

Double-mixing CP Violation

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Based on arXiv: 2301.05848

Outline

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

CP violation

- SM precision test

Unitarity

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

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

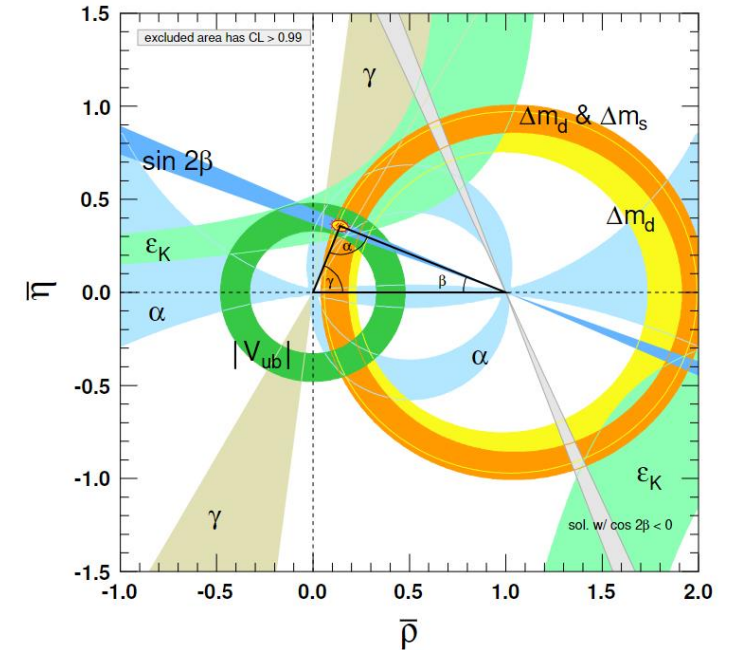
Search for new **CPV**

How?

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

Sakharov conditions

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



[PDG, 2021]

CPV observables

Common CPV :

- Direct CP violation:

$$\left| \frac{\bar{A}_f}{A_f} \right| \neq 1 \iff \Gamma(M \rightarrow f) \neq \Gamma(\bar{M} \rightarrow \bar{f})$$

- CPV in mixing:

$$\left| \frac{q}{p} \right| \neq 1 \iff \Gamma(M^0 \rightarrow \bar{M}^0) \neq \Gamma(\bar{M}^0 \rightarrow M^0)$$

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

$$\underline{(M^0 \rightarrow f)} + \underline{(M^0 \rightarrow \bar{M}^0 \rightarrow f)}$$

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

$$(P \rightarrow \underline{M^0}) + (P \rightarrow \bar{M}^0 \rightarrow \underline{M^0})$$

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

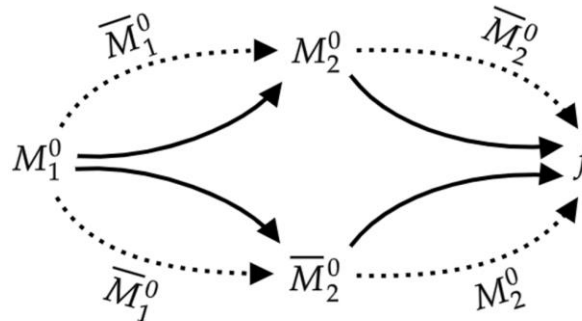
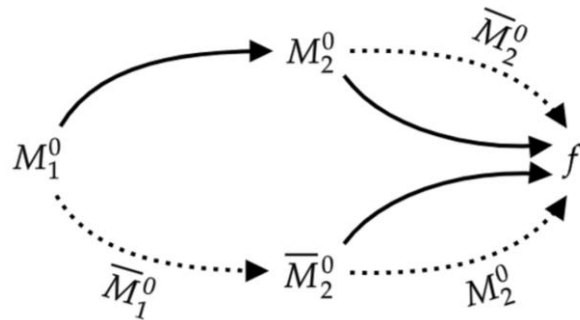
New type of CPV

