γ/ϕ_3 in CKM unitarity triangle and $B \to DP$ puzzle beyond the standard model

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(ongoing work)

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Introduction

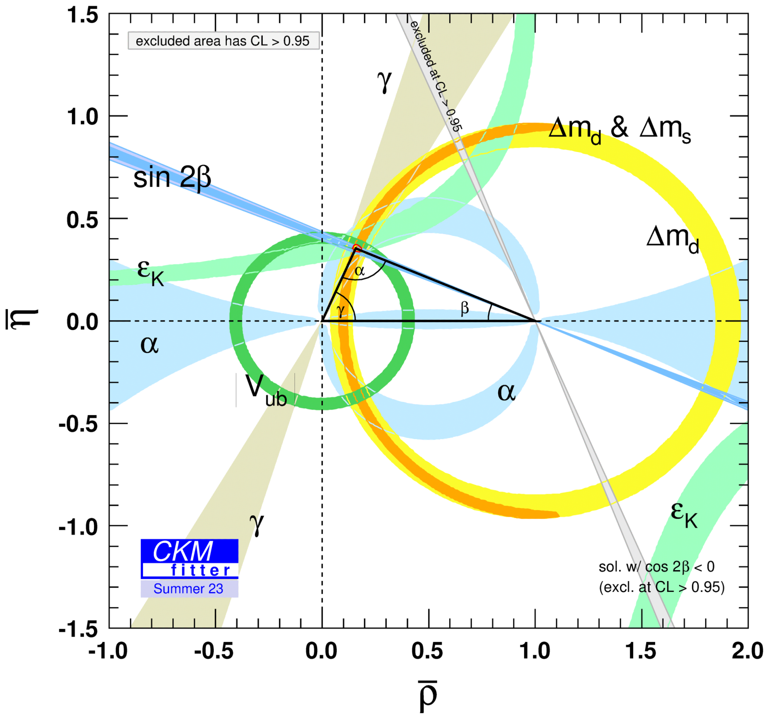
◉ Recent measurements in flavor factories precisely determine Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, by which CP violation in the SM is characterized.

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

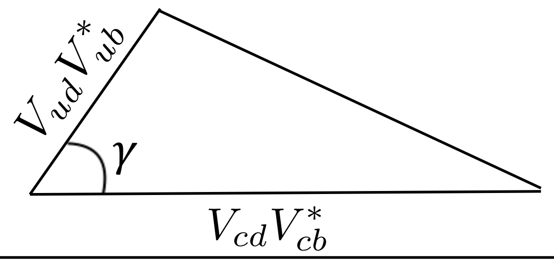
Unitarity of the CKM matrix

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

Experimental constraints (CKM fitter)

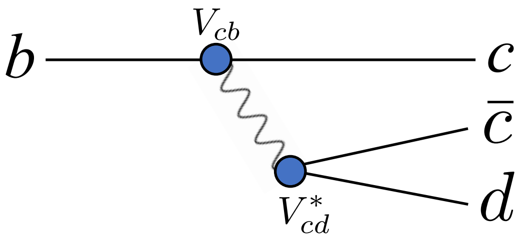


Unitarity triangle



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

Determination of γ → *B*-meson two-body hadronic decays



◉ Abundant data for *B*-meson decays enable us to test beyond the standard model (BSM).

Puzzles for branching ratios for B-meson non-leptonic decays

Channels	SM Cai *et al.* [2103.04138]	Exp. (PDG2024)	significance
$B_s^0 \to D_s^- \pi^+$	$(4.61^{+0.23}_{-0.39})\times 10^{-3}$	$(2.98 \pm 0.14) \times 10^{-3}$	3.9σ
$B_s^0 \to D_s^{*-} \pi^+$	$(3.84^{+0.90}_{-0.85})\times 10^{-3}$	$(1.9^{+0.5}_{-0.4}) \times 10^{-3}$	2.0σ
$B^0 \to D^- K^+$	$(3.48^{+0.14}_{-0.28})\times 10^{-4}$	$(2.05 \pm 0.08) \times 10^{-4}$	4.9σ
$B^0 \to D^{*-} K^+$	$(3.10^{+0.19}_{-0.28})\times 10^{-4}$	$(2.16 \pm 0.08) \times 10^{-4}$	3.2σ
$B^0 \to D^- K^{*+}$	$(5.94^{+0.46}_{-0.61})\times 10^{-4}$	$(4.5 \pm 0.7) \times 10^{-4}$	1.6σ

