Double-mixing CP Violation

Yin-Fa Shen

Huazhong University of Science and Technology

Collaborated with Wen-Jie Song, Qin Qin

Based on arXiv: 2301.05848

Outline

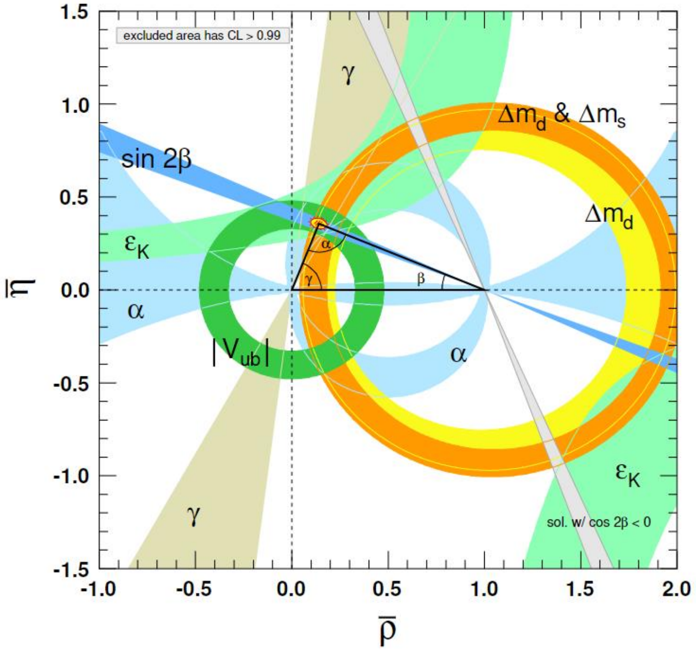
- Background and motivation
- Theoretical framework
- Numerical results
- CKM phase extraction
- Summary

CP violation

- SM precision test

Unitarity

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



[PDG, 2021]

- A necessary condition for baryogenesis, the process of dynamically generating the matter-antimatter asymmetry of the Universe.

Search for new **CPV**

How?

- Baryon number violation
- C and CP violation
- Thermodynamic non equilibrium

Sakharov conditions

[A.D.Sakharov et al, Fiz.5,32-35 (1967)]

CPV observables

Common CPV :

- Direct CP violation:

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1 \quad \Longleftrightarrow \quad \Gamma(M \to f) \neq \Gamma(\bar{M} \to \bar{f})$$

- CPV in mixing:

$$\left|\frac{q}{p}\right| \neq 1 \quad \Longleftrightarrow \quad \Gamma(M^0 \to \overline{M^0}) \neq \Gamma(\overline{M^0} \to M^0)$$

- CPV in interference between a decay without **initial** mixing

$$(\underline{M^0} \to f) + (\underline{M^0} \to \overline{M^0} \to f)$$

✓ CPV in interference between a decay without **final** mixing

$$(P \to \underline{M^0}) + (P \to \overline{M^0} \to \underline{M^0})$$

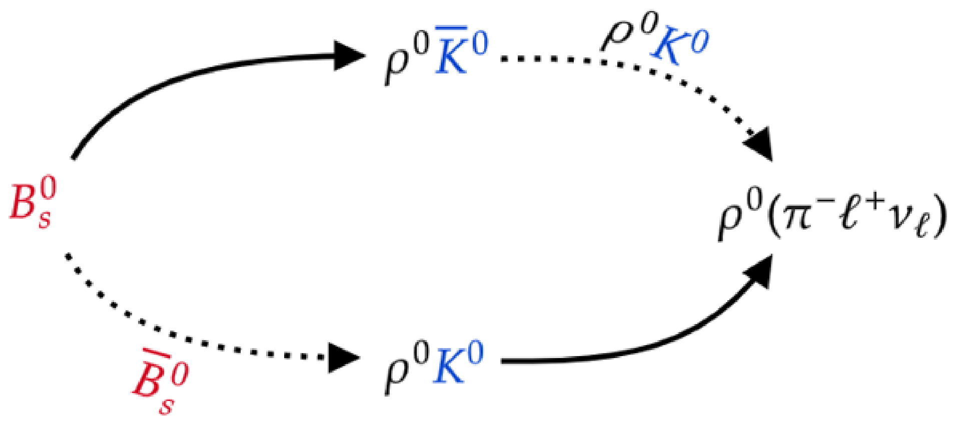
[Wang, Yu, Li, *PRL* 119(2017)181802]

