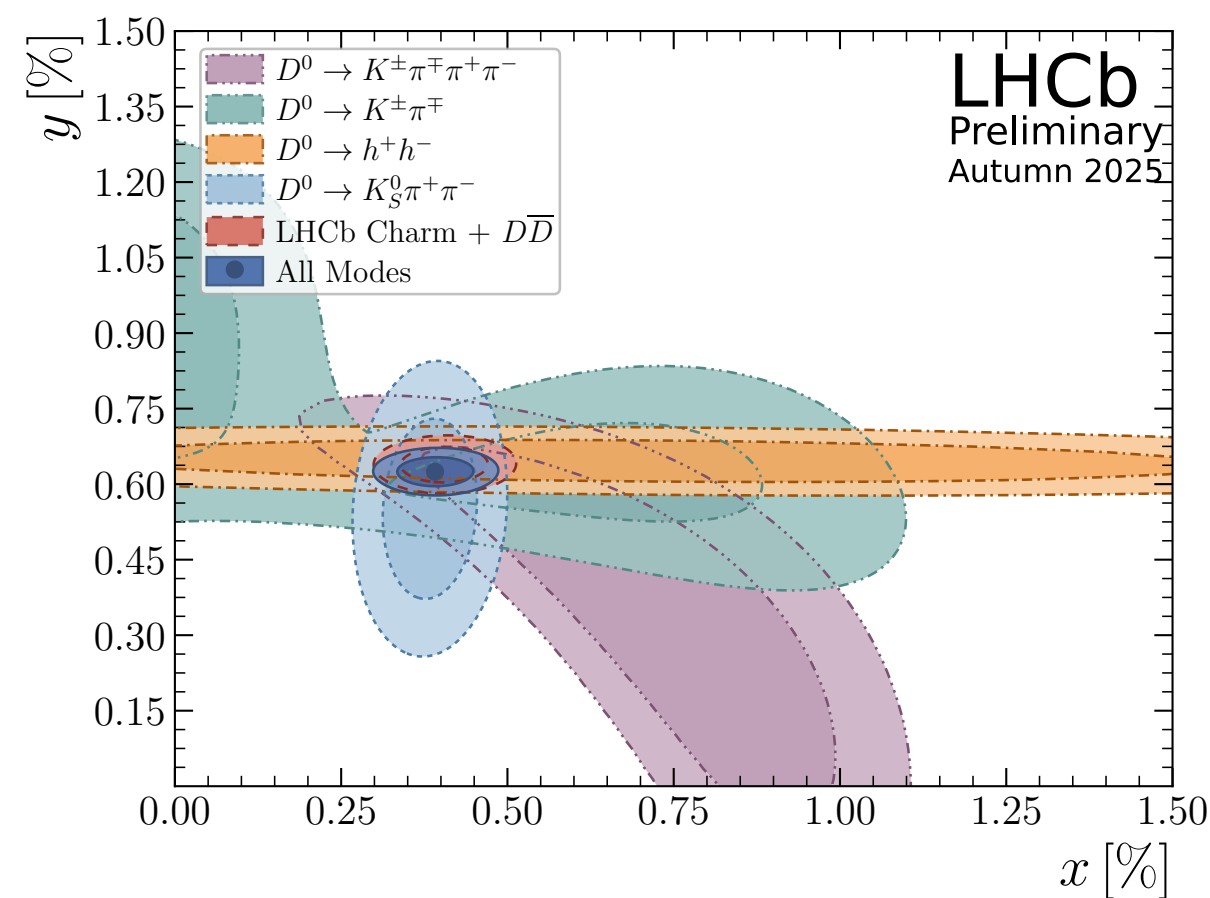
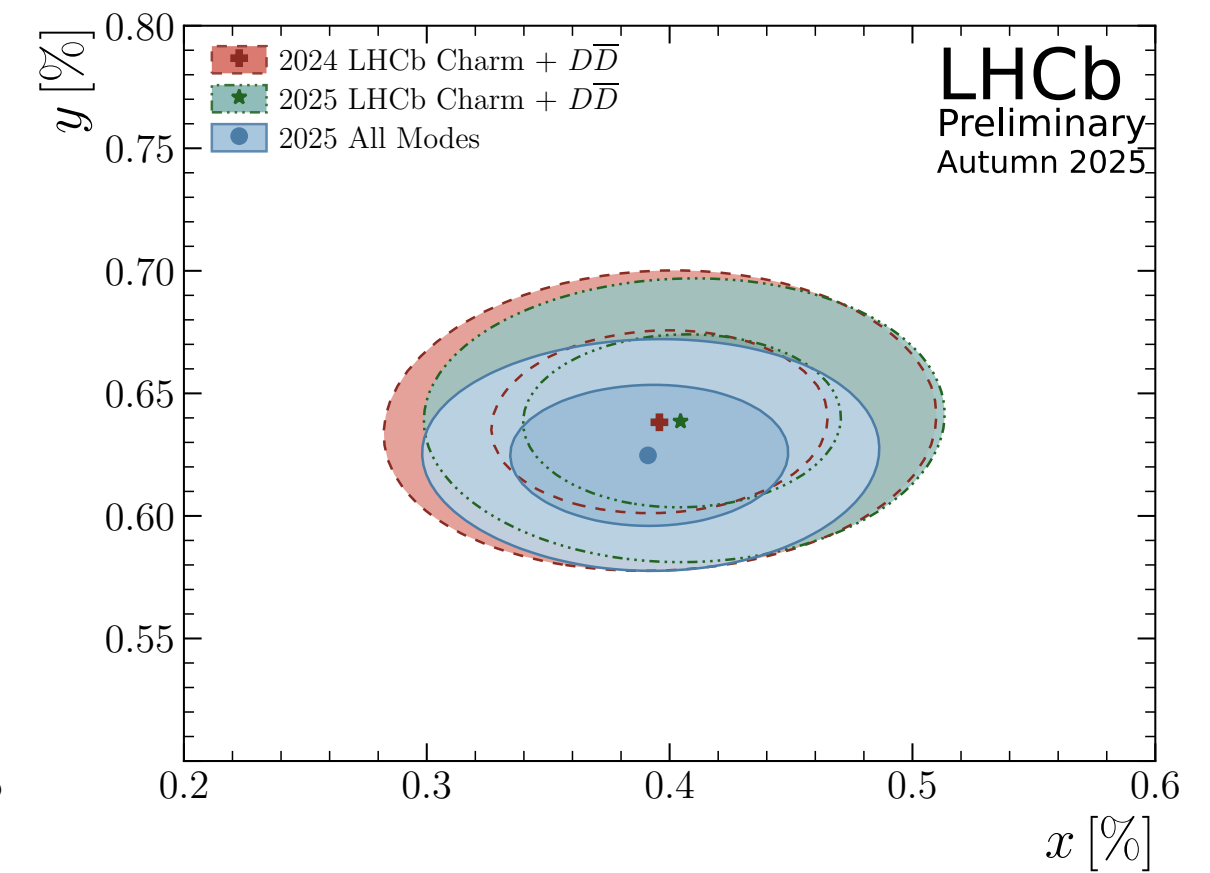
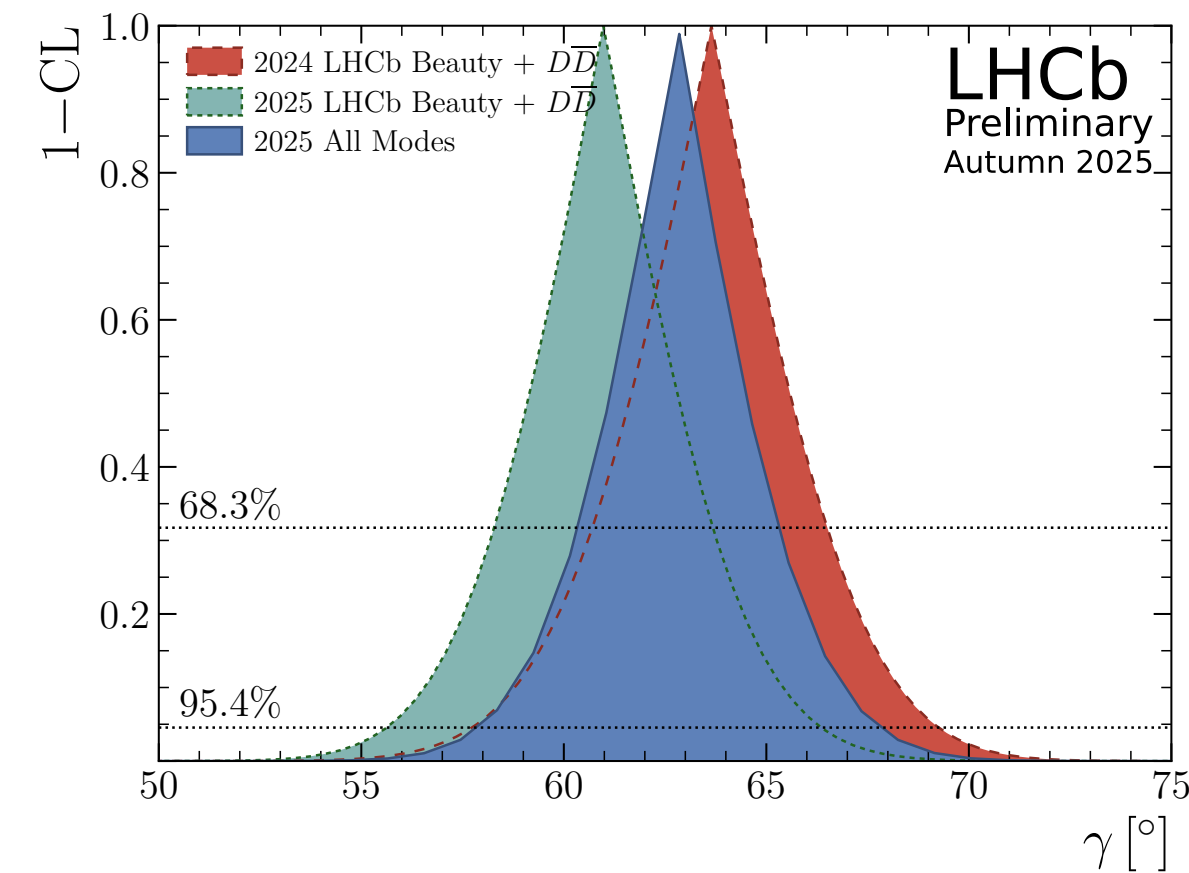
LHCb: $D^0 \rightarrow K\pi\pi\pi$ [2514.04963]