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

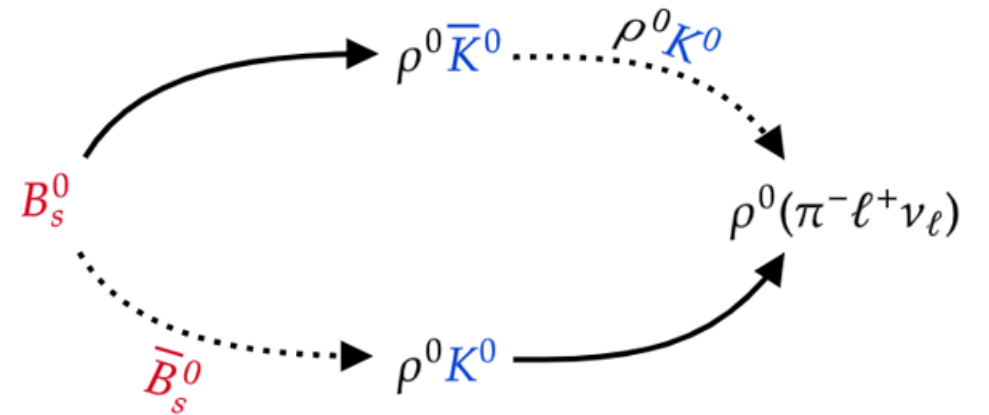
Lower path $B_s^0 \rightarrow \bar{B}_s^0 \rightarrow \rho^0 K^0 \rightarrow \rho^0(\pi^- \ell^+ \nu_\ell)$

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

- More complicated cases




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



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

Double mixing CPV

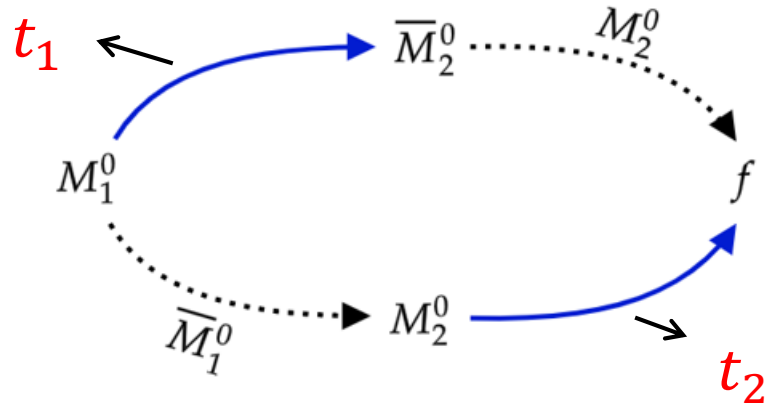
Adv:

- 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**

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

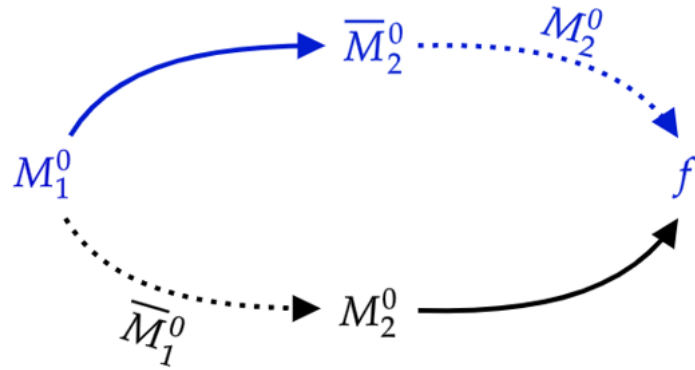
- The two-dimensional time-dependent CP asymmetry is defined as