QCD factorization (QCDF) Beneke *et al.* [0006124]

tensions

Bordone *et al.*, [2007.10338]

$\mathcal{O}(10\%)$ corrections are required to explain data.

Discussions in the literature

(1) Higher order corrections/final-state interactions

- Estimation of $1/m_b$ suppressed corrections are $\mathcal{O}(0.1\%)$. Bordone *et al.*, [2007.10338]
- Quasi-inelastic rescattering in the SU(3) limit cannot explain the discrepancy. Endo, Iguro and Mishima [2109.10811]
- Light-cone sum rules results have uncertainties from non-perturbative input that are still sizable. Piscopo and Rusov [2307.07594]

(2) BSM contributions to $b \to c\bar{u}q$ $(q = d, s)$ transitions.

$\overline{B_s^0} \to D_s^+ K^-$ decays

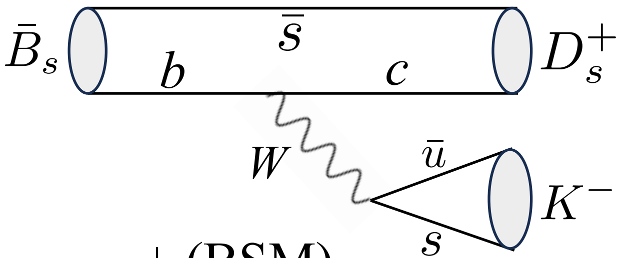
Phase space

$$\Phi_{\rm Ph} \equiv \frac{1}{16\pi m_{B_s}} \Phi\left(\frac{m_{D_s}}{m_{B_s}}, \frac{m_K}{m_{B_s}}\right)$$

$$\Phi(x,y) \equiv \sqrt{[1-(x+y)^2][1-(x-y)^2]}$$

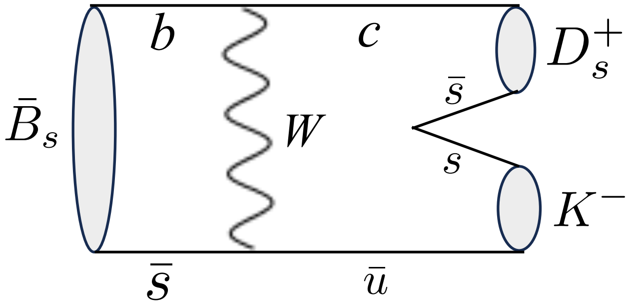
Fleischer [0304027]

T (color-allowed tree)



+ (BSM)

E (exchange diagram)

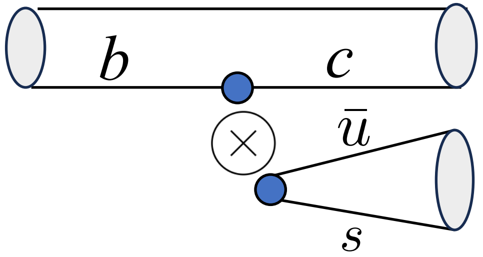


Decay amplitude: $\mathcal{A} = T + E = \langle DP | \mathcal{H}_{\Delta B=1} | B \rangle$

Branching ratio: $\mathrm{Br}[B \to DP] = |\mathcal{A}|^2 \Phi_{\rm PS}\, \tau_{B_s}$