New type of CPV

Consider $B_s^0 \dashrightarrow \rho^0 K \dashrightarrow \rho^0(\pi^- \ell^+ \nu_\ell)$

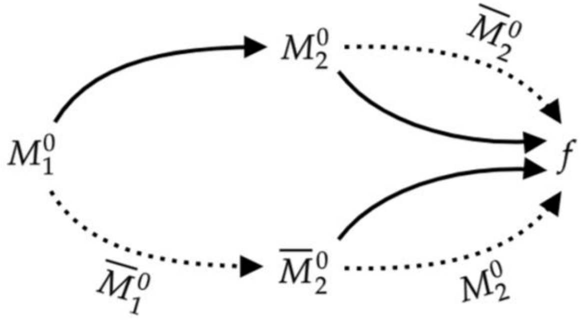
Upper path $B_s^0 \to \rho^0 \overline{K}^0 \to \rho^0 K^0 \to \rho^0(\pi^- \ell^+ \nu_\ell)$

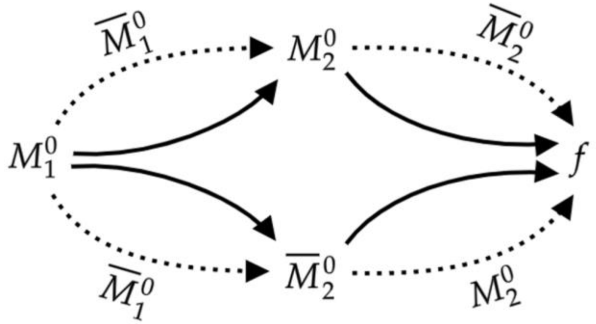
Lower path $B_s^0 \to \bar{B}_s^0 \to \rho^0 K^0 \to \rho^0(\pi^- \ell^+ \nu_\ell)$



- Induced by interferences between two mixing processes in one cascade decay.

- More complicated cases





[Yin-Fa Shen, Song, Qin, 2301.05848]

Double mixing CPV

Adv:

- It does not require nonzero strong phases, providing opportunities to directly extract weak phases without strong pollution.
- Strong phases can be extracted from experiment data without theoretical input.
- The two-dimensional time-dependent CP asymmetry can be analyzed. ⇒ $A_{CP}(t_1, t_2)$
- The **double mixing CPV** can be very significant and practically measurable by experiments.

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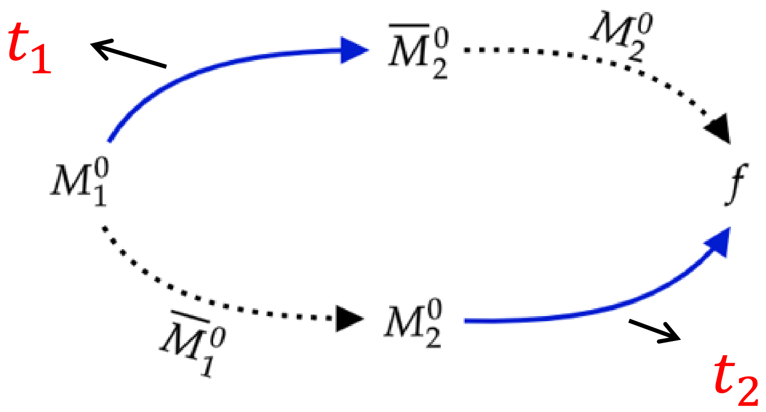
CP asymmetry