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

Theoretical framework

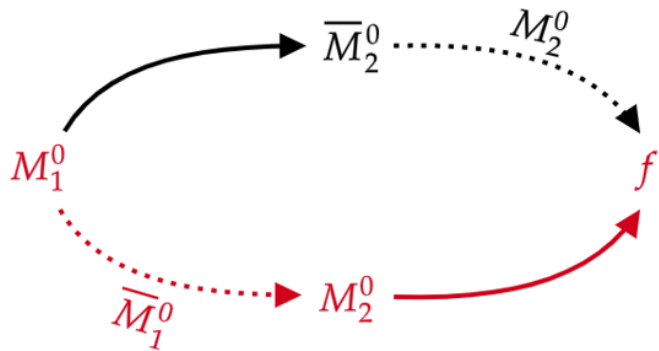
✓ Take $B_s^0 \rightarrow \rho^0 \bar{K}^0 \rightarrow \rho^0 (\pi^- \ell^+ \nu_\ell)$ as an example (penguin ≈ 0)

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



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

CP violation in M_2^0 mixing



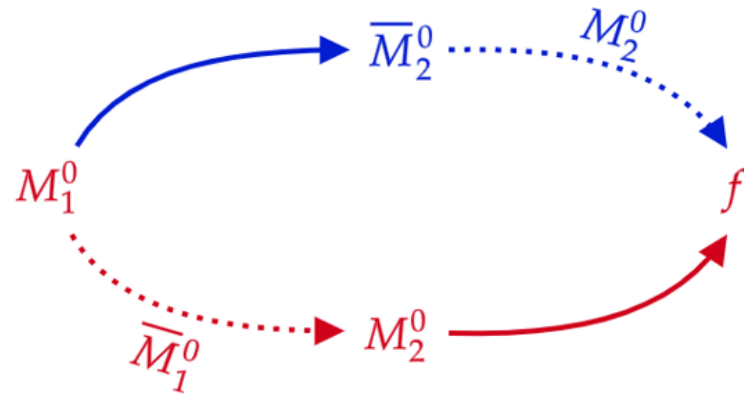
$$\propto |g_{1,-}(t_1)|^2 |g_{2,+}(t_2)|^2 \left(\frac{|q_1|^2}{|p_1|^2} - \frac{|p_1|^2}{|q_1|^2} \right)$$

CP violation in M_1^0 mixing

Double mixing CPV

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

$$\Gamma_2 = \frac{\Gamma_S + \Gamma_L}{2} \approx \frac{\Gamma_S}{2} = \frac{1}{2\tau_S}$$



$$K_S \otimes K_L$$

$$A_h(t_1, t_2) \propto e^{-\Gamma_1 t_1} \sinh \frac{\Delta\Gamma_1 t_1}{2} [2S_{n_2}(t_2) \sin(\phi_1 + \phi_2 + 2\delta)]$$

$$K_S + K_L$$

$$A_n(t_1, t_2) \propto e^{-\Gamma_1 t_1} \sin \Delta m_1 t_1 [2S_{h_2}(t_2) \sin(\phi_1 + \phi_2 + 2\delta)]$$

