CP violation in the Standard Model and Beyond

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"Synergies towards the future Standard Model"
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Outline

◇ Main focus: **CP violation (CPV) in weak decays of quarks**

◇ Outline

- ⋆ Introduction
- ⋆ CPV in Bottom sector
- ⋆ CPV in Charm sector
- ⋆ CPV in Kaons decays

◇ Strong CP violation [see talk by Carlos Tamarit]

◇ Electroweak Baryogenesis [see talk by Lisa Biermann]

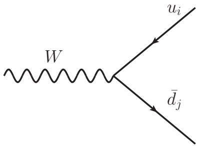
◇ Many talks on CP violation and mixing at the CKM workshop, 15–19 September 2025, Cagliari, Sardinia, Italy

Introduction

Cabibbo-Kobayashi-Maskawa (CKM) matrix

- The quark flavour-changing weak interactions are described by:

$$\mathcal{L}_{Wq} = \frac{g}{\sqrt{2}}(\bar{u}_L, \bar{c}_L, \bar{t}_L)\gamma^\mu \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{\rm CKM}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_\mu^\dagger + \text{h.c.}$$

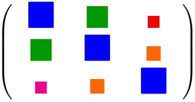


- V_{CKM} - the quark-mixing Cabibbo-Kobayashi-Maskawa (CKM) matrix
- In terms of three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ and one CP-violating phase δ

$$V_{\rm CKM} = \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta} & c_{23}\, c_{13} \end{pmatrix}$$

$s_{ij} = \sin\theta_{ij} \qquad c_{ij} = \cos\theta_{ij}$

$V_{\rm CKM} \sim$



CKM triangle

- The Wolfenstein parametrisation (it terms of A, λ, ρ, η)

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \qquad \lambda \approx 0.22$$

- Unitarity of the CKM matrix

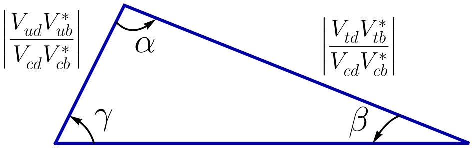
$$V_{\rm CKM}^\dagger V_{\rm CKM} = 1 \quad \Rightarrow \quad \text{e.g. } V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- The CKM triangle angles

$$\alpha \equiv \varphi_2 \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta \equiv \varphi_1 \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\gamma \equiv \varphi_3 \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



CP-violation and matter-antimatter asymmetry

- CP-violation is needed for matter-antimatter asymmetry (one of the Sakharov conditions)

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

- CP violation within SM is **not** sufficient

$$\frac{J}{T_c^{12}}(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \sim 10^{-19}$$

$J = c_{12} c_{13}^2 c_{23} s_{12} s_{13} s_{23} \sin\delta \approx 3 \cdot 10^{-5}$ – Jarlskog invariant

$T_c \sim 100$ GeV

$\Rightarrow$ New mechanism (New Physics) is required!

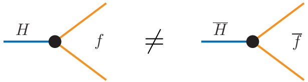
History of CP violation

- 1956 Observation of parity violation in weak interactions [Wu experiment]
  $\rightarrow$ 1957 Nobel Prize to Lee, Yang
- 1964 Observation of CPV in Kaon decays ($K_L \rightarrow \pi\pi$) [Christenson et al.]
  $\rightarrow$ 1980 Nobel Prize to Cronin, Fitch
- 1973 Kobayashi-Maskawa mechanism $\rightarrow$ 2008 Nobel Prize
- 2001 Observation of CPV in B^0-meson decays [BaBar & Belle]
- 2012 Observation of CPV in B^--meson decays [LHCb]
- 2013 Observation of CPV in B_s^0-meson decays [LHCb]
- 2019 Observation of CPV in D^0-meson decays [LHCb]
- 2025 Observation of CPV in baryon (Λ_b^0) decays [LHCb]

Three types of CP asymmetry

- Direct CP violation

$$\mathcal{A}_{\rm dir} = \frac{\Gamma(H \to f) - \Gamma(\overline{H} \to \overline{f})}{\Gamma(H \to f) + \Gamma(\overline{H} \to \overline{f})}$$

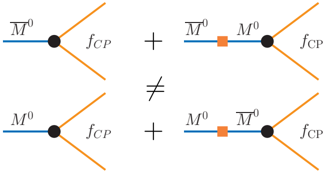


- CP violation in mixing (flavour-specific CP asymmetry)

$$\mathcal{A}_{\rm fs} = \frac{\Gamma(\overline{M}^0(t) \to f) - \Gamma(M^0(t) \to \overline{f})}{\Gamma(\overline{M}^0(t) \to f) + \Gamma(M^0(t) \to \overline{f})}$$

- CP violation in interference of mixing and decay (indirect CP violation)

$$\mathcal{A}_{\rm ind} = \frac{\Gamma(\overline{M}^0 \to f_{\rm CP})(t) - \Gamma(M^0 \to f_{\rm CP})(t)}{\Gamma(\overline{M}^0 \to f_{\rm CP})(t) + \Gamma(M^0 \to f_{\rm CP})(t)}$$



Direct CP asymmetry

- Decomposing an amplitude of $H \to f$ transition

$$A(H \to f) = \underbrace{\lambda_1 e^{i\alpha_1}}_{\text{weak int.}} \underbrace{A_1 e^{i\varphi_1}}_{\text{QCD}} + \underbrace{\lambda_2 e^{i\alpha_2}}_{\text{weak int.}} \underbrace{A_2 e^{i\varphi_2}}_{\text{QCD}}$$