LHCb: $D \rightarrow K^\mp\pi^\pm$ Doble Tag [JHEP03(2025)149]

BESIII: $D \rightarrow K^-\pi^+$ [PRD112(2025)072006]

BESIII: $D \rightarrow h^+h^-\pi^0$ [PRD111(2025)012007]

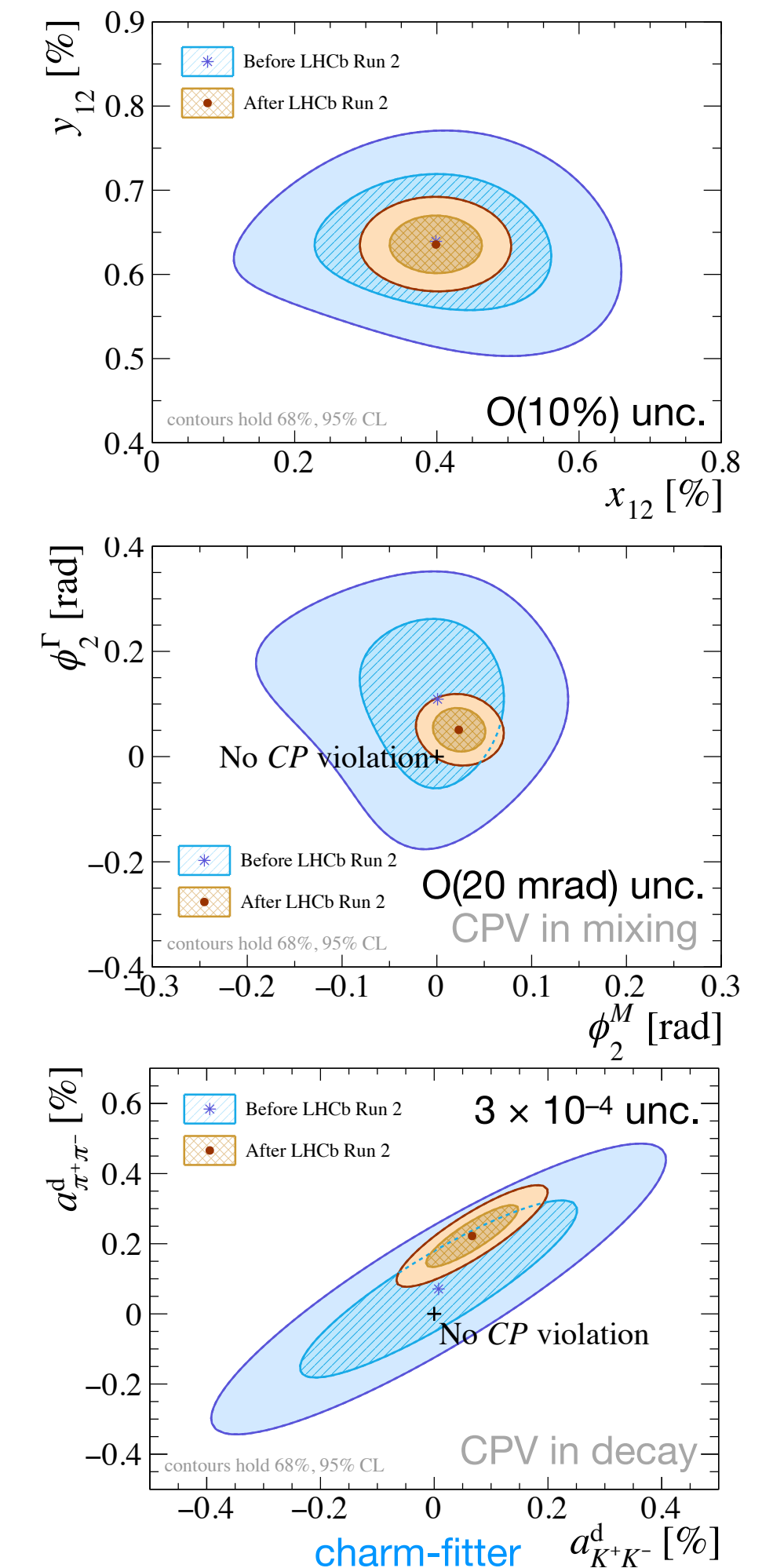
Parameter	Value
γ [°]	62.8 ± 2.6
$r_{B^\pm}^{DK^\pm}$ [%]	$9.72^{+0.19}_{-0.18}$
$\delta_{B^\pm}^{DK^\pm}$ [°]	$123.3^{+2.8}_{-3.0}$
$r_{B^\pm}^{D\pi^\pm}$ [%]	$0.49^{+0.06}_{-0.05}$
$\delta_{B^\pm}^{D\pi^\pm}$ [°]	$282.9^{+9.8}_{-10.4}$
x [%]	0.391 ± 0.042
y [%]	0.625 ± 0.020
$r_D^{K\pi}$ [%]	5.857 ± 0.009
$\delta_D^{K\pi}$ [°]	192.7 ± 2.3
$ q/p $	$0.990^{+0.011}_{-0.012}$
ϕ [°]	-1.2 ± 0.9