Integrate out

heavy particles



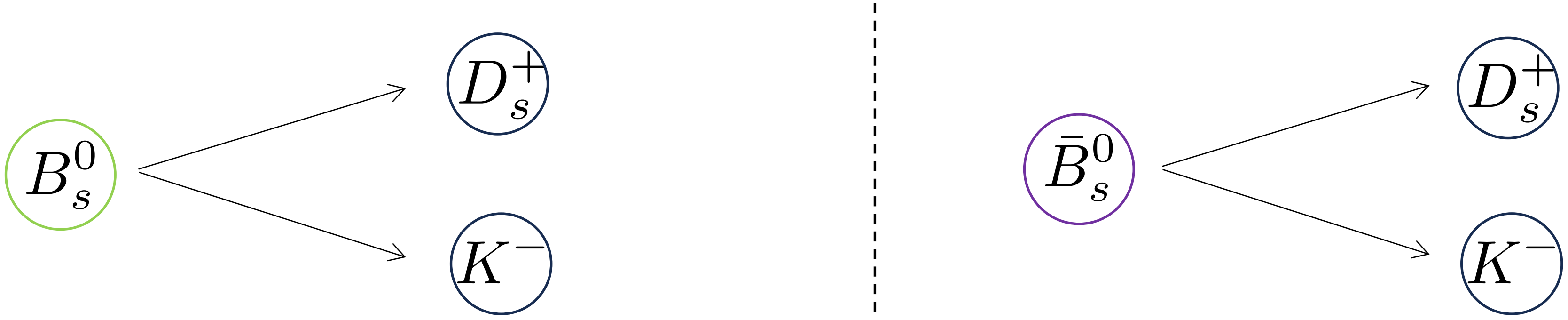
Effective field theory: $\mathcal{H}_{\Delta B=1} = \frac{G_F}{\sqrt{2}}(c_1 \mathcal{O}_1^q + c_2 \mathcal{O}_2^q)$

Wilson coefficient: $c_i = c_i^{\rm SM} + c_i^{\rm NP}$ $(i = 1, 2)$

(model-independent analysis)

$O_1^q = (\bar{b}_L^\alpha \gamma_\mu c_L^\beta)(\bar{u}_L^\beta \gamma^\mu q_L^\alpha)$ $O_2^q = (\bar{b}_L^\alpha \gamma_\mu c_L^\alpha)(\bar{u}_L^\alpha \gamma^\mu q_L^\alpha)$

γ determination with $B_s^0 - \bar{B}_s^0$ mixing



Time-dependent rate asymmetry

Fleischer [0304027]

$$\frac{\Gamma[B_s^0(t)\to D_s^+K^-]-\Gamma[\bar{B}_s^0(t)\to D_s^+K^-]}{\Gamma[B_s^0(t)\to D_s^+K^-]+\Gamma[\bar{B}_s^0(t)\to D_s^+K^-]} = \frac{C\cos(\Delta M_s t)+S\sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2)-\mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_s t/2)}$$

LHCb [1712.07428]: $C = -0.73\pm0.15$ $S = +0.49\pm0.21$ $\mathcal{A}_{\Delta\Gamma} = +0.31\pm0.32$

Definitions of coefficients: $C=\frac{1-|\xi|^2}{1+|\xi|^2}, \quad S=\frac{2\mathrm{Im}\xi}{1+|\xi|^2}, \quad \mathcal{A}_{\Delta\Gamma}=\frac{2\mathrm{Re}\xi}{1+|\xi|^2}.$

$$\xi = -e^{-i\phi_s}\frac{A[\bar{B}_s^0\to D_s^+K^-]}{A[B_s^0\to D_s^+K^-]}$$

$\phi_s = 2\arg(V_{ts}^*V_{tb})$ *CP* phase from B_s^0-$\overline{B_s^0}$ mixing

determined from other measurement, $B_s \to J/\psi\phi$

convention
$CP|B_s^0\rangle = +|\bar{B}_s^0\rangle$

γ determination from B_s decays

Time-dependent rate asymmetry

Fleischer [0304027]

$D_s^+ K^-$

$$\frac{\Gamma[B_s^0(t) \to D_s^+ K^-] - \Gamma[\bar{B}_s^0(t) \to D_s^+ K^-]}{\Gamma[B_s^0(t) \to D_s^+ K^-] + \Gamma[\bar{B}_s^0(t) \to D_s^+ K^-]} = \frac{C \cos(\Delta M_s t) + S \sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}_{\Delta\Gamma} \sinh(\Delta\Gamma_s t/2)}$$