- The amplitude of the *CP*-conjugated mode

$$A(\overline{H} \to \overline{f}) = \underbrace{\lambda_1 e^{-i\alpha_1}}_{\text{weak int.}} \underbrace{A_1 e^{i\varphi_1}}_{\text{QCD}} + \underbrace{\lambda_2 e^{-i\alpha_2}}_{\text{weak int.}} \underbrace{A_2 e^{i\varphi_2}}_{\text{QCD}}$$

$$\Rightarrow \quad \mathcal{A}_{\text{dir}} = \frac{-2\left|\frac{\lambda_1}{\lambda_2}\right| \sin(\alpha_1 - \alpha_2) \left|\frac{A_1}{A_2}\right| \sin(\varphi_1 - \varphi_2)}{1 + 2\left|\frac{\lambda_1}{\lambda_2}\right| \cos(\alpha_1 - \alpha_2) \left|\frac{A_1}{A_2}\right| \cos(\varphi_1 - \varphi_2) + \left|\frac{\lambda_1}{\lambda_2}\right|^2 \left|\frac{A_1}{A_2}\right|^2}$$

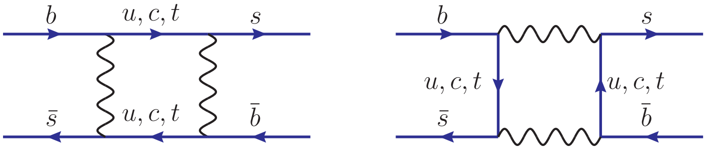
- Both parts of the amplitude could be the SM ones (e.g. tree-level and penguin contributions) or the SM and Beyond SM (BSM) ones

Neutral-meson mixing

◇ Neutral-meson time evolution (enabling $\overline{M}^0 \leftrightarrow M^0$ transitions)

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

◇ Box diagrams in the SM (for example, for $\overline{B}_s^0 - B_s$ mixing)



⋆ Γ_{12} – absorptive part of the box diagrams (on-shell)
⋆ M_{12} – dispersive part of the box diagrams (off-shell)
⋆ $\phi_{12} \equiv -\arg(-M_{12}/\Gamma_{12})$ – relative phase

Neutral-meson mixing and CP violation

- The meson mass eigenstates $|M_H\rangle$ and $|M_L\rangle$

$$\begin{cases} |M_L\rangle &= p|M^0\rangle + q|\overline{M}^0\rangle \\ |M_H\rangle &= p|M^0\rangle - q|\overline{M}^0\rangle \end{cases} \qquad |p|^2 + |q|^2 = 1$$

- Diagonalisation of the 2×2 matrix yields:

$$\Delta M^2 - \frac{1}{4}\Delta\Gamma^2 = 4\,|M_{12}|^2 - |\Gamma_{12}|^2 \qquad \Delta M\,\Delta\Gamma = 4\,|M_{12}|\,|\Gamma_{12}|\cos(\phi_{12})$$

  - $\Delta M = M_H - M_L$ - mass difference
  - $\Delta\Gamma = \Gamma_L - \Gamma_H$ - decay width difference

- $|q/p| \neq 1 \quad \Rightarrow \quad$ CP-violation in mixing

$$1 - \left|\frac{q}{p}\right| \approx \frac{a_{\rm fs}}{2} \qquad \text{for } a_{\rm fs} \ll 1$$

- $a_{\rm fs}$ coincides with CP-asymmetry in flavour-specific decays

CP violation in interference of decay and mixing

- CP violation in interference between a decay without mixing, $M^0 \to f$, and a decay with mixing, $M^0 \to \overline{M}^0 \to f$
- Denoting an amplitude of $M \to f$ transition

$$A_f = \langle f|\mathcal{H}_{\rm eff}|M\rangle \qquad \bar{A}_f = \langle f|\mathcal{H}_{\rm eff}|\bar{M}\rangle$$

$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

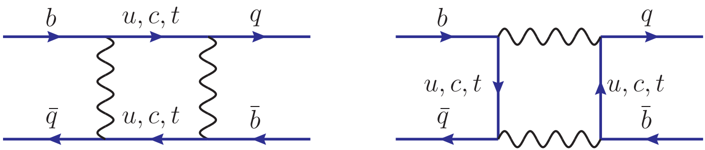
- For $|q/p| \approx 1$:

$$\mathcal{A}_{\rm ind}(t) = \frac{S_f \sin(\Delta M t) - C_f \cos(\Delta M t)}{\cosh(\Delta\Gamma t/2) - A_f^{\Delta\Gamma} \sinh(\Delta\Gamma t/2)}$$

$$S_f \equiv \frac{2\,{\rm Im}\lambda_f}{1+|\lambda_f|^2} \qquad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad A_f^{\Delta\Gamma} \equiv -\frac{2\,{\rm Re}\lambda_f}{1+|\lambda_f|^2}$$

Bottom sector

$B_q - \bar{B}_q$ mixing and CP violation



◇ $\Gamma_{12}^q \ll M_{12}^q$ $\qquad q = d, s$

$\Rightarrow$ $\Delta M_q \approx 2|M_{12}^q|$ $\qquad \Delta\Gamma_q \approx 2|\Gamma_{12}^q| \cos\phi_{12}^q$ $\qquad a_{\rm fs}^q = \left|\frac{\Gamma_{12}^q}{M_{12}^q}\right| \sin\phi_{12}^q$

◇ Experimental data [HFLAV (2025)]