$e^{-\Gamma_S t_2} - e^{-\Gamma_L t_2}$

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

$$q_1/p_1 = |q_1/p_1| e^{-i\phi_1}$$

$$q_2/p_2 = |q_2/p_2| e^{-i\phi_2}$$

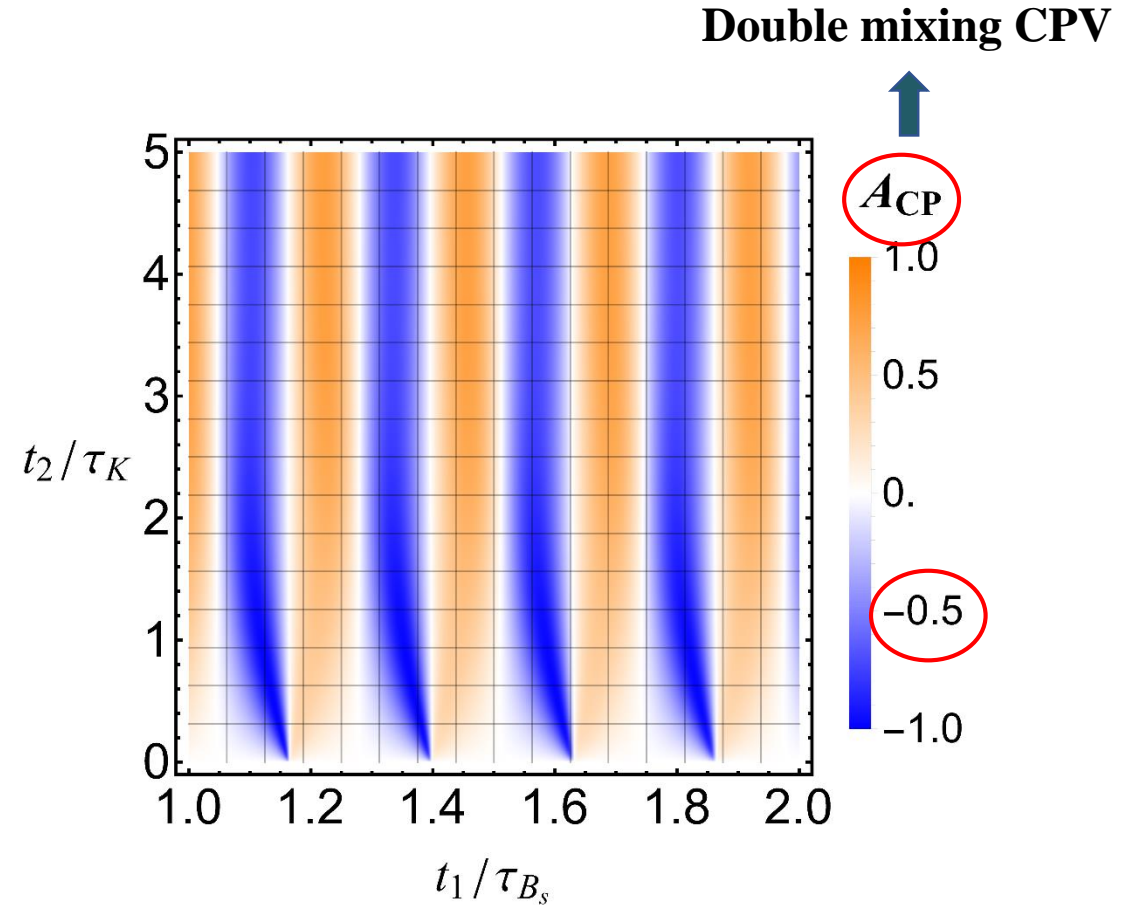
$$\langle \rho^0 \bar{K}^0 | B_s^0 \rangle = \langle \rho^0 K^0 | \bar{B}_s^0 \rangle e^{2i\delta}$$

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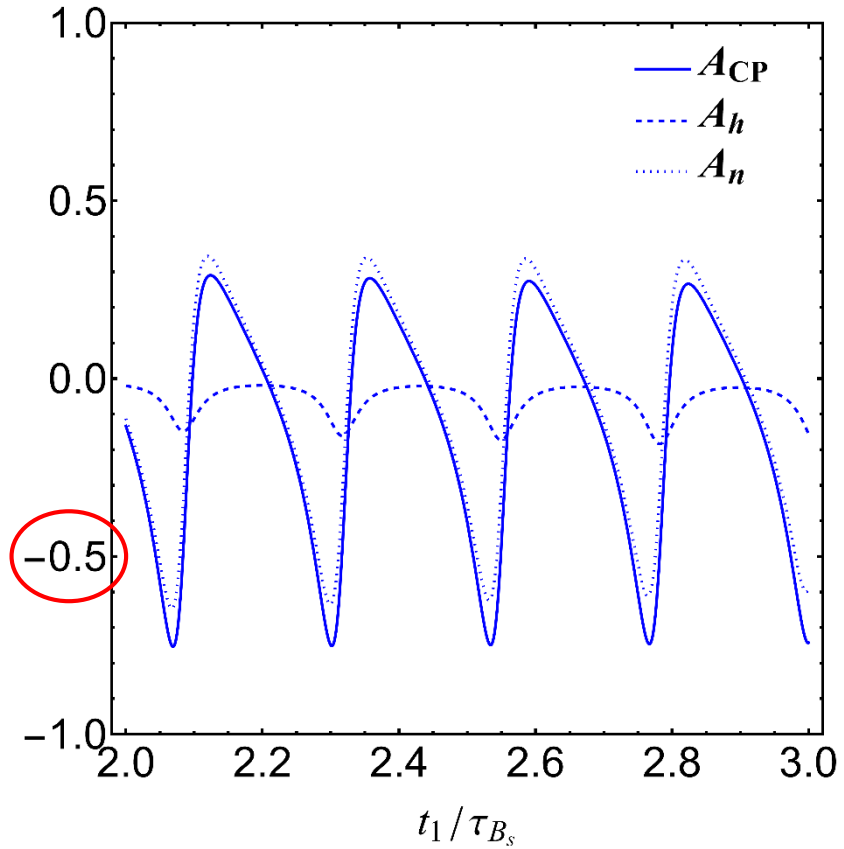
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t_1, t_2 Dependence