LHCb [1712.07428]: $C = -0.73 \pm 0.15$ $S = +0.49 \pm 0.21$ $\mathcal{A}_{\Delta\Gamma} = +0.31 \pm 0.32$

$$C = \frac{1-|\xi|^2}{1+|\xi|^2}, \quad S = \frac{2\mathrm{Im}\xi}{1+|\xi|^2}, \quad \mathcal{A}_{\Delta\Gamma} = \frac{2\mathrm{Re}\xi}{1+|\xi|^2}.$$

$D_s^- K^+$

$$\frac{\Gamma[B_s^0(t) \to D_s^- K^+] - \Gamma[\bar{B}_s^0(t) \to D_s^- K^+]}{\Gamma[B_s^0(t) \to D_s^- K^+] + \Gamma[\bar{B}_s^0(t) \to D_s^- K^+]} = \frac{\bar{C} \cos(\Delta M_s t) + \bar{S} \sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) - \bar{\mathcal{A}}_{\Delta\Gamma} \sinh(\Delta\Gamma_s t/2)}$$

LHCb [1712.07428]: $\bar{C} = +0.73 \pm 0.15$ $\bar{S} = +0.52 \pm 0.21$ $\bar{\mathcal{A}}_{\Delta\Gamma} = +0.39 \pm 0.32$

$$\bar{C} = \frac{1-|\bar{\xi}|^2}{1+|\bar{\xi}|^2}, \quad \bar{S} = \frac{2\mathrm{Im}\bar{\xi}}{1+|\bar{\xi}|^2}, \quad \bar{\mathcal{A}}_{\Delta\Gamma} = \frac{2\mathrm{Re}\bar{\xi}}{1+|\bar{\xi}|^2}.$$

<u>Cancellation of hadronic uncertainties</u> Fleischer [0304027]

$$\xi \times \bar{\xi} = e^{-i2(\phi_s+\gamma)} \longrightarrow \boxed{\text{Determination of } \gamma}$$

proportional to CP phase

ϕ_s: CP violating phase in B_s mixing determined from $B_s \to J/\psi\phi$

Observables in the presence of BSM

$$A[\bar{B}_s^0 \to D_s^+ K^-] = T_{D_s K} + E_{D_s K}$$

T: QCDF approach: $T = \frac{G_F}{\sqrt{2}} V_{us}^* V_{cb} f_{K^+} F_0^{B_s \to D_s}(m_{K^+}^2)(m_{B_s}^2 - m_{D_s}^2) a_1^{c\bar{u}s}$

$$a_1^{c\bar{u}s} = (a_1)_{\rm SM} + \overbrace{c_{\rm 2NP}^{c\bar{u}s} + \frac{c_{\rm 1NP}^{c\bar{u}s}}{3}}^{\text{BSM}}$$

Analysis at NNLO Huber, Krankl and Li [1606.02888]

E: Discussion in Fleischer and Malami [2109.04950]

$|a_1^{D_s K}| = 1.07 \pm 0.02$, [2109.04950]

Size of E from data $r_E^{D_s K} \equiv \left| 1 + \frac{E_{D_s K}}{T_{D_s K}} \right| = 1.00 \pm 0.08$, E leads to small corrections

γ/ϕ_3 determinations

$$\xi \times \bar{\xi} = \overbrace{e^{-i2(\phi_s + \gamma)}}^{\text{SM weak phase}} \times \underbrace{\frac{T_{D_s K} T_{K D_s}}{\bar{T}_{D_s K} \bar{T}_{K D_s}}}_{\text{including BSM}}$$