$[1^\circ \approx 1.7 \times 10^{-2} \text{ rad}]$

Conclusions

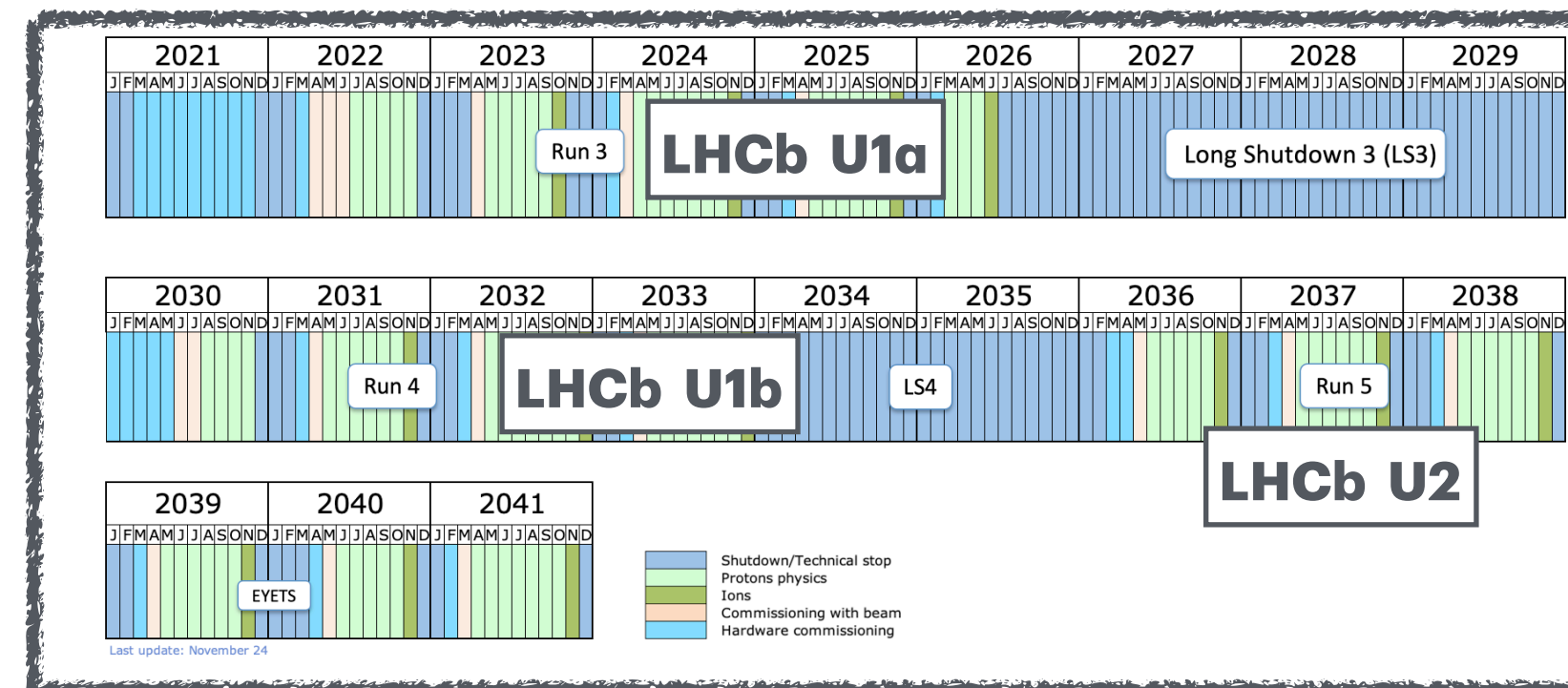
- After 50 years, Charm is still a “young” and “attractive” field with many open questions and is moving fast.
- The last decade has been astonishing, launching us into a level of precision never seen before. Still plenty of room for unexpected things.
- **Theory input essential for the success of current and future experiments.** Not only CP asymmetries (BFs, strong phases,...). Guidance and new ideas on where to look next are very welcome. **Please don't be afraid to ask for specific decay process or for new observables.**
- **Multibody decays are becoming more and more important.** We welcome feedback on how to best tackle them (besides amplitude analyses) to make the results most useful for theorists while waiting for new CPV observations



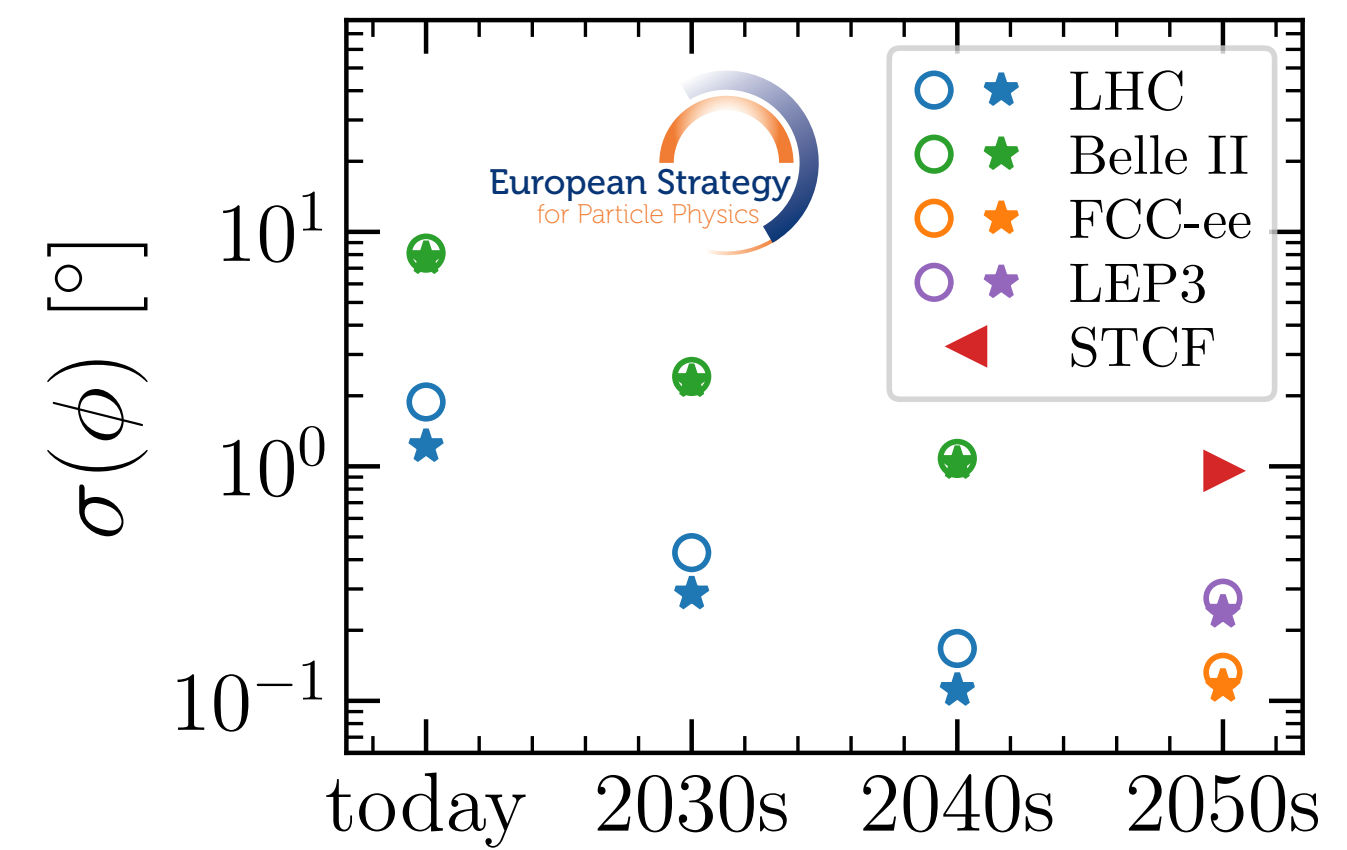
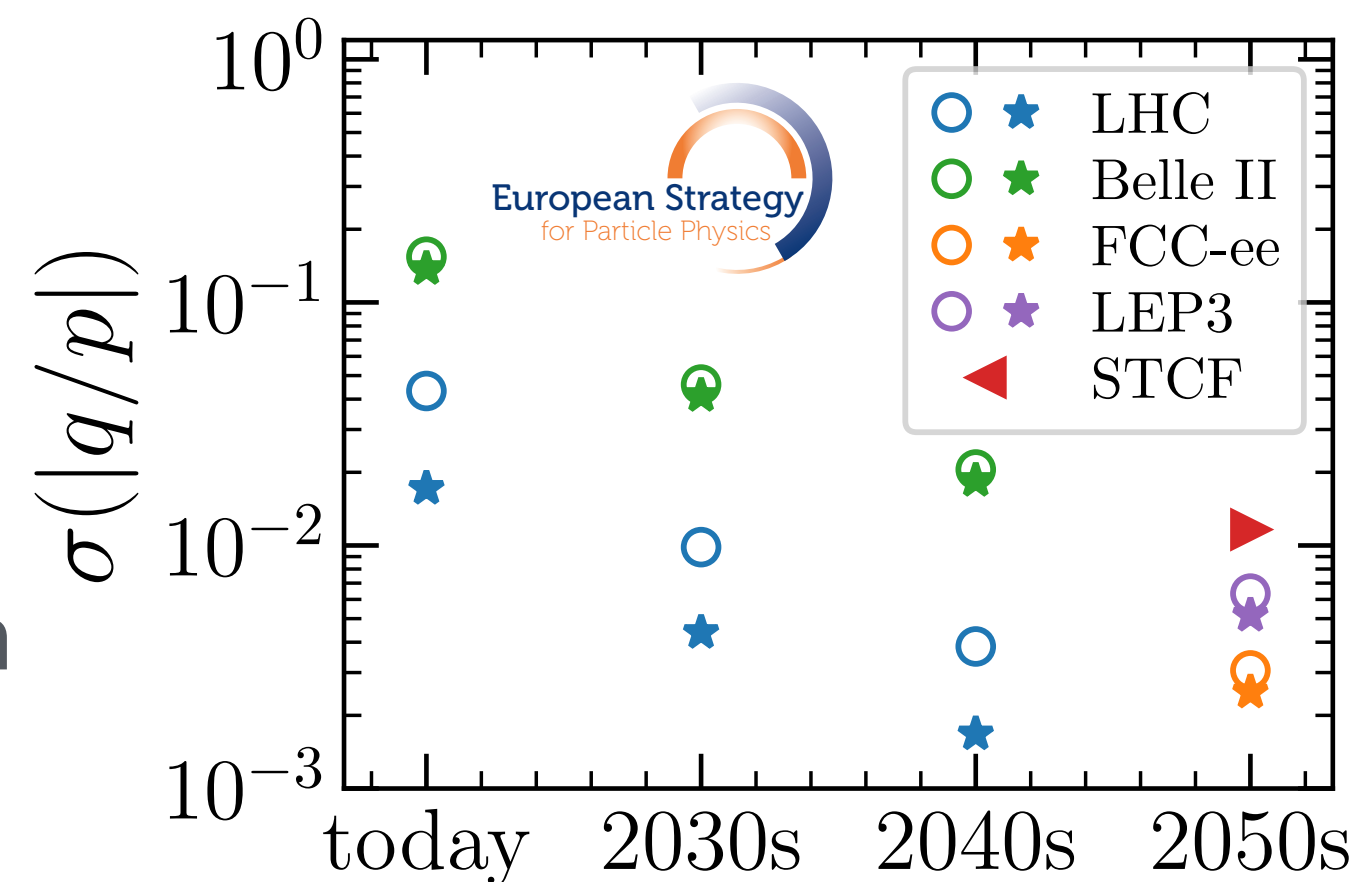
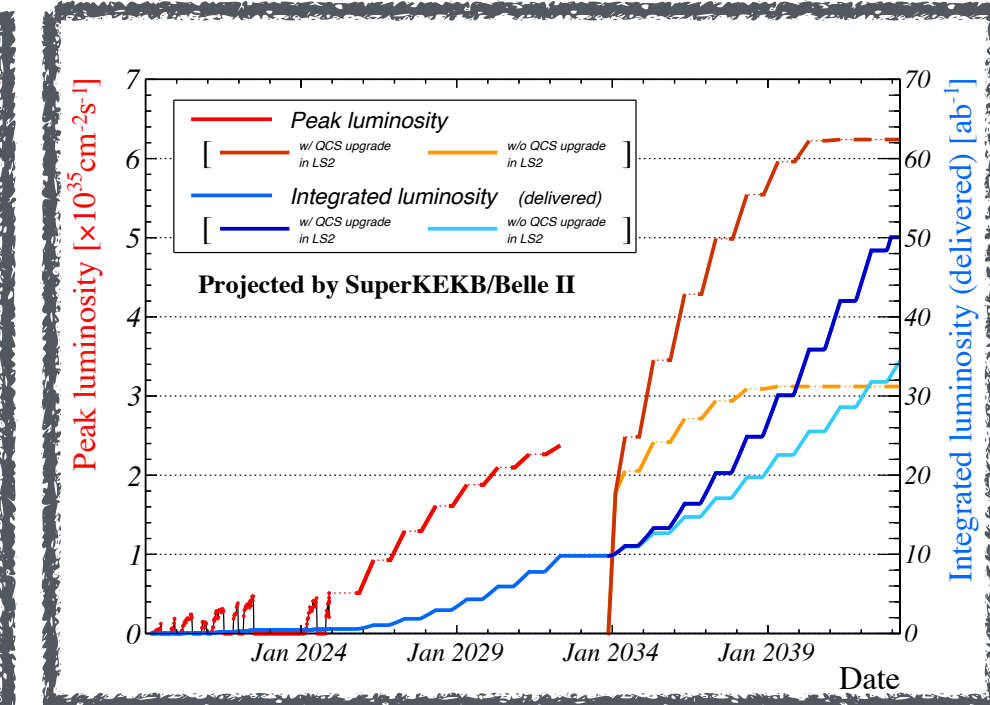
Future perspectives