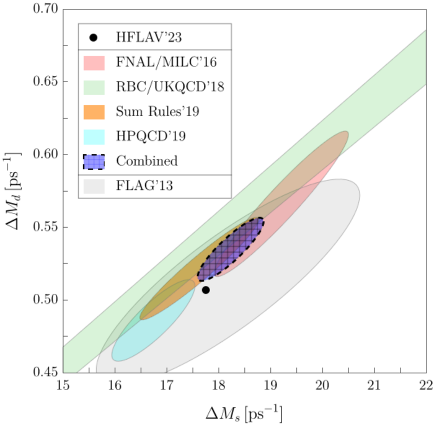
$$\Delta M_s = (17.765 \pm 0.006)\,\mathrm{ps}^{-1} \qquad \Delta M_d = (0.5069 \pm 0.0019)\,\mathrm{ps}^{-1}$$

$$\Delta\Gamma_s = (0.082 \pm 0.005)\,\mathrm{ps}^{-1} \qquad \Delta\Gamma_d = (0.7 \pm 6.6) \times 10^{-3}\,\mathrm{ps}^{-1}$$

$$a_{\rm fs}^s = (-6 \pm 28) \cdot 10^{-4} \qquad a_{\rm fs}^d = (-21 \pm 17) \cdot 10^{-4}$$

$B_q - \bar{B}_q$ mixing and CP violation

- M_{12}^q is dominated by diagrams with top-quark



- SM predictions for $\Delta M_{d,s}$
  e.g. [Albrecht, Bernlochner, Lenz, Rusov (2024)]

$$\Delta M_s = (18.23 \pm 0.63)\,\mathrm{ps}^{-1}$$
$$\Delta M_d = (0.535 \pm 0.021)\,\mathrm{ps}^{-1}$$

$B_q - \bar{B}_q$ mixing and CP violation

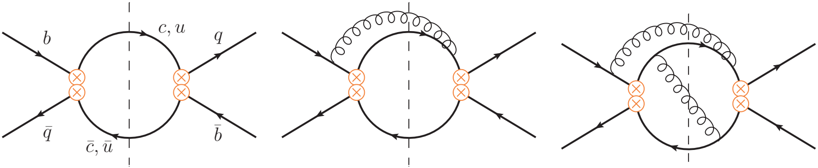
- $\Gamma_{12}^q = \frac{1}{2m_{B_q}} \mathrm{Im} \langle B_q | \, i \int d^4x \, T\left\{\mathcal{H}_{\rm eff}^{\Delta B=1}(x), \mathcal{H}_{\rm eff}^{\Delta B=1}(0)\right\} | \bar{B}_q \rangle$
- The Effective $\Delta B = 1$ Hamiltonian

$\lambda_{q_1 q_2 q} = V_{q_1 q}^* V_{q_2 b}$

$$\mathcal{H}_{\rm eff}^{\Delta B=1} = \frac{4G_F}{\sqrt{2}} \left[\sum_{i=1}^{2} \left(\lambda_{ccq} Q_i^{ccq} + \lambda_{cuq} Q_i^{cuq} + \lambda_{ucq} Q_i^{ucq} + \lambda_{uuq} Q_i^{uuq} \right) - \lambda_{ttq} \sum_{i=3}^{6,8} C_i Q_i \right] + \mathrm{h.c.}$$

$Q_1^{q_1 q_2 q} = (\bar{q}_1^i \gamma_\mu (1-\gamma_5) b^j)(\bar{q}^j \gamma^\mu (1-\gamma_5) q_2^i)$ etc.

- Determined using the Heavy Quark Expansion (HQE) method



$B_q - \bar{B}_q$ mixing and CP violation

- Determination of $\Delta\Gamma_q$ at NNLO (up to second order in m_c/m_b expansion)
  [Gerlach, Nierste, Shtabovenko, Steinhauser (2021,2022)]

- Completing NNLO corrections by including full dependence on m_c/m_b
  [Gerlach, Nierste, Reeck, Shtabovenko, Steinhauser (2025)]

⇒ First determination of a_{fs}^q at NNLO

- SM predictions of both $\Delta\Gamma_q$ and a_{fs}^q at NNLO
  [Gerlach, Nierste, Reeck, Shtabovenko, Steinhauser (2025)]

$$\Delta\Gamma_s = (0.077 \pm 0.016)\,\mathrm{ps}^{-1} \qquad \Delta\Gamma_d = (2.11 \pm 0.45)\cdot 10^{-3}\,\mathrm{ps}^{-1}$$

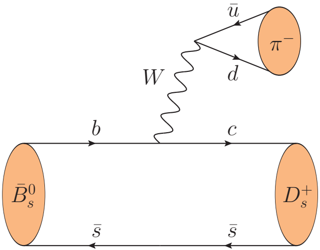
$$a_{\mathrm{fs}}^s = (2.28 \pm 0.14)\cdot 10^{-5} \qquad a_{\mathrm{fs}}^d = -(5.21 \pm 0.32)\cdot 10^{-4}$$

- CP-violation in B-mixing (within the SM) is small

- Not yet observed!

$$a_{\mathrm{fs}}^s = (-6 \pm 28)\cdot 10^{-4} \qquad a_{\mathrm{fs}}^d = (-21 \pm 17)\cdot 10^{-4}$$

$\bar{B}^0 \to D^+ K^-$ and $\bar{B}_s^0 \to D_s^+ \pi^-$ decays

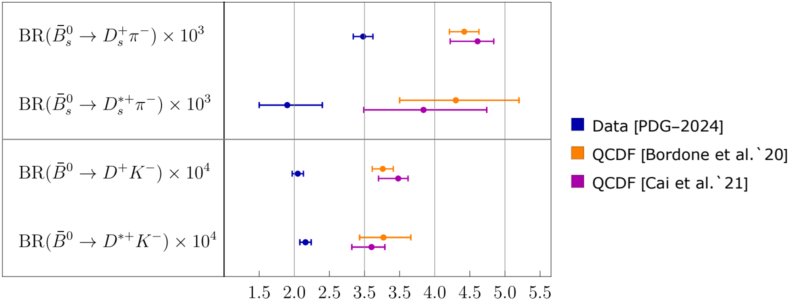


- Tree-level decays induced by $b \to c\bar{u}q$ transitions $\qquad q = d, s$
- No penguin and annihilation topologies
- "Golden" modes for the QCD factorisation (QCDF) approach