- $B_S^0 \rightarrow \rho^0 \bar{K}^0 \rightarrow \rho^0 (\pi^- \ell^+ \nu_\ell)$
- 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%**.

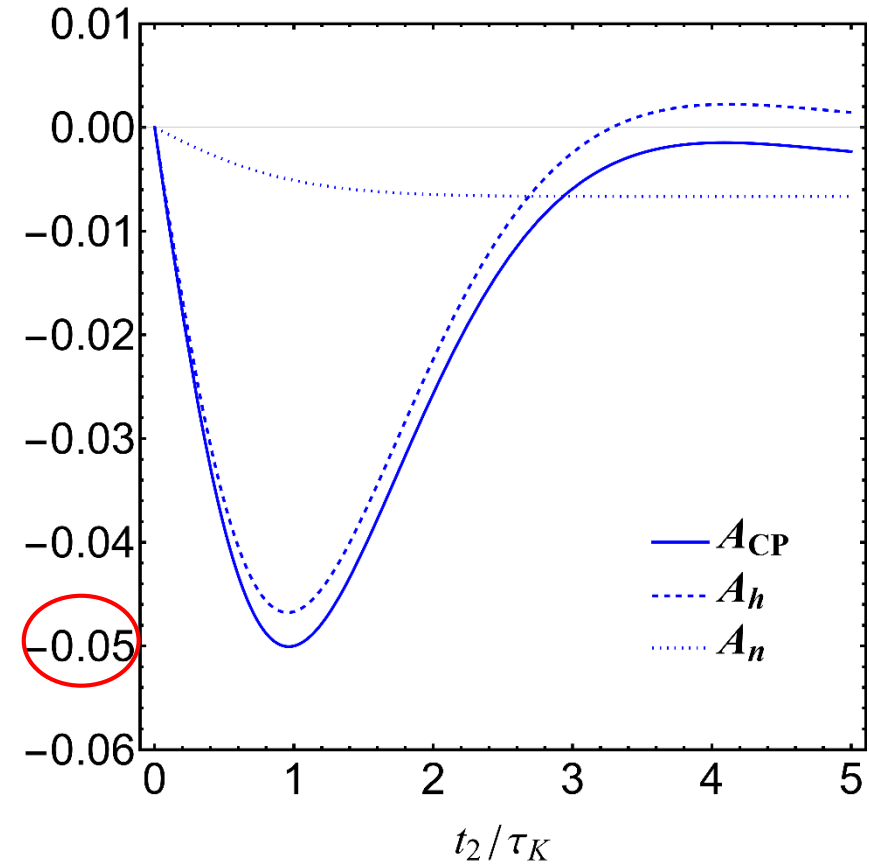


t_1 Dependence



- Integral out the t_2 from 0 to τ_K

t_2 Dependence



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

Outline

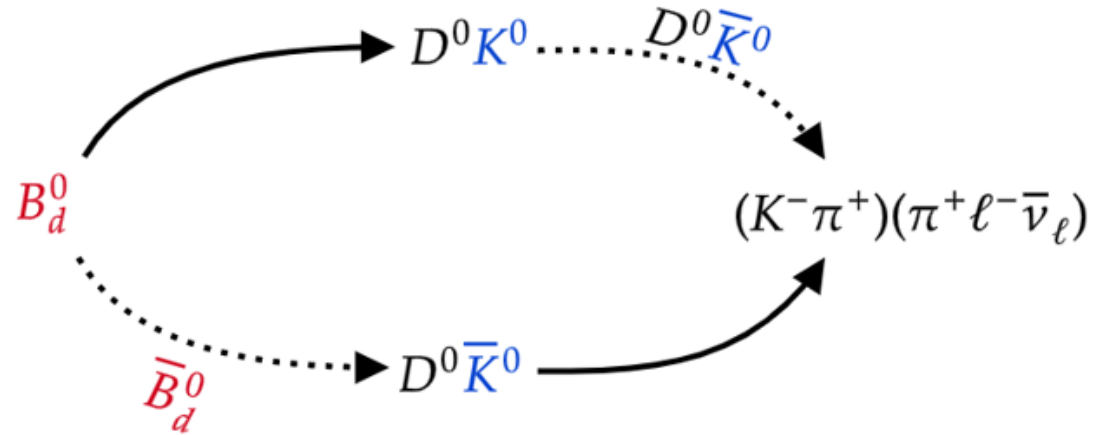
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CKM phase extraction

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

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

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



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

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

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

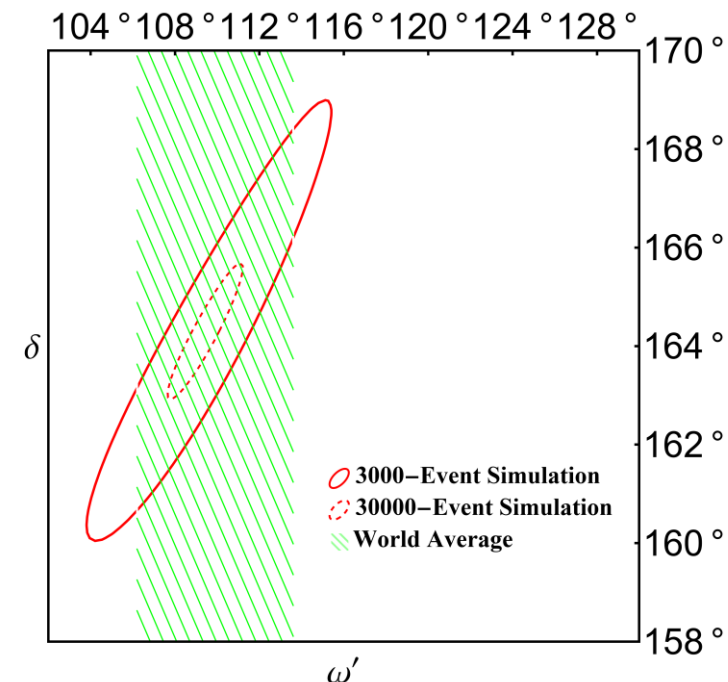
$$q_K/p_K = |q_K/p_K| e^{-i\phi_2}$$

CKM phase extraction

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

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

$$\omega = \phi_2 - \phi_1 + \theta_1 - \theta_2 \propto 2\beta + \gamma \longrightarrow 109.9^\circ \pm 3.7^\circ \text{ (World Average)}$$



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Discussion

- Double mixing could still exist even when the final state is non-CP eigenstate, like the **semileptonic** decay of K^0 meson.
- That implies the interesting and potential features of double mixing, e.g., the interference between K_L and K_S , enables to access the **K_L physics at collider**
- It's possible to be observed at LHCb in the future (about 10^2 events), and given the higher efficiency of CEPC, it can be studied in detail at Tera-Z. (See reports of Fengling Li, Yuexin Wang, Mingrui Zhao on the first day)
- It also calls for the experimental study of the **semileptonic** decay of K^0 meson **at collider**.

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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.

$$\text{e.g. } B_S^0 \rightarrow \rho^0 \bar{K}^0 \rightarrow \rho^0 (\pi^- \ell^+ \nu_\ell)$$

Thanks !