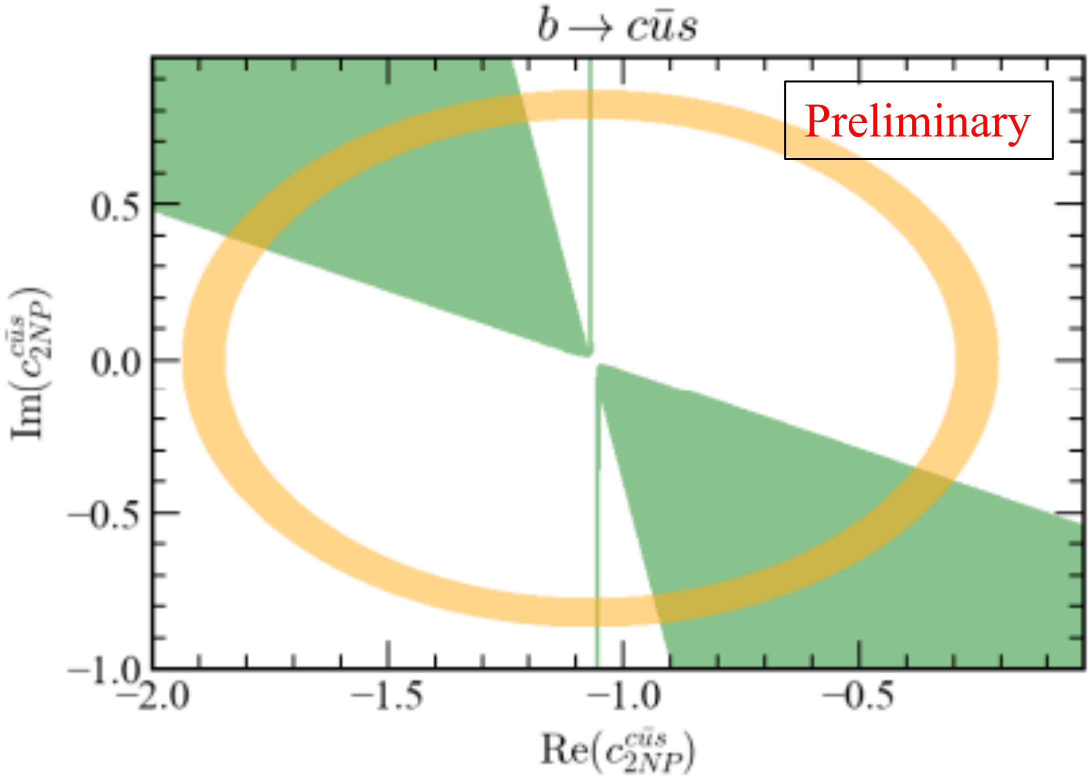
in the absence of the exchange diagram

$$\longrightarrow \gamma_{\rm exp} = \gamma - \overbrace{\frac{1}{2} \arg \left[\frac{a_1^{c\bar{u}s}}{(a_1^{c\bar{u}s})^*} \right]}^{\text{BSM}}$$