[Beneke, Buchalla, Neubert, Sachrajda (1999-2001)]

Anomalies in non-leptonic B-meson decays

- There are discrepancies between SM and exp. data on several two-body non-leptonic tree-level B-meson decays



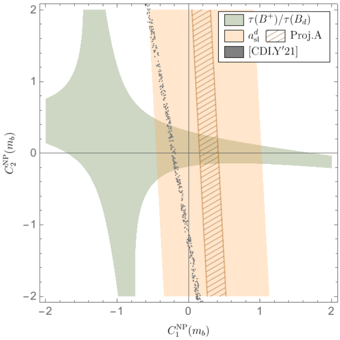
- Underestimated power corrections? Enhanced QED or/and re-scattering effects? New Physics?

$B_q - \bar{B}_q$ mixing and CP-violation

- Assuming New Physics effects in tree-level non-leptonic b-quark decays in a model-independent way

$$\mathcal{H}_{\rm eff}^{\rm NP} = \frac{4G_F}{\sqrt{2}} V_{cb} V_{ud}^* \sum_{i=1}^{10} \left[C_i^{\rm NP}\, Q_i + C_i'^{\rm NP}\, Q_i' \right] + {\rm h.c.},$$

- Impact on B-meson lifetimes and mixing
- Complementary constraints on NP Wilson coefficients from
  - ⋆ Non-leptonic B-meson decays [Cai, Deng, Li, Yang (2021)]
  - ⋆ B-meson lifetime ratios
  - ⋆ $\Delta\Gamma_{d,s}$ and $a_{\rm fs}^{d,s}$ [Müller, Lenz, Piscopo, Rusov (2022)]



Flavour-specific CP asymmetry

$$\mathcal{A}_{\rm fs}^{q} = \frac{\Gamma\left(\bar{B}_q(t) \to f\right) - \Gamma\left(B_q(t) \to \bar{f}\right)}{\Gamma\left(\bar{B}_q(t) \to f\right) + \Gamma\left(B_q(t) \to \bar{f}\right)}$$

- For a flavour-specific decay: $\mathcal{A}_{\bar{f}} = 0 = \bar{\mathcal{A}}_f$

  Examples: $\bar{B}_s^0 \to D_s^+ \ell^- \bar{\nu}_\ell$, $\bar{B}_s^0 \to D_s^+ \pi^-$, $\bar{B}_s^0 \to K^+ \pi^-$

- Absence of direct CP violation: $\bar{\mathcal{A}}_{\bar{f}} = \mathcal{A}_f$

  Examples: $\bar{B}_s^0 \to D_s^+ \pi^-$, $\bar{B}^0 \to D^+ K^-$

- Therefore, for example, within the SM

$$\mathcal{A}_{\rm fs}(\bar{B}_s^0 \to D_s^+ K^-) = \mathcal{A}_{\rm fs}(\bar{B}_s^0 \to D_s^+ \ell^- \nu_\ell) = a_{fs}^s$$

- Null-test of the SM: $\mathcal{A}_{\rm fs}(\bar{B}_s^0 \to D_s^+ K^-) - \mathcal{A}_{\rm fs}(\bar{B}_s^0 \to D_s^+ \ell^- \bar{\nu}_\ell) = 0$

[Fleischer, Vos (2016)]; [Gershon, Lenz, Rusov, Skidmore (2021)]

Flavour-specific CP asymmetry

[Gershon, Lenz, Rusov, Skidmore (2021)]

◇ Under the presence of general New Physics in tree-level decays

$$\begin{aligned} A_f &= \left|A_f^{\rm SM}\right| e^{i\phi^{\rm SM}} e^{i\varphi^{\rm SM}} + \left|A_f^{\rm BSM}\right| e^{i\phi^{\rm BSM}} e^{i\varphi^{\rm BSM}} \\ &=: \left|A_f^{\rm SM}\right| e^{i\phi^{\rm SM}} e^{i\varphi^{\rm SM}} \left(1 + r e^{i\phi} e^{i\varphi}\right) \end{aligned}$$

$\phi = \phi^{\rm BSM} - \phi^{\rm SM}$ – relative strong phase
$\varphi = \varphi^{\rm BSM} - \varphi^{\rm SM}$ – relative weak phase
$r = |A_f^{\rm BSM}|/|A_f^{\rm SM}|$ $\quad r \sim (10 - 20)\%$

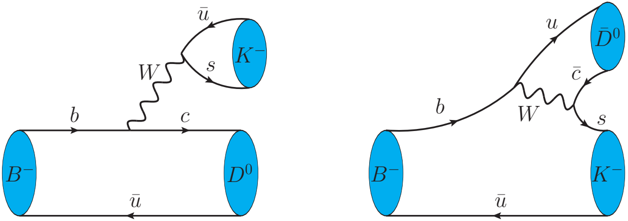
◇ $$\mathcal{A}_{\rm fs}^q = \frac{a_{\rm fs}^q - 2r\sin\phi\sin\varphi + 2a_{\rm fs}^q r\cos\phi\cos\varphi + a_{\rm fs}^q r^2}{1 + 2r\cos\phi\cos\varphi + r^2 - 2a_{\rm fs}^q r\sin\phi\sin\varphi} \approx a_{\rm fs}^q - \mathcal{A}_{\rm dir}^q$$

$\mathcal{A}_{\rm dir}^q \approx 2r\sin\phi\sin\varphi$

◇ Enhancement from $a_{fs}^q \sim 10^{-5}$ (in the SM) up to 0.4 possible !

