

Double-mixing CP Violation

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Based on arXiv: 2301.05848

Outline

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

CP violation

- SM precision test

Unitarity

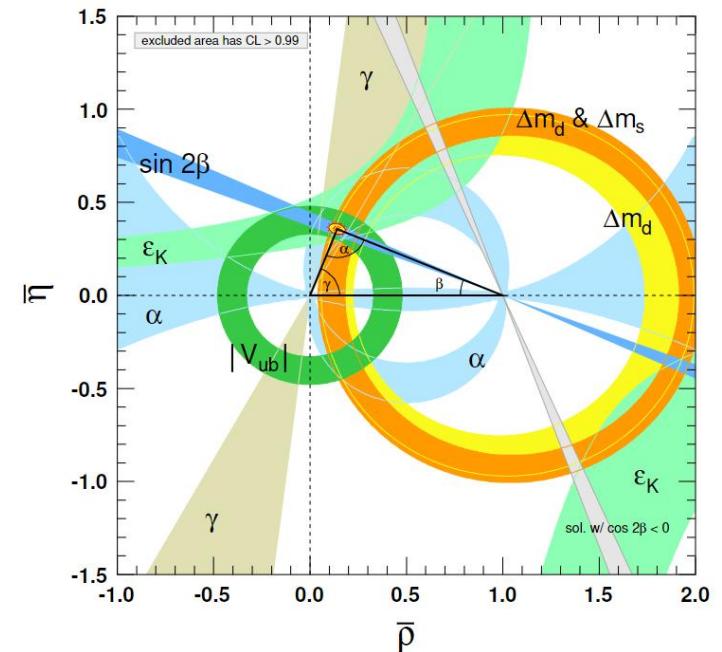
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- 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



[PDG, 2021]



Sakharov conditions

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

CPV observables

Common CPV :

- Direct CP violation:

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

- 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]

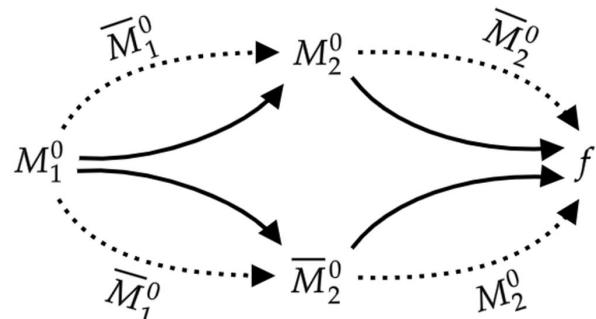
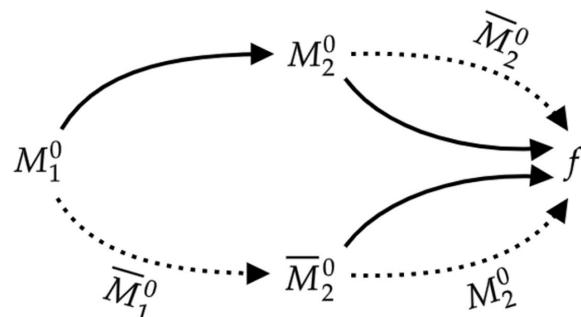
New type of CPV

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

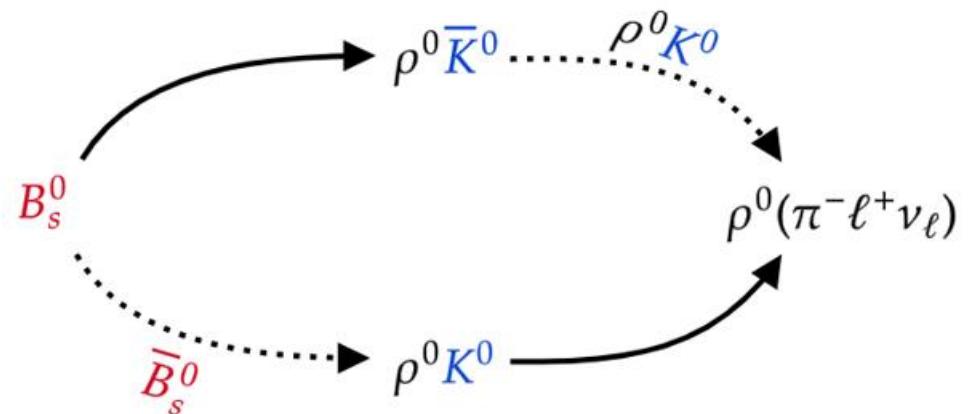
Lower path $B_s^0 \rightarrow \bar{B}_s^0 \rightarrow \rho^0 K^0 \rightarrow \rho^0(\pi^- \ell^+ \nu_\ell)$

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

- More complicated cases



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



[Shen, WJS, 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. $\rightarrow A_{CP}(t_1, t_2)$
- The **double mixing CPV** can be very **significant** and practically measurable by experiments.