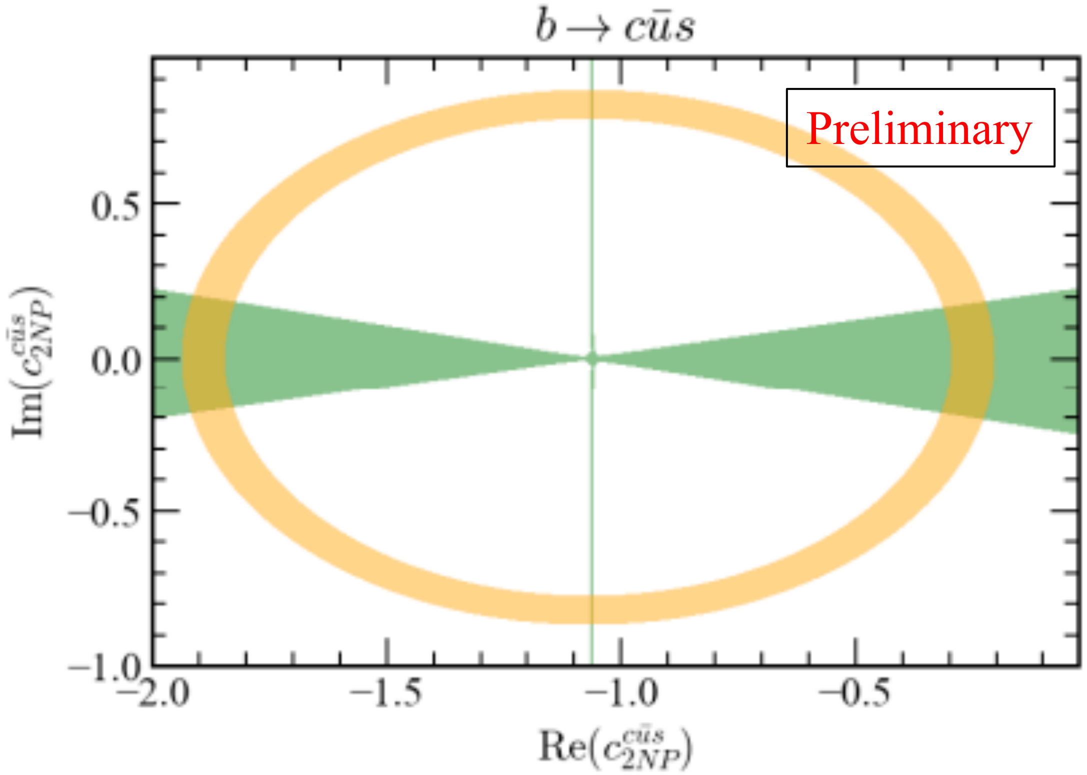
$c_1^{c\bar{u}s} = 0$

Constraint on NP coupling for $b \to c\bar{u}s$

$\gamma = (127^{+18}_{-26})^\circ$ LHCb Run 1 [1712.07428]



$\gamma = (74 \pm 12)^\circ$ LHCb Run 2 [2412.14074]



1σ regions
- Green: γ constraint from $B_s \to D_s^\pm K^\mp$
- Yellow: $\mathrm{Br}[\overline{B_s} \to D_s^+ K^-]$ constraint