Determination of γ

- Consider, for example, tree-level decays $B^- \to D^0 K^-$ and $B^- \to \overline{D}^0 K^-$

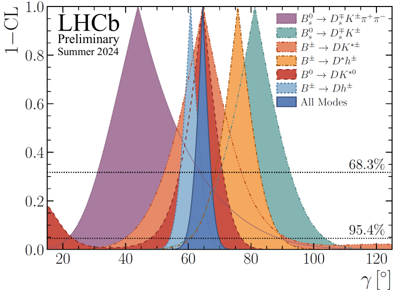


- $A(B^- \to D^0 K^- \to f\,K^-) = A_1\, e^{i\varphi_1}$ $\qquad$ $A(B^- \to \overline{D}^0 K^- \to f\,K^-) = A_2\, e^{i(\varphi_2 - \gamma)}$
- $A(B^- \to f\,K^-) = A_1 e^{i\varphi_1}(1 + r_B e^{i(\delta_B - \gamma)})$ $\qquad$ $r_B \equiv |A_2|/|A_1|$
- $A(B^+ \to f\,K^+) = A_1 e^{i\varphi_1}(1 + r_B e^{i(\delta_B + \gamma)})$ $\qquad$ $\delta_B \equiv \varphi_2 - \varphi_1$
- Clean determination of CKM angle γ from data for various multi-body states f (within the SM!) [Brod, Zupan (2013)]

Determination of γ

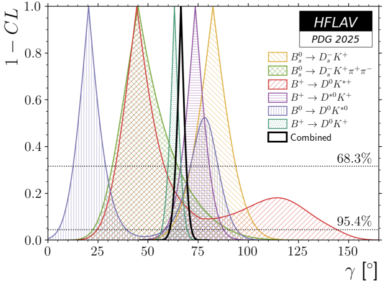
◇ Direct determination of γ from measurements

[LHCb-CONF-2024-004]



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

[HFLAV 2025]



$\gamma = (66.4^{+2.7}_{-2.8})^\circ$

◇ Consistent with indirect determination: $\gamma = (66.29^{+0.72}_{-1.86})^\circ$

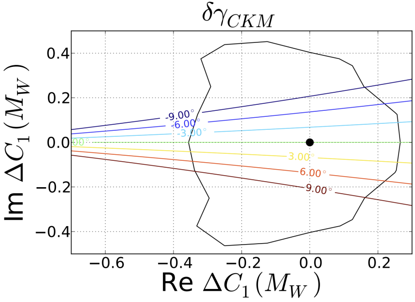
[CKMfitter (2023)]

Determination of γ

- Assumption of NP in tree-level non-leptonic b-quark decays could lead to sizeable modification of the extracted angle γ

  e.g. [Brod, Lenz, Tetlalmatzi-Xolocotzi, Wiebusch (2014)]
  [Lenz, Tetlalmatzi-Xolocotzi (2019)]

- e.g. modifying Wilson coefficients of the Q_1 and Q_2 operators

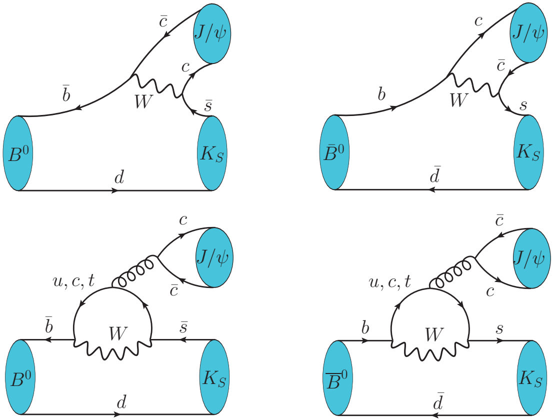


$$\gamma \to \gamma + (r_A - r_{A'})\frac{\mathrm{Im}[\Delta C_1]}{C_2}$$

$$r_A = \frac{\langle DK|Q_1^{u\bar{c}s}|B\rangle}{\langle DK|Q_2^{u\bar{c}s}|B\rangle}$$

$$r_{A'} = \frac{\langle DK|Q_1^{c\bar{u}s}|B\rangle}{\langle DK|Q_2^{c\bar{u}s}|B\rangle}$$

- Golden channel $B^0 \to J/\psi K_S$



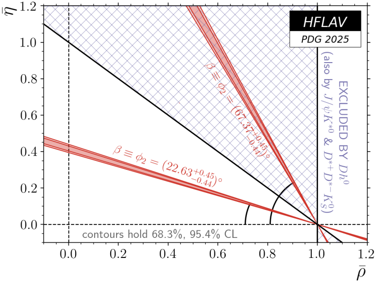
- Loop $\times$ λ^2 suppression of "penquin" amplitude compared to "tree" one

Determination of β

◇ $A_{J/\psi K_S} \simeq \bar{A}_{J/\psi K_S} \quad \Rightarrow \quad C_{J/\psi K_S} \simeq 0,\ S_{J/\psi K_S} \simeq \sin(2\beta)$