- LHCb Upgrade I (Run3) will end by June 2026. Already collected 9(12) fb⁻¹ during 2024(2025) of good data.
 - For hadronic channels efficiency/fb-1 improved by a factor of 2 wrt Run2.
- LHCb will collect data after LS3 during Run4, and during Run5 with an Upgraded detector (Phase 2) with a goal of 300 fb-1.
- With a similar time scale Belle II (and its upgrades) aims at collecting 50 ab-1 of data.
- **LHCb and BelleII very competitive in charm physics, even in the era of future facilities.**

LHC schedule (today)



BelleII projections

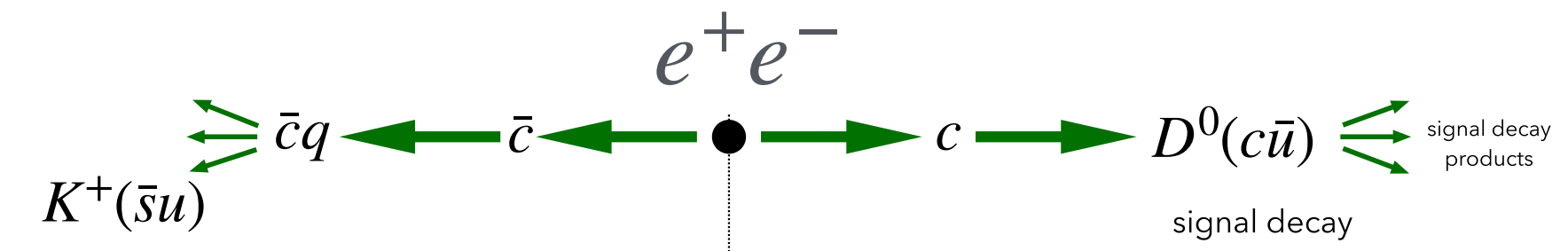


Physics Briefing Book — Input for the 2026 update of the European Strategy for Particle Physics [2511.03883]

Backup

How we measure CP asymmetries

- D^0 flavour cannot be inferred from the final state if this is shared by D^0 and $\bar{D}^0$. Rely on production.
 - Strong decay $D^{*+}(2010) \rightarrow D^0 \pi^+$
 - Semi-leptonic decay. i.e. $B^+ \rightarrow \bar{D}^0 \ell^+ \nu_\ell$
 - Charm Flavor Tagger at B-Factories [[PRD 107, 112010 \(2023\)](#)]
 - Quantum correlated production in $e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$ (**allow measurement of strong phases**).



$$A_{\text{raw}}(f) = \frac{N(D \rightarrow f) - N(\bar{D} \rightarrow \bar{f})}{N(D \rightarrow f) + N(\bar{D} \rightarrow \bar{f})} \approx \boxed{A_{CP}(f)} + \boxed{A_{\text{det}}(f)} + \boxed{A_{\text{prod}}(D)}$$

a_f^d + small time-dependent contribution (for D^0)

Detection asymmetry of π^+ tag and final-state (if not self-conjugate)

production asymmetry

Removed by difference with raw asym. of one or more control samples CF decays (assuming CPV=0), often include K_S^0 limiting sensitivity ($D^+ \rightarrow K_S^0 \pi^+$, $D_s^+ \rightarrow K_S^0 K^+$, ...). Use also CS decays for which CPV is known with better precision.

A first look into the future

- LHCb-Upgrade I will collect by the end of Run3 (Jun 2026) more than 20 fb⁻¹ of good data **with eff./fb⁻¹ > 2 wrt Run2 (for hadrons)**.
- ΔA_{CP} expected to quickly reach precision $\approx 1 \times 10^{-4}$
- $A_{CP}(D^0 \rightarrow K^+ K^-)$ more challenging, being dominated by calibration channels. New calibration modes needed:
 - $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ very promising already with Run2 data ($\approx 5 \times 10^{-4}$). See N. Kleijne at [Moriond EW 2024](#). Potentially much better in Run 3.
 - $\Lambda_c^+ \rightarrow p K^- \pi^+$ and $\Lambda_c^+ \rightarrow K_S^0 p$,
- Increase the knowledge of kaon asymmetry $A(K^0)$ in order to not limit precision on future measurements. Large samples of K_S^0 mesons with higher decay time very desirable.