$c_1^{c\bar{u}d} = 0$

Constraint on NP coupling for $b \to c\bar{u}d$

$B_s \to D_s^{\pm} K^{\mp}$

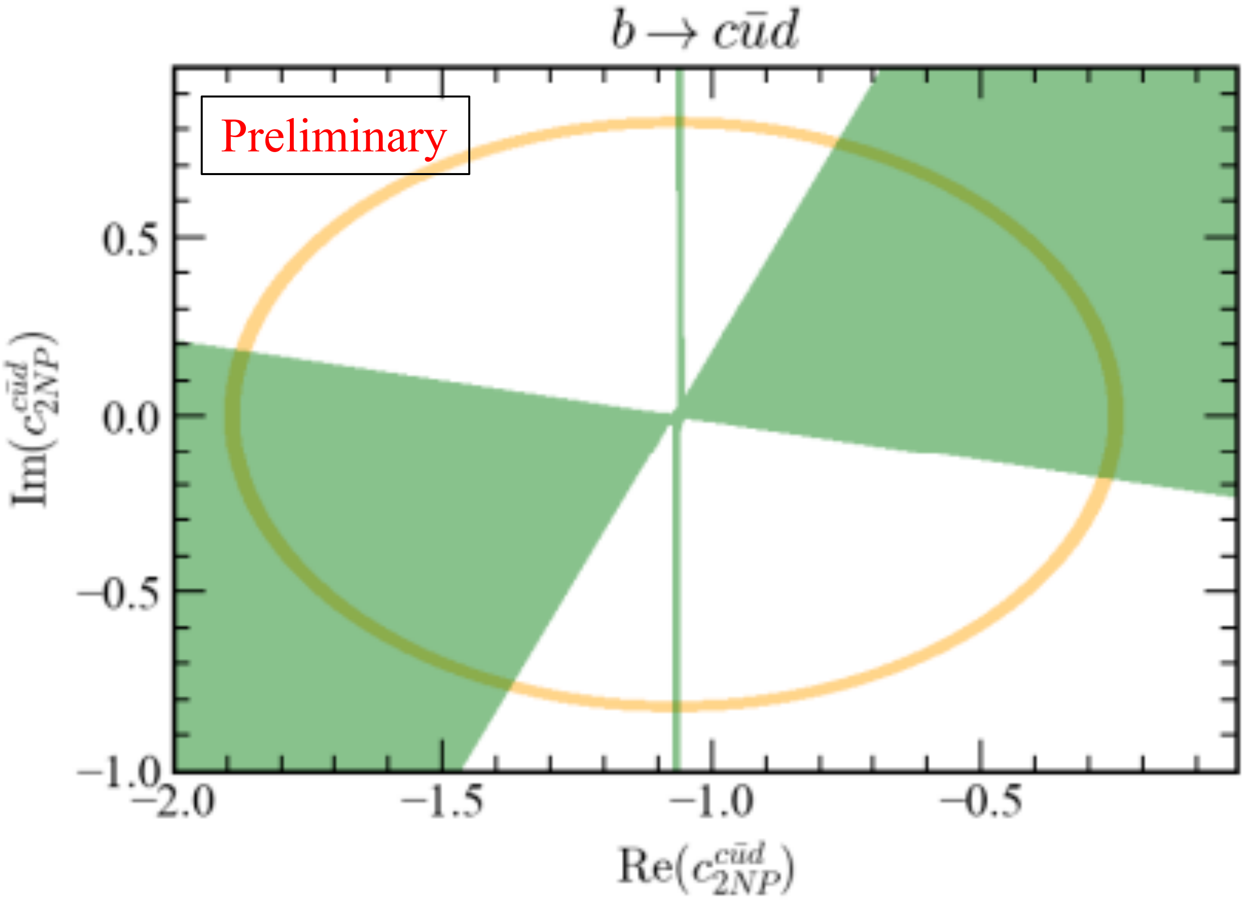
↓ replacement

$B_d \to D^{\pm}\pi^{\mp}$

Determination of $2\beta + \gamma$

$\gamma \in [5, 86]^\circ \cup [185, 266]^\circ$ LHCb [1805.03448]

with $\beta = (22.2 \pm 0.7)^\circ$ HFLAV as of 2016



1σ regions
- Green: γ constraint from $B_d \to D^{\pm}\pi^{\mp}$
- Yellow: $\mathrm{Br}[B_d \to D^-\pi^+]$ constraint

Summary

- In view of the $B \to D\pi$ (and $B \to DK$) tensions, we have discussed constraints on NP from unitarity triangle for γ/ϕ_3.

- The complex-valued Wilson coefficients are stringently constrained by LHCb data of the unitarity triangle.

- Future works

  -- Constraint from τ_{B^+}/τ_{B_d} and $\Delta\Gamma$ in $B^0 - \overline{B^0}$ mixing.

  -- Constraints from γ/ϕ_3 from processes of GLW and ADS.

  -- Prediction for $\mathcal{A}_{\rm SL}^d$ (indirect CP violation in B_d system)

Gronau and London 1991
Gronau and Wyler 1991
Atwood, Dunietz and Soni 1997

Back up

Exchange diagram

$$\begin{cases} A[\bar{B}_d^0 \to D^+ K^-] = T_{D_d K} \\ A[\bar{B}_s^0 \to D_s^+ K^-] = T_{D_s K} + E_{D_s K} \end{cases}$$

Ratio: $$\left|\frac{T_{D_s K}}{T_{D_d K}}\right|^2 \left|1 + \frac{E_{D_s K}}{T_{D_s K}}\right|^2 = \frac{\tau_{B_d}}{\tau_{B_s}} \frac{m_{B_s}}{m_{B_d}} \left[\frac{\Phi(m_{D_d}/m_{B_d}, m_K/m_{B_d})}{\Phi(m_{D_s}/m_{B_s}, m_K/m_{B_s})}\right] \left[\frac{\mathcal{B}(\bar{B}_s^0 \to D_s^+ K^-)_{\rm th}}{\mathcal{B}(\bar{B}_d^0 \to D_d^+ K^-)}\right]$$

$$\left|\frac{T_{D_s K}}{T_{D_d K}}\right| \left|1 + \frac{E_{D_s K}}{T_{D_s K}}\right| = 1.03 \pm 0.08$$