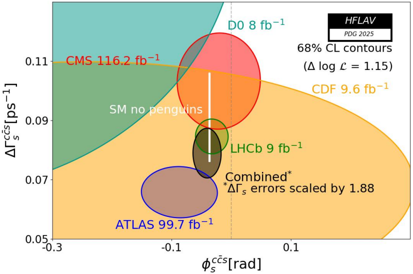
$\Rightarrow \mathcal{A}_{\rm ind}(B^0 \to J/\psi K_S)(t) \simeq \sin(2\beta)\,\sin(\Delta M_d\, t) \qquad$ (for $\Delta\Gamma_d \approx 0$)

[HFLAV (2025)]



$\beta = (22.63^{+0.45}_{-0.44})^\circ$

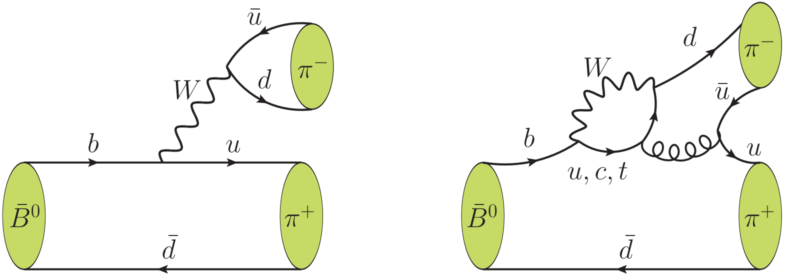
[HFLAV (2025)]



Indirect determination $\beta = (24.21^{+0.74}_{-1.12})^\circ$ [CKMfitter (2023)]

Determination of α

◇ Consider, for example, the $B^0 \to \pi^+\pi^-$ decays

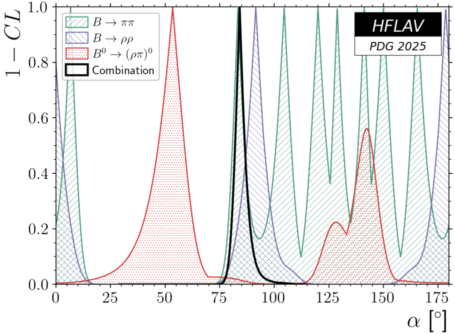


◇ Interference between the tree-level and penquin contributions which are both of the same CKM suppression $\sim \lambda^3$

$\Rightarrow$ Less clean extraction of α from data

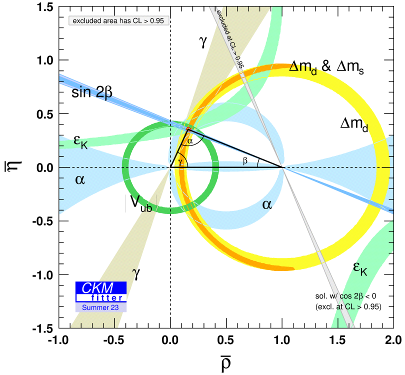
Determination of α

[HFLAV 2025]



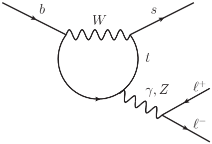
$$\alpha = (84.1^{+3.7}_{-3.0})^\circ$$

[CKMfitter 2023]

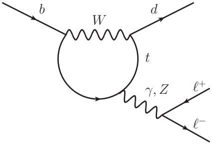


$$\alpha = (91.3^{+4.0}_{-1.8})^\circ$$

$b \to d\ell^+\ell^-$ vs $b \to s\ell^+\ell^-$



vs



- $b \to d$ are CKM suppressed vs $b \to s$: $|V_{tb}V_{td}^*|^2/|V_{tb}V_{ts}^*|^2 \approx 0.05$
- $b \to d$ transitions induce non-vanishing direct CP-asymmetry
  - ⋆ In $b \to s$: $|V_{tb}V_{ts}^*| \sim |V_{cb}V_{cs}^*| \sim \lambda^2 \gg |V_{ub}V_{us}^*| \sim \lambda^4$
  - ⋆ In $b \to d$: $|V_{tb}V_{td}^*| \sim |V_{cb}V_{cd}^*| \sim |V_{ub}V_{ud}^*| \sim \lambda^3$
- The LHCb data [arXiv: 1509.00414]

$$\mathcal{A}_{\rm dir}(B^\pm \to \pi^\pm\mu^+\mu^-) = -0.11 \pm 0.12 \pm 0.01$$

- SM prediction at large hadronic recoil [Hambrock, Khodjamirian, Rusov (2015)]

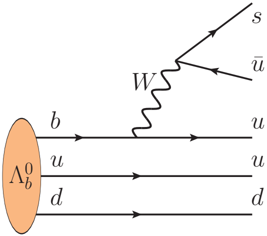
$$\mathcal{A}_{\rm dir}(B^\pm \to \pi^\pm\mu^+\mu^-)[q^2 \in (1-6)\,\mathrm{GeV}^2] = -0.143^{+0.035}_{-0.029}$$

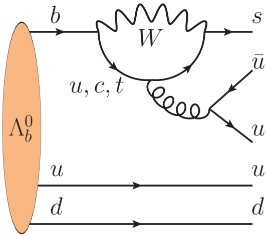
First observation of CP violation in baryon decay

◇ Observation of CP violation in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decay by LHCb
[Nature 643 (2025) 8074, 1223-1228]

$$\mathcal{A}_{\rm dir}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (2.45 \pm 0.46 \pm 0.10)\%$$

◇ CPV induced by interference of the tree and penguin contributions





◇ Study with $N\pi$ scatterings [Wang, Yu (arXiv: 2407.04110)]