Outline

- Background and motivation

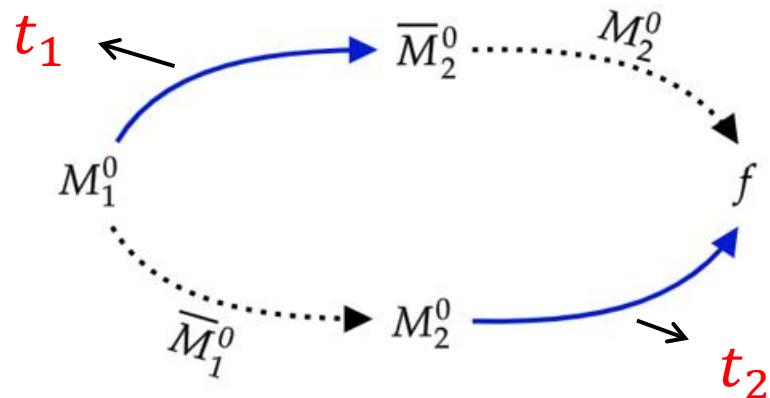
- Theoretical framework

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CP asymmetry



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

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

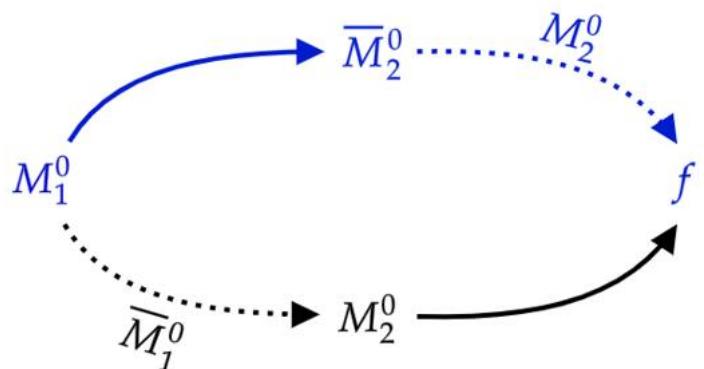
- The two-dimensional time-dependent CP asymmetry is defined as

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

Theoretical framework

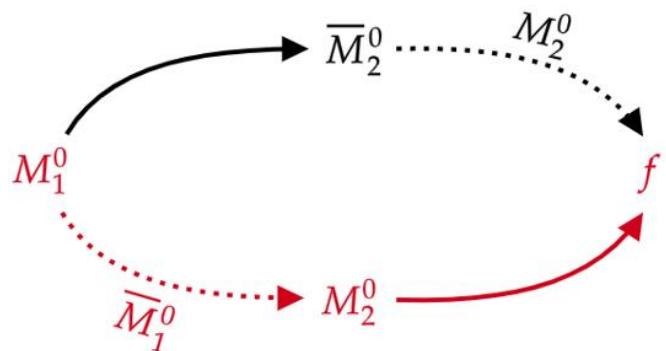
- ✓ Take $B_s^0 \rightarrow \rho^0 \bar{K}^0 \rightarrow \rho^0 (\pi^- \ell^+ \nu_\ell)$ as an example (penguin ≈ 0)

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



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

CP violation in $\textcolor{blue}{M}_2^0$ mixing

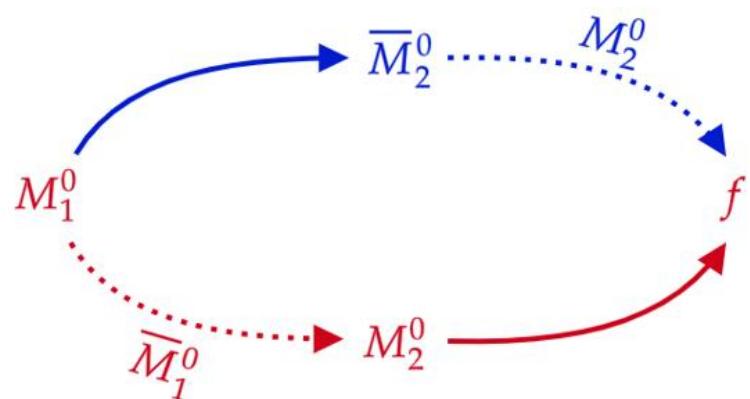


$$\propto |g_{1,-}(t_1)|^2 |g_{2,+}(t_2)|^2 \left(\left| \frac{q_1}{p_1} \right|^2 - \left| \frac{p_1}{q_1} \right|^2 \right)$$