New method to measure $A_{CP}(K^+ K^-)$ My PhD thesis

Signal decay: $D^0 \rightarrow K^+ K^-$
 Calibration decay: $D^0 \rightarrow \pi^+ \pi^-$

$$A_{obs}(D^{*+} \rightarrow D^0(\rightarrow K^+ K^-) \pi_{tag}^+) = A_{CP}(K^+ K^-) + A_P(D^{*+}) + A_D(\pi_{tag}^+)$$

$$A_{obs}(D^{*+} \rightarrow D^0(\rightarrow \bar{K}^0 \pi^+ \pi^-) \pi_{tag}^+) = A_{CP}(\bar{K}^0 \pi^+ \pi^-) + A_P(D^{*+}) + A_D(\pi_{tag}^+) + A_D(\pi^+ \pi^-) + A_D(\bar{K}^0)$$

N. Kleijne at [Moriond EW 2024](#). 6/7

A side note on $A_{CP}(D^+ \rightarrow \phi \pi^+)$

What we measure at LHCb

$$\Delta A_{K_S^0}(t) \equiv A_{\text{raw}}(D^+ \rightarrow K_S^0 \pi^+) - A_{\text{raw}}(D^+ \rightarrow \phi \pi^+)$$

$$= A_{\text{det}}(K_S^0, t) - A_{CP}(D^+ \rightarrow \phi \pi^+)$$

CPV in charm decay: $\text{Im}(\frac{V_{cb}^* V_{ub}}{V_{cb}^* V_{ub}}) \approx 10^{-5}$

CPV in kaon mixing: $\approx \text{Re}(e) \approx 10^{-3}$

CPV in interference between D⁺ decay and kaon mixing: $\text{Im}(e) \text{Re}(\frac{V_{cb}^* V_{ub}}{V_{cb}^* V_{ub}}) \approx 10^{-3}$

$A_{\text{det}}(K_S^0, t) = A_{CP}^{\text{charm}} + A_{CP}^{\text{kaon}}(t) + \text{regeneration (and interference)}$

crucially depends on

$$\frac{A(D^+ \rightarrow K^0 \pi^+)}{A(D^+ \rightarrow \bar{K}^0 \pi^+)} \equiv r_{\pi} e^{i\delta_{\pi}}$$

Yu Wang Li: Phys. Rev. Lett. 119 (2017) 18, 181802

12th Charm Workshop - 14 May 2025

T. Pajero at [CHARM 2025](#).

Kind request to our theory colleagues

Values fitted to data in the FAT approach:

$$r_{\pi^+} = -0.073 \pm 0.004, \quad \delta_{\pi^+} = -1.39 \pm 0.05$$

Yu Wang Li: Phys. Rev. Lett. 119 (2017) 18, 181802

What systematic uncertainties should we assign?
 Can solid predictions be provided?
 Otherwise treating them as nuisance parameters will limit our precision in Upgrade I

Note: with the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ multiple interfering CF/DCS amplitudes. See next.

12th Charm Workshop - 14 May 2025

Mixing and CPV with $D^0 \rightarrow K\pi$

Nuisance asymmetries removal

Physics observable

$$R_{K\pi}^{\pm}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})t + (c'_{K\pi} \pm \Delta c'_{K\pi})t^2.$$

Experimental observable includes instrumental asymmetries, A_i^I , in each decay-time bin i (production and π tag asymmetries)

$$\tilde{R}_i^{\pm} = R_i^{\pm}(1 \pm 2A_i^I),$$

Correct using raw asymmetry of $D^{*+} \rightarrow D^0(\rightarrow K^+K^-)\pi^+$

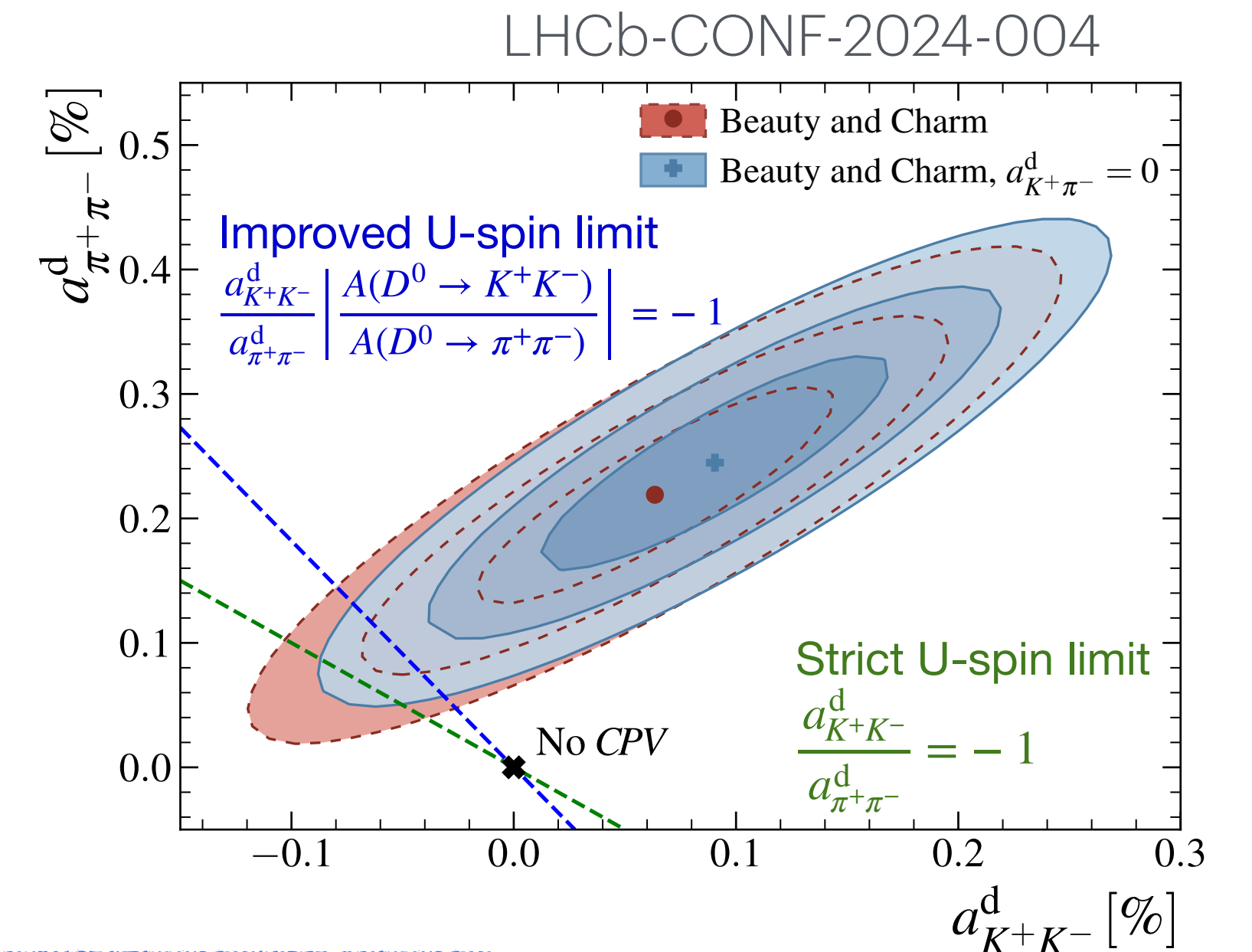
$$A_i^I = A_{\text{raw}}(KK)_i - (a_{K^+K^-}^d + \Delta Y_{K^+K^-} \cdot \langle t_i \rangle)$$

$$\tilde{A}_{K\pi} \approx A_{K\pi} - 2a_{K^+K^-}^d \approx a_{K^+\pi^-}^d - 2a_{K^+K^-}^d \leftarrow$$

$$\Delta \tilde{c}_{K\pi} \approx \Delta c_{K\pi} - c_{K\pi} a_{K^+K^-}^d - 2\sqrt{R_{K\pi}} \Delta Y_{K^+K^-}$$

$$\Delta \tilde{c}'_{K\pi} \approx \Delta c'_{K\pi} - 2c'_{K\pi} a_{K^+K^-}^d - 2\sqrt{R_{K\pi}} c_{K\pi} \Delta Y_{K^+K^-}$$