QCDF approach →

$$\left|\frac{T_{D_s K}}{T_{D_d K}}\right| = \left[\frac{F_0^{B_s \to D_s}(m_K^2)}{F_0^{B_d \to D_d}(m_K^2)}\right] \left[\frac{m_{B_s}^2 - m_{D_s}^2}{m_{B_d}^2 - m_{D_d}^2}\right] \left|\frac{a_1^{D_s K}}{a_1^{D_d K}}\right| = 1.03 \pm 0.03$$

$$r_E^{D_s K} \equiv \left|1 + \frac{E_{D_s K}}{T_{D_s K}}\right| = 1.00 \pm 0.08$$

Branching ratio of $\bar{B}_s^0 \to D_s^+ K^-$ and $B_s^0 \to D_s^+ K^-$

Experimental branching ratio $$\mathcal{B}_{\rm exp} = \frac{1}{2}\int_0^\infty \left[\Gamma(\bar{B}_s^0(t) \to D_s^+ K^-) + \Gamma(B_s^0(t) \to D_s^+ K^-)\right] \mathrm{d}t$$ time-integrated

$$\mathcal{B}_{\rm th} \equiv \frac{1}{2}\left[\mathcal{B}(\bar{B}_s^0 \to D_s^+ K^-)_{\rm th} + \mathcal{B}(B_s^0 \to D_s^+ K^-)_{\rm th}\right]$$

$$\mathcal{B}_{\rm th} = \left[\frac{1-y_s^2}{1+\mathcal{A}_{\Delta\Gamma_s} y_s}\right]\mathcal{B}_{\rm exp}$$

$$\mathcal{B}_{\rm th} = \frac{1}{2}\left(1+|\xi|^2\right)\mathcal{B}_{\rm th}(B_s^0 \to D_s^+ K^-) = \frac{1}{2}\left(1+|\xi|^{-2}\right)\mathcal{B}_{\rm th}(\bar{B}_s^0 \to D_s^+ K^-)$$

Branching fractions without mixing

$$\begin{cases} \mathcal{B}(\bar{B}_s^0 \to D_s^+ K^-)_{\rm th} = 2\left(\dfrac{|\xi|^2}{1+|\xi|^2}\right)\mathcal{B}_{\rm th} \\ \mathcal{B}(B_s^0 \to D_s^+ K^-)_{\rm th} = 2\left(\dfrac{1}{1+|\xi|^2}\right)\mathcal{B}_{\rm th} \end{cases}$$

$$\begin{cases} \mathcal{B}(\bar{B}_s^0 \to D_s^+ K^-)_{\rm th} = |A(\bar{B}_s^0 \to D_s^+ K^-)|^2\,\Phi_{\rm Ph}\,\tau_{B_s} \\ \mathcal{B}(B_s^0 \to D_s^+ K^-)_{\rm th} = |A(B_s^0 \to D_s^+ K^-)|^2\,\Phi_{\rm Ph}\,\tau_{B_s} \end{cases}$$

$\bar{B}_s^0 \to D_s^- K^+$ [2109.04950]

$$A^{\rm SM}_{\bar{B}_s^0 \to K^+ D_s^-} = \frac{G_{\rm F}}{\sqrt{2}}\, V_{cs}^* V_{ub}\; f_{D_s}\; F_0^{B_s \to K}(m_{D_s}^2)\; (m_{B_s}^2 - m_K^2)\; a_{1\,\rm eff}^{KD_s}$$

$$a_{1\,\rm eff}^{KD_s} = a_1^{KD_s}\left(1 + \frac{E_{KD_s}}{T_{KD_s}}\right)$$

$$|a_1^{KD_s}| = 1.1 \pm 0.1$$