CP violation in $\textcolor{blue}{M}_1^0$ 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)



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

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

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

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

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

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

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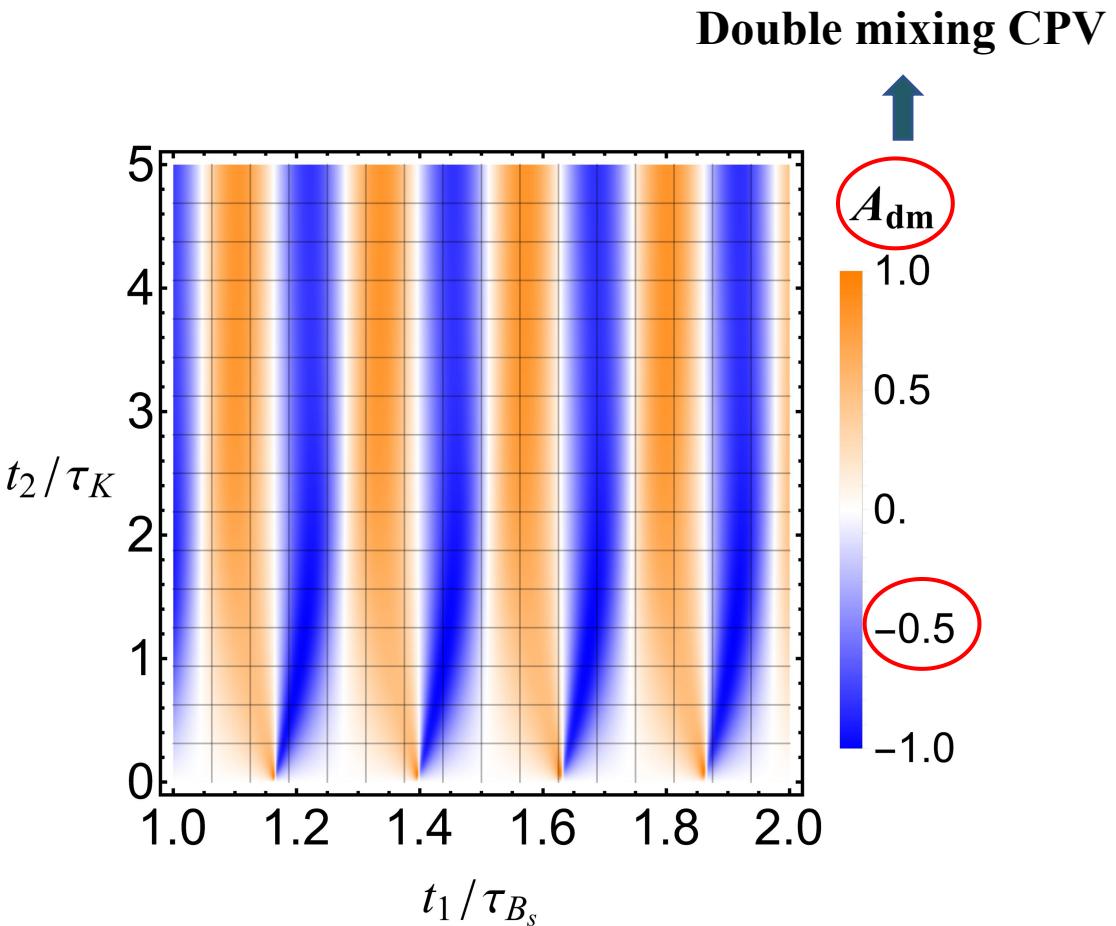
- Numerical results