- Sensitive to $a_{K^+K^-}^d$ if assuming no CPV in DCS decays ($a_{K^+\pi^-}^d = 0$).
- Probe a CP-violating observable free from any assumption.
- Competitive by increasing the accuracy on $\Delta c_{K\pi} \approx \phi_2^M x_{12}$.



$$a_{K^+K^-}^d = (6.4 \pm 5.3) \times 10^{-4}$$

$$a_{\pi^+\pi^-}^d = (21.9 \pm 5.8) \times 10^{-4}$$

$$a_{K^+K^-}^d = (9.1 \pm 5.2) \times 10^{-4}$$

$$a_{\pi^+\pi^-}^d = (24.5 \pm 5.7) \times 10^{-4}$$

Time-dependent measurement in $D^0 \rightarrow h^+ h^-$

ΔY and y_{CP}

$$A_{CP}(f, t) \approx a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}},$$

$$\begin{aligned} \phi_f^M &\equiv \phi_2^M + \delta\phi_f \\ \delta\phi_f &= -a_f^d \cot \delta_f \end{aligned}$$

$$\Delta Y_f \approx (-x_{12} \sin \phi_f^M + y_{12} a_f^d) \approx -x_{12} \sin \phi_2^M + y_{12} a_f^d \left(1 + \frac{x_{12}}{y_{12}} \cot \delta_f \right)$$

Less than 0.1×10^{-4} by using experimental info on $a_{\pi^+\pi^-}^d$ and $a_{K^+K^-}^d$.

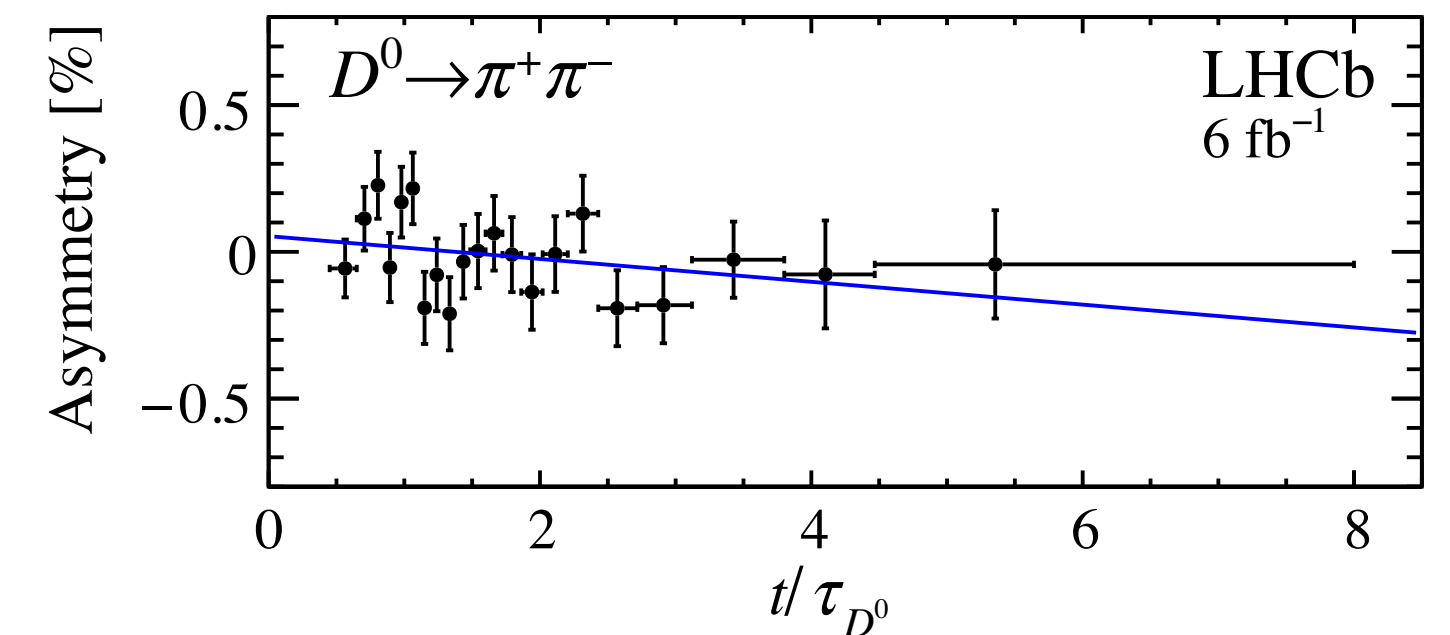
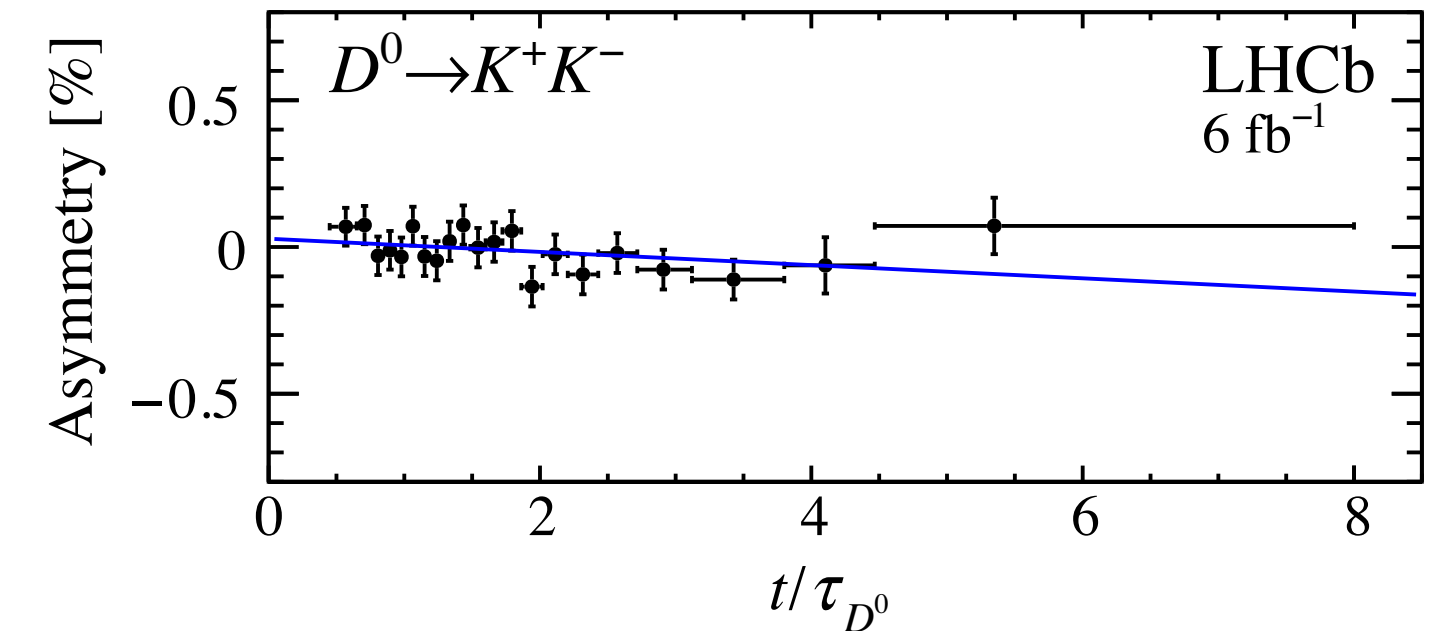
Can enhance the dependence on the final state, even though the phase δ_f is expected to be of $\mathcal{O}(1)$ due to large rescattering at the charm mass scale.

$$\frac{\hat{\Gamma}(D^0 \rightarrow f) + \hat{\Gamma}(\bar{D}^0 \rightarrow f)}{\hat{\Gamma}(D^0 \rightarrow K^- \pi^+) + \hat{\Gamma}(\bar{D}^0 \rightarrow K^+ \pi^-)} - 1 \approx y_{CP}^f - y_{CP}^{K\pi}.$$

$$y_{CP}^f = y_{12} \cos \phi_f^\Gamma,$$

Current experimental accuracy probes
mixing (strong phase in WS/RS $D^0 \rightarrow K\pi$)

$$y_{CP}^{K\pi} \approx \sqrt{R_D}(x_{12} \cos \phi_2^M \sin \delta_{K\pi} + y_{12} \cos \phi_2^\Gamma \cos \delta_{K\pi}) \approx -0.4 \times 10^{-3}$$



$$\Delta Y = (-2.7 \pm 1.3 \pm 0.3) \times 10^{-4},$$

Phys. Rev. D 104 (2021) 072010

$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}.$$

Phys. Rev. D 105(2022) 092013



LHCb-CONF-2025-003
November 5, 2025

Simultaneous determination of the CKM angle γ and parameters related to mixing and CP violation in the charm sector