Charm sector

Discovery of CP-violation in charm sector

- Discovery of CP-violation in D-meson decays by LHCb [arXiv: 1903.08726]

$$\Delta A_{\mathrm{CP}} \equiv \mathcal{A}_{\mathrm{CP}}(D^0 \to K^+K^-) - \mathcal{A}_{\mathrm{CP}}(D^0 \to \pi^+\pi^-)$$

$$\mathcal{A}_{\mathrm{CP}}(D^0 \to f; t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)}$$

$$\Delta\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}} = (-15.7 \pm 2.9) \times 10^{-4}$$

- Measurement of $\mathcal{A}_{\mathrm{CP}}(D^0 \to K^+K^-)$ by LHCb [arXiv: 2209.03179]
  - Combining with measured value of $\Delta\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}$

$$\begin{aligned} \mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(D^0 \to K^+K^-) &= (7.7 \pm 5.7) \times 10^{-4} \\ \mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-) &= (23.2 \pm 6.1) \times 10^{-4} \end{aligned}$$

Theory of $D^0 \to \pi^-\pi^+(K^-K^+)$ decays

- The effective Hamiltonian (neglecting penguin operators)

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \sum_{q=d,s} \lambda_q \Big(C_1 O_1^q + C_2 O_2^q \Big) + \text{h.c.} \equiv - \sum_{q=d,s} \lambda_q\, \mathcal{O}^q + \text{h.c.}$$

$\lambda_q \equiv V_{cq}^* V_{uq}$

$$O_1^q = (\bar{q}^i \Gamma_\mu c^i)(\bar{u}^j \Gamma^\mu q^j) \qquad O_2^q = (\bar{q}^i \Gamma_\mu c^j)(\bar{u}^j \Gamma^\mu q^i)$$

- The amplitudes

$$A(D^0 \to \pi^+\pi^-) = \lambda_d\, \mathcal{T}_{\pi\pi} \left[1 - \frac{\lambda_b}{\lambda_d} \frac{\mathcal{P}_{\pi\pi}}{\mathcal{T}_{\pi\pi}} \right]$$

$$A(D^0 \to K^+K^-) = \lambda_s\, \mathcal{T}_{KK} \left[1 - \frac{\lambda_b}{\lambda_s} \frac{\mathcal{P}_{KK}}{\mathcal{T}_{KK}} \right]$$

- $|\lambda_b / \lambda_{s,d}| \sim 10^{-3}$

$$\mathcal{T}_{\pi\pi} \equiv \langle \pi^+\pi^- | \mathcal{O}^d | D^0 \rangle - \langle \pi^+\pi^- | \mathcal{O}^s | D^0 \rangle$$

$$\mathcal{T}_{KK} \equiv \langle K^+K^- | \mathcal{O}^s | D^0 \rangle - \langle K^+K^- | \mathcal{O}^d | D^0 \rangle$$

$$\mathcal{P}_{\pi\pi} \equiv \langle \pi^+\pi^- | \mathcal{O}^s | D^0 \rangle \qquad \mathcal{P}_{KK} = \langle K^+K^- | \mathcal{O}^d | D^0 \rangle$$

Theory of $D^0 \to \pi^-\pi^+(K^-K^+)$ decays

- Branching fractions

$$\mathrm{Br}(D^0 \to K^+K^-) \sim |\lambda_s|^2 |\mathcal{T}_{KK}|^2 \left|1 - \frac{\lambda_b}{\lambda_s}\frac{\mathcal{P}_{KK}}{\mathcal{T}_{KK}}\right|^2 \simeq |\lambda_s|^2 |\mathcal{T}_{KK}|^2$$

$$\mathrm{Br}(D^0 \to \pi^+\pi^-) \sim |\lambda_d|^2 |\mathcal{T}_{\pi\pi}|^2 \left|1 - \frac{\lambda_b}{\lambda_d}\frac{\mathcal{P}_{\pi\pi}}{\mathcal{T}_{\pi\pi}}\right|^2 \simeq |\lambda_s|^2 |\mathcal{T}_{\pi\pi}|^2$$

- Difference of direct CP asymmetries

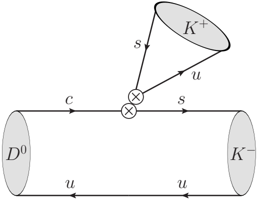
$$\Delta\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}} \simeq -2\left|\frac{\lambda_b}{\lambda_s}\right| \sin\gamma \left(\left|\frac{\mathcal{P}_{KK}}{\mathcal{T}_{KK}}\right| \sin\phi_{KK} + \left|\frac{\mathcal{P}_{\pi\pi}}{\mathcal{T}_{\pi\pi}}\right| \sin\phi_{\pi\pi}\right)$$

$\phi_{KK} \equiv \arg\left(\mathcal{P}_{KK}/\mathcal{T}_{KK}\right) \qquad \gamma \equiv -\arg(\lambda_b/\lambda_s)$

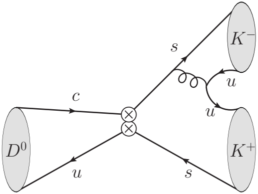
- Naive estimate $\mathcal{P}_{KK}/\mathcal{T}_{KK} \sim \mathcal{P}_{\pi\pi}/\mathcal{T}_{\pi\pi} \sim \mathcal{O}(0.1)$

$\Rightarrow \qquad |\Delta\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}| \leq 2.5 \times 10^{-4}$

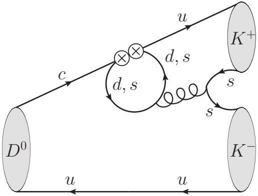
Diagrams



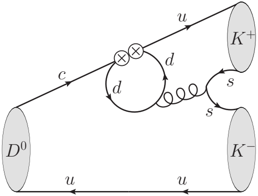
$\mathcal{T}_{KK}$



$\mathcal{T}_{KK}$



$\mathcal{T}_{KK}$



$\mathcal{P}_{KK}$

(Similar for $D^0 \to \pi^+\pi^-$)