- CKM phase extraction

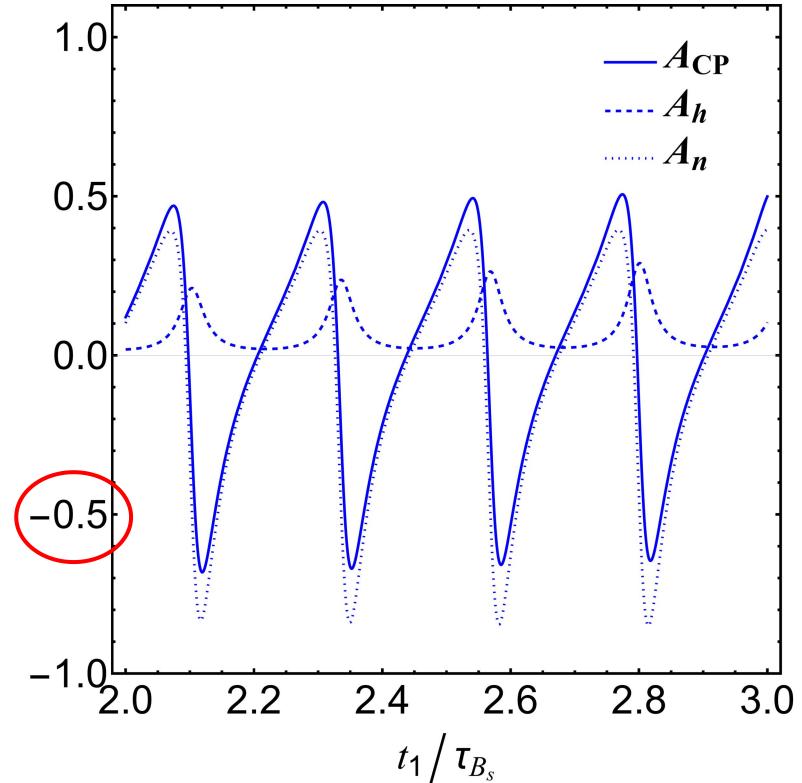
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t_1, t_2 Dependence

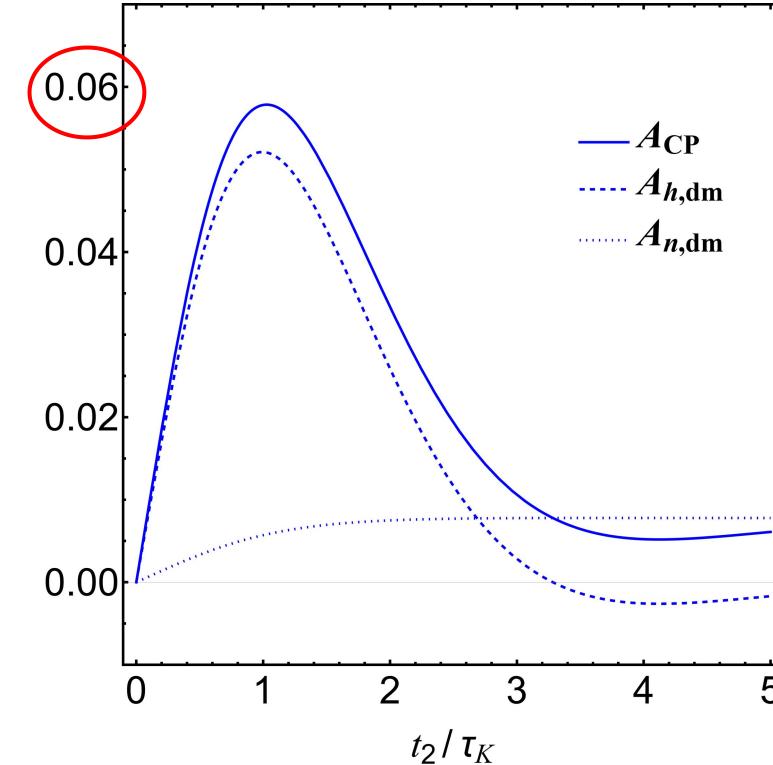
- $B_s^0 \rightarrow \rho^0 \bar{K}^0 \rightarrow \rho^0 (\pi^- \ell^+ \nu_\ell)$
- The $A_{CP}(t_1, t_2)$ dependence on t_1 and t_2 .
- The magnitude of the peak values can be larger than **50%**.