✓ CPV in M_1^0 mixing
✓ CPV in M_2^0 mixing
✓ Double mixing CPV

$\in \quad A_{CP}(t_1, t_2)$

- The two-dimensional time-dependent CP asymmetry is defined as

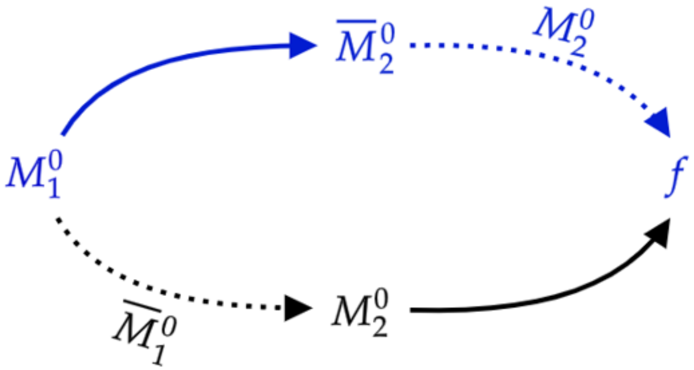
$$A_{CP}(t_1,t_2) \equiv \frac{\Gamma_f(t_1,t_2) - \Gamma_{\bar{f}}(t_1,t_2)}{\Gamma_f(t_1,t_2) + \Gamma_{\bar{f}}(t_1,t_2)} = \frac{N(t_1,t_2)}{D(t_1,t_2)}$$

Theoretical framework

$$|M^0(t)\rangle = g_+(t)|M^0\rangle - \frac{q}{p}g_-(t)|\bar{M}^0\rangle$$

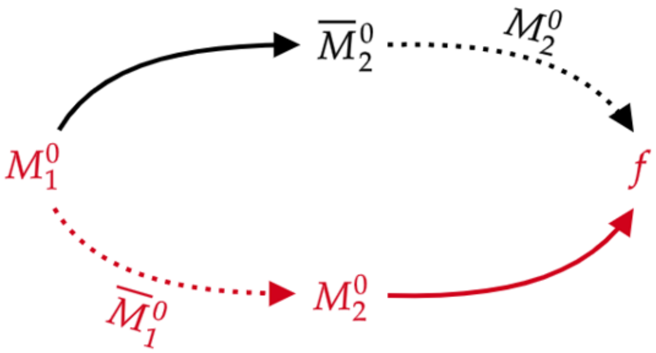
$$|\bar{M}^0(t)\rangle = g_+(t)|\bar{M}^0\rangle - \frac{p}{q}g_-(t)|M^0\rangle$$

✓ Take $B_s^0 \to \rho^0 \bar{K}^0 \to \rho^0(\pi^- \ell^+ \nu_\ell)$ as an example (penguin ≈ 0)



$$\propto \quad |g_{1,+}(t_1)|^2 |g_{2,-}(t_2)|^2 \left(\left|\frac{p_2}{q_2}\right|^2 - \left|\frac{q_2}{p_2}\right|^2 \right)$$

CP violation in $\boldsymbol{M_2^0}$ **mixing**

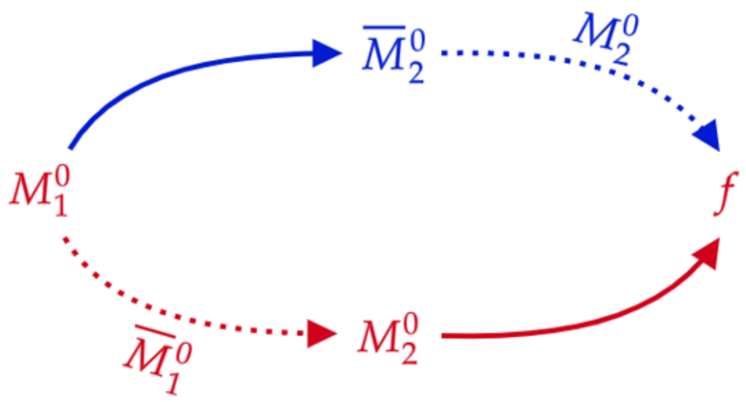


$$\propto \quad |g_{1,-}(t_1)|^2 |g_{2,+}(t_2)|^2 \left(\left|\frac{q_1}{p_1}\right|^2 - \left|\frac{p_1}{q_1}\right|^2 \right)$$