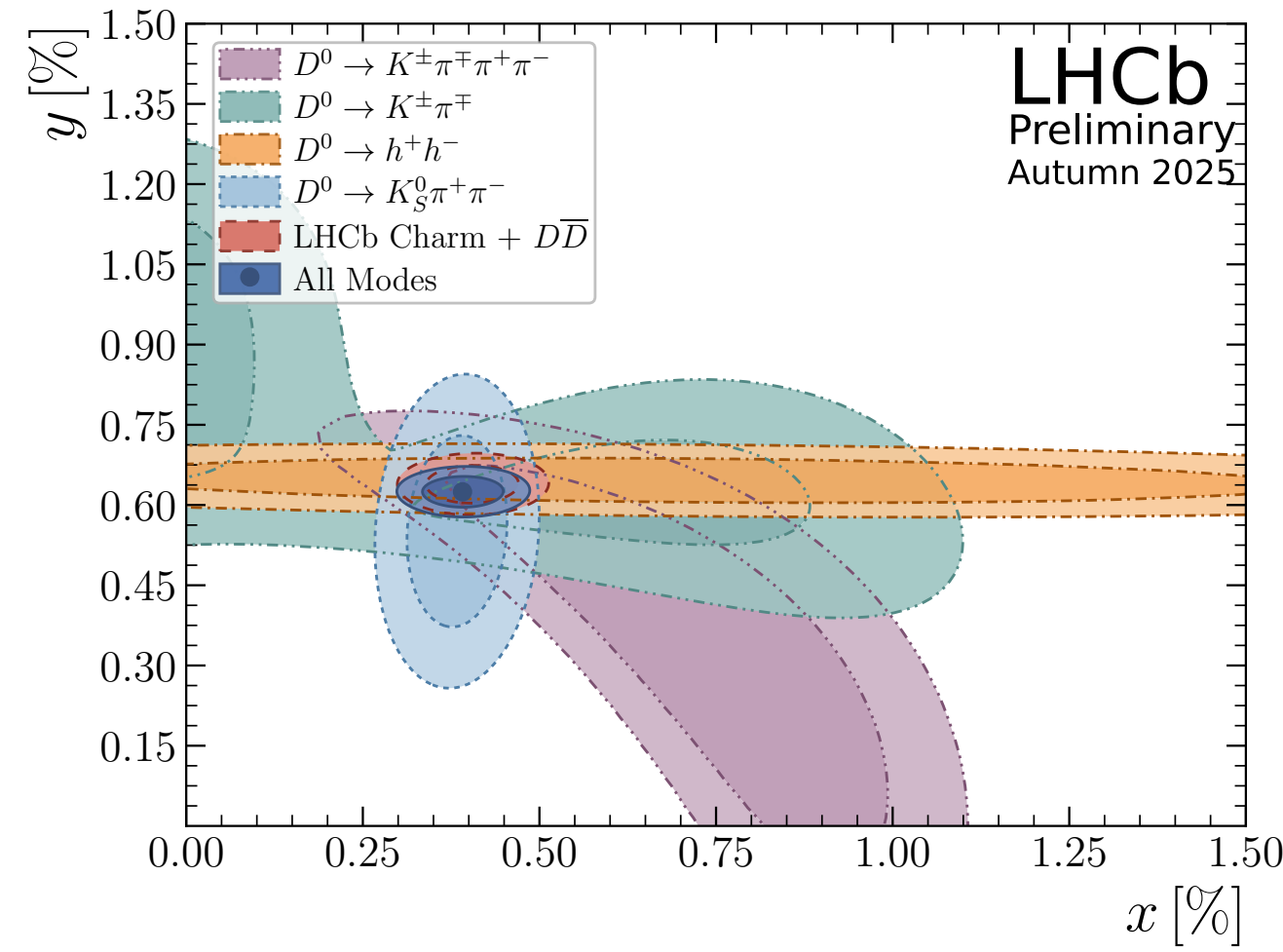
LHCb collaboration[†]

Abstract

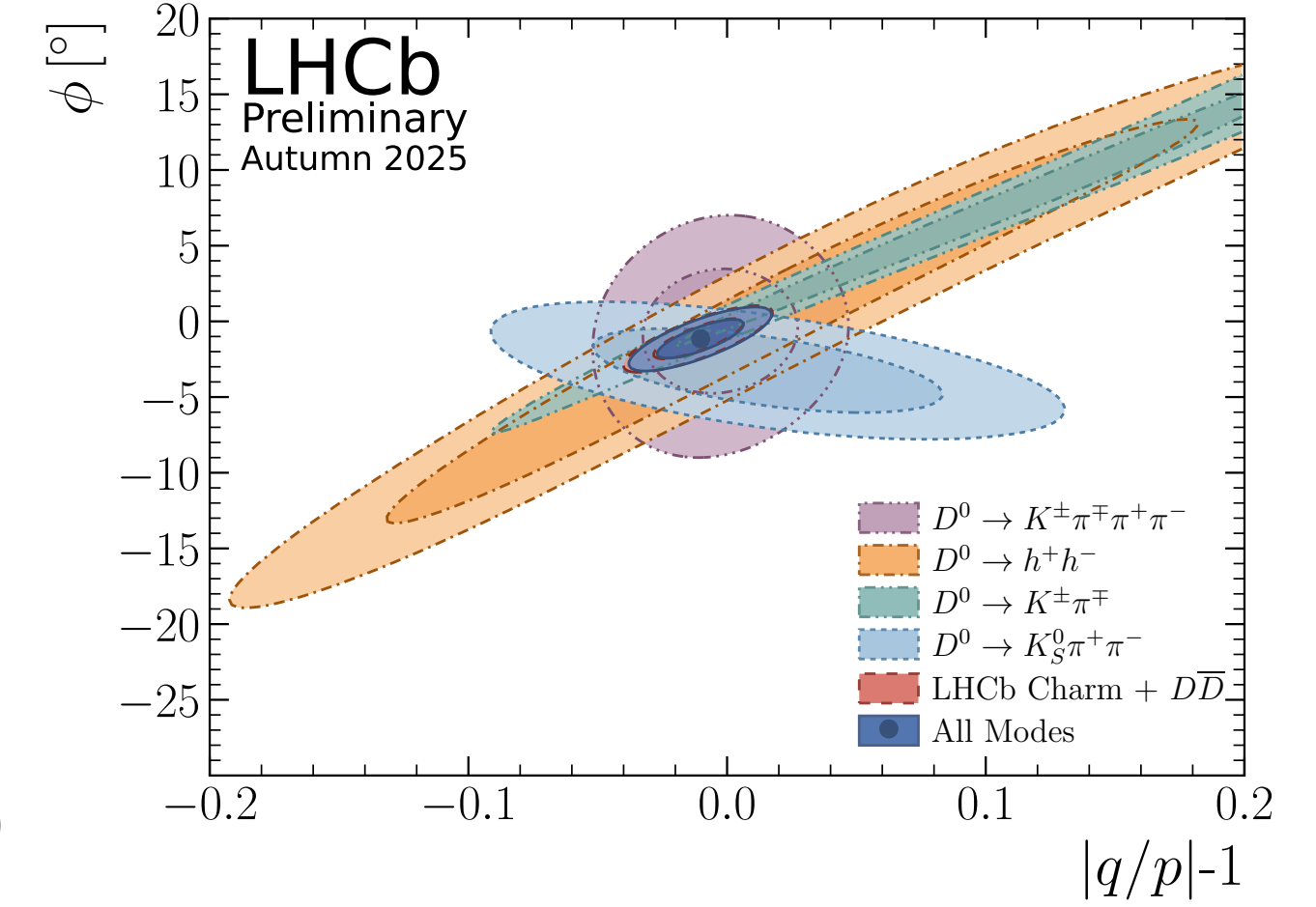
A combination of measurements sensitive to the CP -violation angle γ of the Cabibbo–Kobayashi–Maskawa unitarity triangle, to the charm mixing parameters that describe oscillations between D^0 and $\bar{D}^0$ mesons, and to the CP asymmetries in the $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays is performed. All relevant beauty and charm results obtained with the data collected during the first two runs of the LHCb experiment at CERN’s Large Hadron Collider are included, with three new inputs compared to the combination presented in 2024. The CKM angle γ is found to be $(62.8 \pm 2.6)^\circ$. External measurements from charm factories are incorporated to constrain CP -conserving phases in D -meson decays. The neutral charm-meson mixing parameters are determined to be $x = (0.391 \pm 0.042)\%$ and $y = (0.625 \pm 0.020)\%$, and the parameters quantifying time-dependent CP violation in D^0 decays to be $|q/p| = 0.990^{+0.011}_{-0.012}$ and $\phi = (-1.2 \pm 0.9)^\circ$.