t_1 Dependence



t_2 Dependence



- Integral out the t_2 from 0 to τ_K

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

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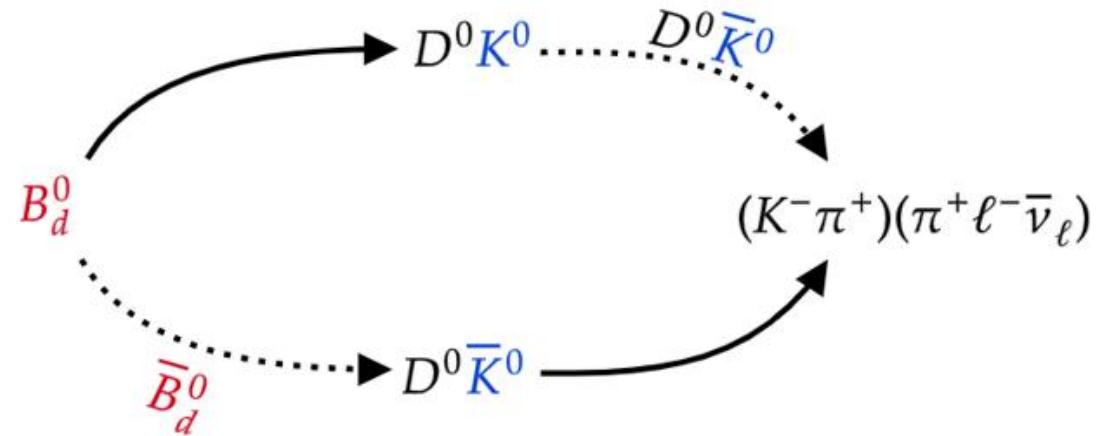
CKM phase extraction

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

$$\begin{aligned} \langle D^0 \bar{K}^0 | \bar{B}_d^0 \rangle &= \langle \bar{D}^0 K^0 | B_d^0 \rangle e^{i\theta_1} \\ \langle D^0 K^0 | B_d^0 \rangle &= \langle \bar{D}^0 K^0 | B_d^0 \rangle r_B e^{i(\delta_B + \theta_2)} \end{aligned}$$

Parameters: r_B , δ_B , $\frac{\phi_2 - \phi_1 + \theta_1 - \theta_2}{\delta_w} \approx 2\beta - \gamma$

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



$$\begin{aligned} q_B/p_B &= |q_B/p_B| e^{-i\phi_1} \\ q_K/p_K &= |q_K/p_K| e^{-i\phi_2} \end{aligned}$$

CKM phase extraction

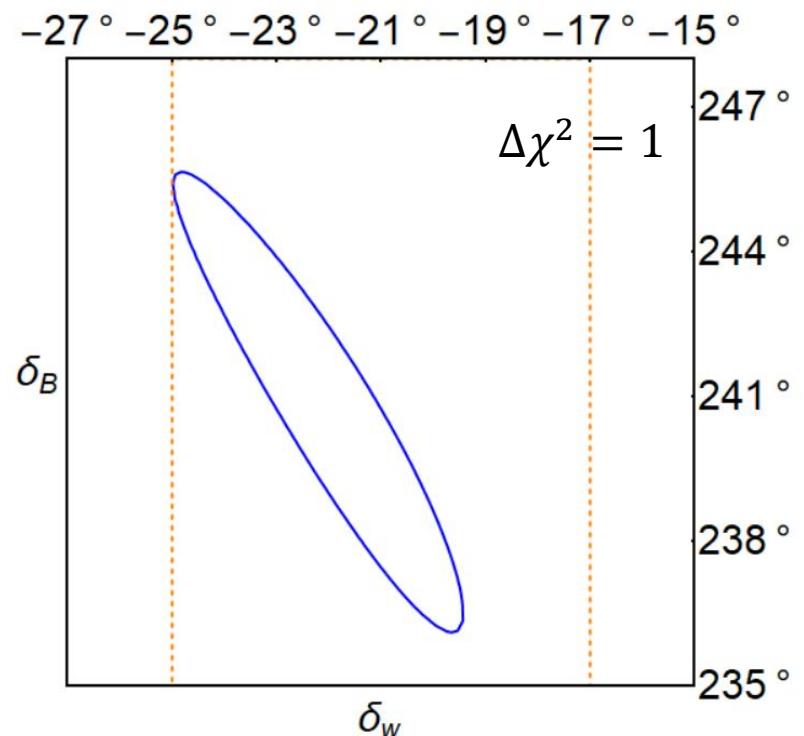
- ✓ Take $B_d^0 \rightarrow D^0 K^0 \rightarrow (K^- \pi^+) (\pi^+ \ell^- \bar{\nu}_\ell)$ as an example (penguin = 0)

$$r_B \in [0.253-\sigma, 0.253+\sigma]$$

Parameter	Central values	Uncertainties
r_B	0.253	0.020
δ_B	240.3°	$\pm 4.7^\circ$
δ_w	-21.7°	$\pm 2.7^\circ$

$$\delta_w = \phi_2 - \phi_1 + \theta_1 - \theta_2$$

→ $-21^\circ \pm 4^\circ$ (Experiment)



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

Thanks !