CP violation in $\boldsymbol{M_1^0}$ **mixing**

Double mixing CPV

✓ Take $B_s^0 \to \rho^0 \bar{K}^0 \to \rho^0(\pi^- \ell^+ \nu_\ell)$ as an example (penguin ≈ 0)



$$A_h(t_1, t_2) \quad \propto \quad -e^{-\Gamma_1 t_1} \sinh \frac{\Delta\Gamma_1 t_1}{2} \, [2S_{n2}(t_2) \, \sin(\phi_1 + \phi_2 + 2\delta)]$$

$K_S \, K_L$

$$A_n(t_1, t_2) \quad \propto \quad e^{-\Gamma_1 t_1} \sin\Delta m_1 t_1 \, [2S_{h2}(t_2) \, \sin(\phi_1 + \phi_2 + 2\delta)]$$

$K_S + K_L$

$$q_1/p_1 = |q_1/p_1| \, e^{-i\phi_1}$$
$$q_2/p_2 = |q_2/p_2| \, e^{-i\phi_2}$$
$$\langle \rho^0 \bar{K}^0 | B_s^0 \rangle = \langle \rho^0 K^0 | \bar{B}_s^0 \rangle e^{2i\delta}$$

- With ϕ_1, ϕ_2, δ the relevant weak phases.

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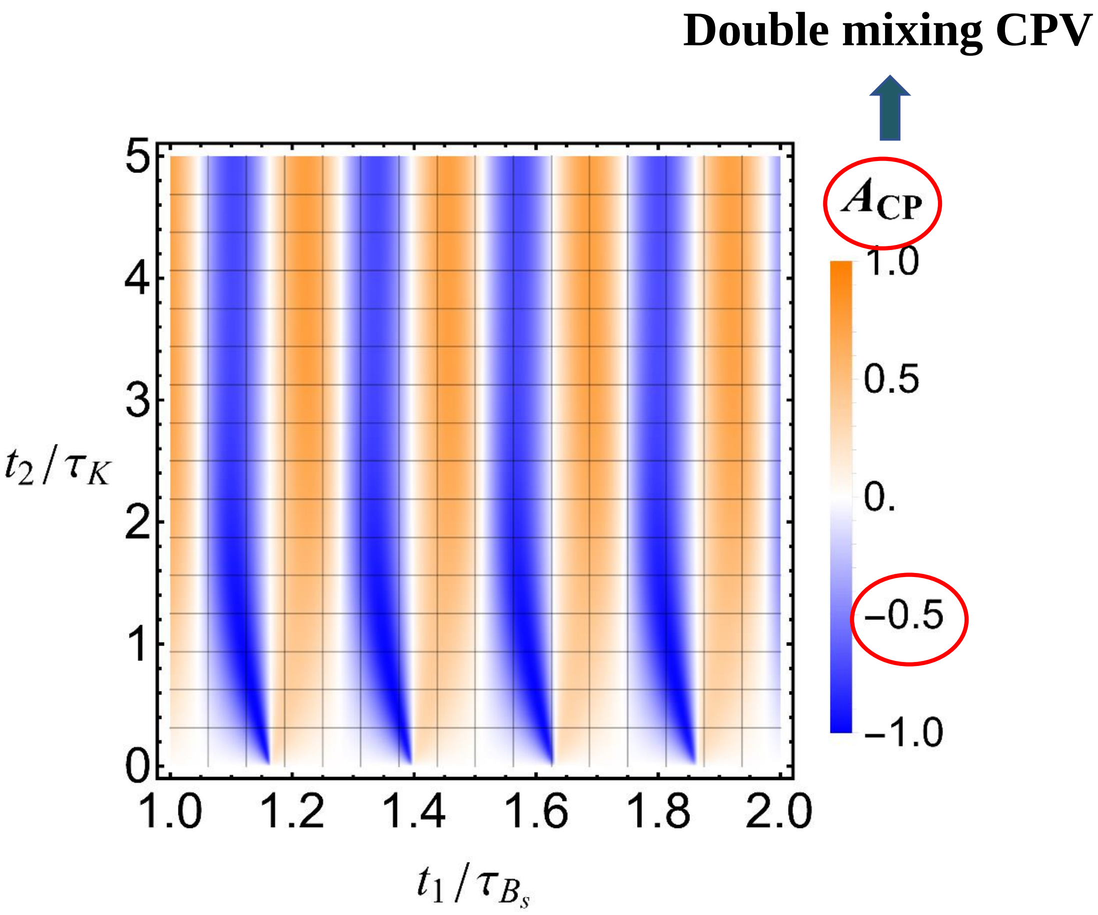
t_1, t_2 Dependence