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[†]Conference report prepared for the 2025 LHCb Implications Workshop (Geneva, Switzerland, 4–7 November 2025). Contact authors: Jordy Butter, jordy.butter@cern.ch Tim Evans, timothy.david.evans@cern.ch Alex Gilman, alexander.leon.gilman@cern.ch Matthew Kenzie, matthew.william.kenzie@cern.ch, Tommaso Pajero, tommaso.pajero@cern.ch, Mark Whitehead, mark.peter.whitehead@cern.ch.



B decay	D decay	Ref.	Dataset	Status since Ref. [16]
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^\pm h'^\mp$	[29]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^+ h^- \pi^+ \pi^-$	[30]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^+ h^- \pi^+ \pi^-$	[20]	Run 1&2	New
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow K^\pm \pi^\mp \pi^+ \pi^-$	[24]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^\pm h'^\mp \pi^0$	[31]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow K_S^0 h^+ h^-$	[32]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow K_S^0 K^\pm \pi^\mp$	[33]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow D^* h^\pm$	$D \rightarrow h^\pm h'^\mp$ (PR)	[29]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow D^* h^\pm$	$D \rightarrow K_S^0 h^+ h^-$ (PR)	[34]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow D^* h^\pm$	$D \rightarrow K_S^0 h^+ h^-$ (FR)	[35]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow DK^{*\pm}$	$D \rightarrow h^\pm h'^\mp$	[36]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow DK^{*\pm}$	$D \rightarrow h^\pm \pi^\mp \pi^+ \pi^-$	[36]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow DK^{*\pm}$	$D \rightarrow K_S^0 h^+ h^-$	[36]	Run 1&2	<i>As before</i>
$B^\pm \rightarrow Dh^\pm \pi^+ \pi^-$	$D \rightarrow h^\pm h'^\mp$	[37]	Run 1	<i>As before</i>
$B^0 \rightarrow DK^{*0}$	$D \rightarrow h^\pm h'^\mp$	[38]	Run 1&2	<i>As before</i>
$B^0 \rightarrow DK^{*0}$	$D \rightarrow h^\pm \pi^\mp \pi^+ \pi^-$	[38]	Run 1&2	<i>As before</i>
$B^0 \rightarrow DK^{*0}$	$D \rightarrow K_S^0 h^+ h^-$	[39]	Run 1&2	<i>As before</i>
$B^0 \rightarrow D^\mp \pi^\pm$	$D^+ \rightarrow K^- \pi^+ \pi^+$	[40]	Run 1	<i>As before</i>
$B_s^0 \rightarrow D_s^\mp K^\pm$	$D_s^+ \rightarrow h^+ h^- \pi^+$	[41, 42]	Run 1&2	<i>As before</i>
$B_s^0 \rightarrow D_s^\mp K^\pm \pi^+ \pi^-$	$D_s^+ \rightarrow h^+ h^- \pi^+$	[43]	Run 1&2	<i>As before</i>
D decay	Observable(s)	Ref.	Dataset	Status since Ref. [16]
$D^0 \rightarrow h^+ h^-$	ΔA_{CP}	[44–46]	Run 1&2	<i>As before</i>
$D^0 \rightarrow K^+ K^-$	$A_{CP}(K^+ K^-)$	[46–48]	Run 2	<i>As before</i>
$D^0 \rightarrow h^+ h^-$	$y_{CP} - y_{CP}^{K^- \pi^+}$	[49, 50]	Run 1&2	<i>As before</i>
$D^0 \rightarrow h^+ h^-$	ΔY	[51–54]	Run 1&2	<i>As before</i>
$D^0 \rightarrow K^\pm \pi^\mp$ (double tag)	$R^\pm, (x^\pm)^2, y'^\pm$	[21, 27]	Run 1&2	Updated
$D^0 \rightarrow K^\pm \pi^\mp$ (single tag)	$R_{K\pi}, A_{K\pi}, c_{K\pi}^{(\prime)}, \Delta c_{K\pi}^{(\sim)(\prime)}$	[55, 56]	Run 1&2	<i>As before</i>
$D^0 \rightarrow K^\pm \pi^\mp \pi^+ \pi^-$	$r, \kappa y', (x^2 + y^2)/4$	[28]	Run 1	<i>As before</i>
$D^0 \rightarrow K^\pm \pi^\mp \pi^+ \pi^-$	$r_i^\pm, (\kappa y'^\pm)_i, x^{2\pm} + y^{2\pm}$	[22]	Run 2	New
$D^0 \rightarrow K_S^0 \pi^+ \pi^-$	x, y	[57]	Run 1	<i>As before</i>
$D^0 \rightarrow K_S^0 \pi^+ \pi^-$	$x_{CP}, y_{CP}, \Delta x, \Delta y$	[58]	Run 1	<i>As before</i>
$D^0 \rightarrow K_S^0 \pi^+ \pi^-$	$x_{CP}, y_{CP}, \Delta x, \Delta y$	[59, 60]	Run 2	<i>As before</i>
$D^0 \rightarrow \pi^+ \pi^- \pi^0$	ΔY^{eff}	[61]	Run 2	<i>As before</i>



Decay	Parameters	Source	Ref.	Status since Ref. [16]
$B^\pm \rightarrow DK^{*\pm}$	$\kappa_{B^\pm}^{DK^{*\pm}}$	LHCb	[63]	<i>As before</i>
$B^0 \rightarrow DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb	[64]	<i>As before</i>
$B^0 \rightarrow D^\mp \pi^\pm$	β	HFLAV	[14]	<i>As before</i>
$B_s^0 \rightarrow D_s^\mp K^\pm (\pi\pi)$	ϕ_s	LHCb	[65]	<i>As before</i>
$D \rightarrow K^+ \pi^-$	$\cos \delta_D^{K\pi}, \sin \delta_D^{K\pi}, (r_D^{K\pi})^2, x^2, y$	CLEO-c	[66]	<i>As before</i>
$D \rightarrow K^+ \pi^-$	$A_{K\pi}, A_{K\pi}^{\pi\pi^0}, r_D^{K\pi} \cos \delta_D^{K\pi}, r_D^{K\pi} \sin \delta_D^{K\pi}$	BESIII	[62, 67, 68]	Updated
$D \rightarrow h^+ h^- \pi^0$	$F_{\pi\pi^0}^+, F_{KK\pi^0}^+$	CLEO-c	[69]	<i>As before</i>
$D \rightarrow h^+ h^- \pi^0$	$F_{\pi\pi^0}^+, F_{KK\pi^0}^+$	BESIII	[70]	New
$D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$	$F_{4\pi}^+$	CLEO-c+BESIII	[69, 71]	<i>As before</i>
$D \rightarrow K^+ K^- \pi^+ \pi^-$	$F_{KK\pi\pi}^+$	BESIII	[72]	<i>As before</i>
$D \rightarrow K^+ \pi^- \pi^0$	$r_D^{K\pi\pi^0}, \delta_D^{K\pi\pi^0}, \kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII	[25, 26]	<i>As before</i>
$D \rightarrow K^\pm \pi^\mp \pi^+ \pi^-$	$r_D^{K3\pi}, \delta_D^{K3\pi}, \kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII	[25, 26]	<i>As before</i>
$D \rightarrow K_S^0 K^\pm \pi^\mp$	$r_D^{K_S^0 K\pi}, \delta_D^{K_S^0 K\pi}, \kappa_D^{K_S^0 K\pi}$	CLEO-c	[73]	<i>As before</i>
$D \rightarrow K_S^0 K^\pm \pi^\mp$	$r_D^{K_S^0 K\pi}$	LHCb	[74]	<i>As before</i>

Backup 2