Theory status

- Determination of $\mathcal{P}_{KK}/\mathcal{T}_{KK}$ and $\mathcal{P}_{\pi\pi}/\mathcal{T}_{\pi\pi}$
  - Symmetry arguments, employing the U-spin and $SU(3)_F$ relations
    e.g. [Grossman, Schacht (2019)]
  - Topological amplitude decomposition method
    e.g. [Li, Lü, Yu, (2019); Cheng, Chiang (2019)]
  - Effects of nearby scalar resonances $f_0(1500), f_0(2020)$
    [Soni (2019); Soni, Schacht (2021)]
  - Final-state interaction using data on $\pi\pi$, KK re-scattering
    [Bediaga, Frederico, Megahlaes (2022)]
    [Pich, Solomonidi, Vale Silva (2023)]
  - Light-cone sum rule (LCSR)
    [Khodjamirian, Petrov (2017); Lenz, Piscopo, Rusov (2023)]
  - Unitarity and isospin symmetry
    [Sinha, Browder, Deshpande, Sahoo, Sinha (2025)]

LCSR prediction

- ◇ Determination of $\mathcal{P}_{KK}, \mathcal{P}_{\pi\pi}$ from LCSR in [Khodjamirian, Petrov (2017)]
- ◇ Determination of $\mathcal{T}_{KK}, \mathcal{T}_{\pi\pi}$ from LCSR in [Lenz, Piscopo, Rusov (2023)]

$\Rightarrow$ Predictions for branching fractions of $D^0 \to PP$ decays within LCSR

- ⋆ Good agreement with data within uncertainties

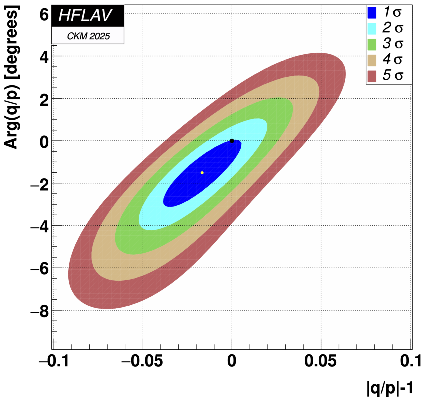
- ◇ Combining the results [Lenz, Piscopo, Rusov (2023)]

$$|\Delta\mathcal{A}_{\rm CP}^{\rm dir}|_{\rm LCSR} \leq 2.4 \times 10^{-4}$$

- ◇ Far below the LHCb value $\Delta\mathcal{A}_{\rm CP}^{\rm dir} = (-15.7 \pm 2.9) \times 10^{-4}$
- ◇ Similar conclusion by investigating final-state interactions
  [Pich, Solomonidi, Vale Silva (2023)]
- ◇ New Physics?
  e.g. [Chala, Lenz, Rusov, Scholtz (2019)]
  [Dery, Nir (2019)]
  [Sinha, Browder, Deshpande, Sahoo, Sinha (2025)]

CPV in D^0-meson mixing

[HFLAV (2025)]



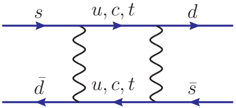
- Not yet measured [HFLAV (2025)]

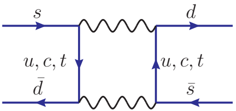
$$|q/p| = 0.983^{+0.015}_{-0.014}$$

- Challenging from theory side because of extreme GIM cancellation

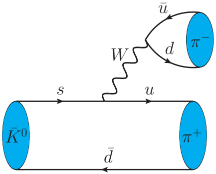
Kaons

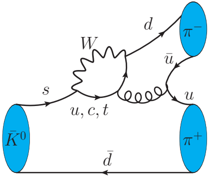
CPV in kaon decays





$$|K_S\rangle = p|K^0\rangle + q|\bar{K}^0\rangle$$
$$|K_L\rangle = p|K^0\rangle - q|\bar{K}^0\rangle$$





$$\frac{\langle \pi^0\pi^0|\mathcal{H}|K_L\rangle}{\langle \pi^0\pi^0|\mathcal{H}|K_S\rangle} \equiv \epsilon - 2\epsilon'$$
$$\frac{\langle \pi^+\pi^-|\mathcal{H}|K_L\rangle}{\langle \pi^+\pi^-|\mathcal{H}|K_S\rangle} \equiv \epsilon + \epsilon'$$

- All three types of CPV have been observed in kaon decays
- Fit to experimental data [PDG (2025)]

$$|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}$$
$$\mathrm{Im}(\varepsilon) = (1.57 \pm 0.02) \times 10^{-3}$$
$$\mathrm{Re}(\epsilon'/\epsilon) = (1.66 \pm 0.23) \times 10^{-3}$$

Conclusion

Conclusion

- ◇ CP violation is established in weak interactions
- ◇ Not sufficient for matter-antimatter asymmetry

$\Rightarrow$ New mechanism is needed

- ◇ Much more data expected from LHCb, CMS, ATLAS, Belle II, BES III...

$\Rightarrow$ More precise measurement of CPV observables and CKM angles

- ◇ From theory side, one should keep scrutinising the SM predictions (higher orders in perturbative series, power corrections, re-scattering effects, etc.)
- ◇ Investigation of clean observables, both theoretically and experimentally

$\Rightarrow$ Indirect searches of New physics

Thank you for your attention!