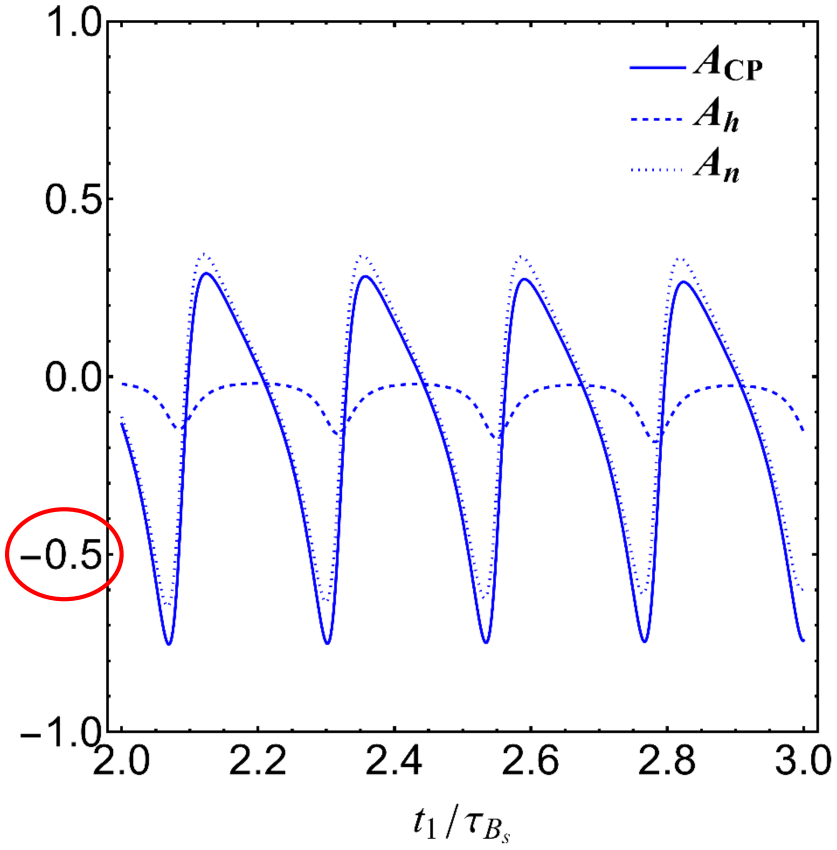
- $B_s^0 \to \rho^0 \overline{K}^0 \to \rho^0(\pi^- \ell^+ \nu_\ell)$

- The $A_{CP}(t_1, t_2)$ dependence on t_1 and t_2.

- The magnitude of the peak values can be larger than **50%**.

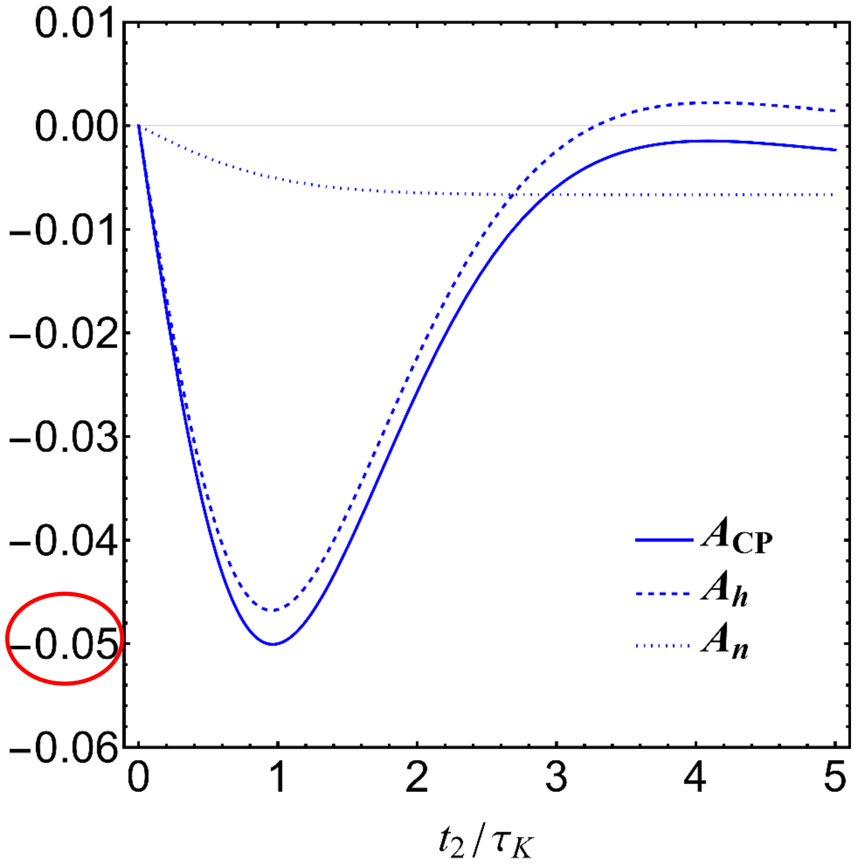


t_1 Dependence



- Integral out the t_2 from 0 to τ_K

t_2 Dependence



- Integral out the t_1 from τ_{B_s} to $5\tau_{B_s}$

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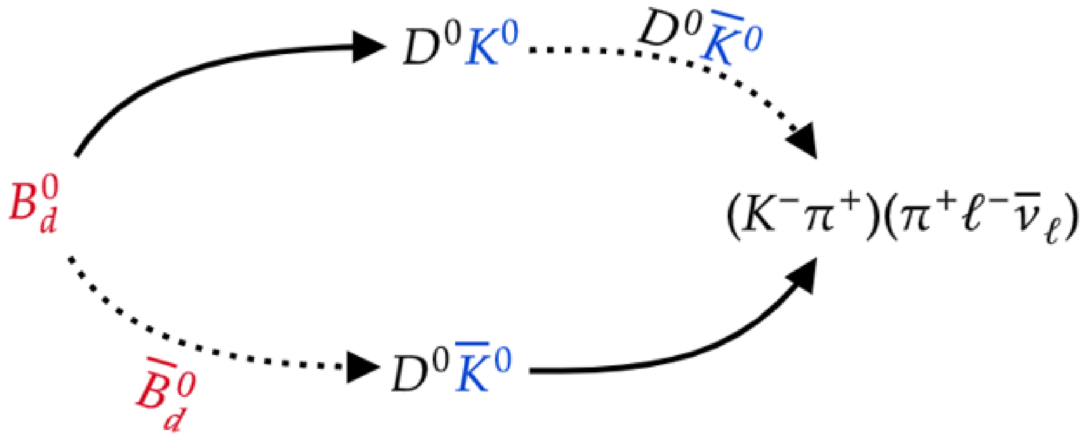
CKM phase extraction

✓ Take $B_d^0 \to D^0 K^0 \to (K^- \pi^+)(\pi^+ \ell^- \overline{\nu}_\ell)$ as an example (penguin = 0)

$$\langle D^0 \overline{K}^0 | \bar{B}_d^0 \rangle = \langle \overline{D}^0 K^0 | B_d^0 \rangle e^{i\theta_1}$$

$$\langle D^0 K^0 | B_d^0 \rangle = \langle \overline{D}^0 K^0 | B_d^0 \rangle \, r_B e^{i(\delta_B + \theta_2)}$$



Parameters: r_B、δ_B、$\underbrace{\phi_2 - \phi_1 + \theta_1 - \theta_2}_{\boldsymbol{\omega}} \propto 2\beta + \gamma$

$$q_B / p_B = |q_B / p_B| \, e^{-i\phi_1}$$

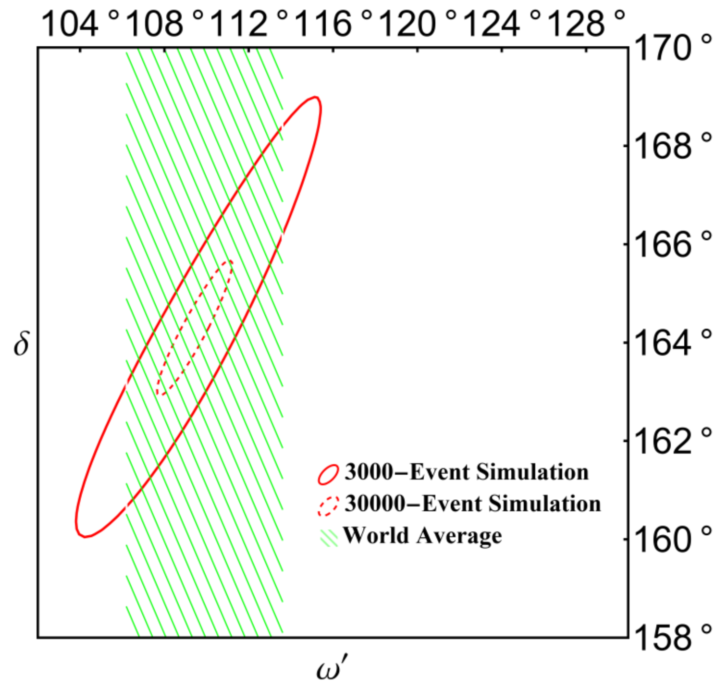
$$q_K / p_K = |q_K / p_K| \, e^{-i\phi_2}$$

Related phases: $\theta_2 \to \gamma$, $\phi_1 \to 2\beta$

CKM phase extraction

✓ Take $B_d^0 \to D^0 K^0 \to (K^- \pi^+)(\pi^+ \ell^- \overline{\nu}_\ell)$ as an example (penguin = 0)

Parameter	Central values (input value)	Uncertainties
r_B	0.370 (0.366)	0.015
δ	163.9° (164°)	$\pm$4.4°
ω'	109.1° (109.9°)	$\pm$5.7°



$\omega = \phi_2 - \phi_1 + \theta_1 - \theta_2 \propto 2\beta + \gamma$ → $109.9° \pm 3.7°$ (World Average)

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Summary

- A novel type of CP violation effect, the **double-mixing** CP asymmetry, is proposed.
- It does not require nonzero strong phases.
- Strong phases can be extracted from experiment data without theoretical input.
- The two-dimensional time-dependent CP asymmetry can be analyzed.
- The double-mixing CP asymmetry can be very **significant** in some decay modes.

e.g. $B_s^0 \to \rho^0 \overline{K}^0 \to \rho^0(\pi^- \ell^+ \nu_\ell)$

Thanks !