CP violation in b physics

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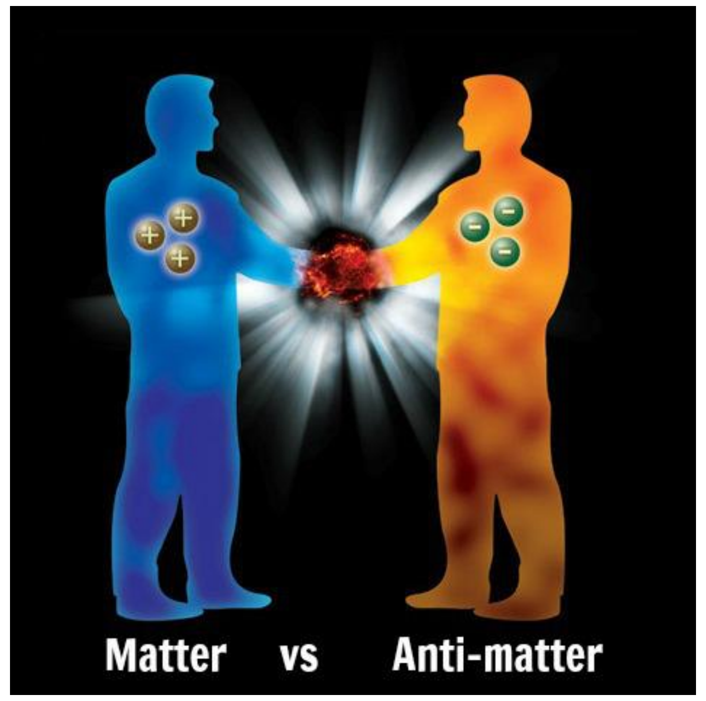
The 2023 international workshop on the high energy Circular Electron-Positron Collider

Nanjing, 23-27 October 2023

CP violation — Holy Grail of flavor physics



- One of the Sakharov's criteria of baryon asymmetry of universe

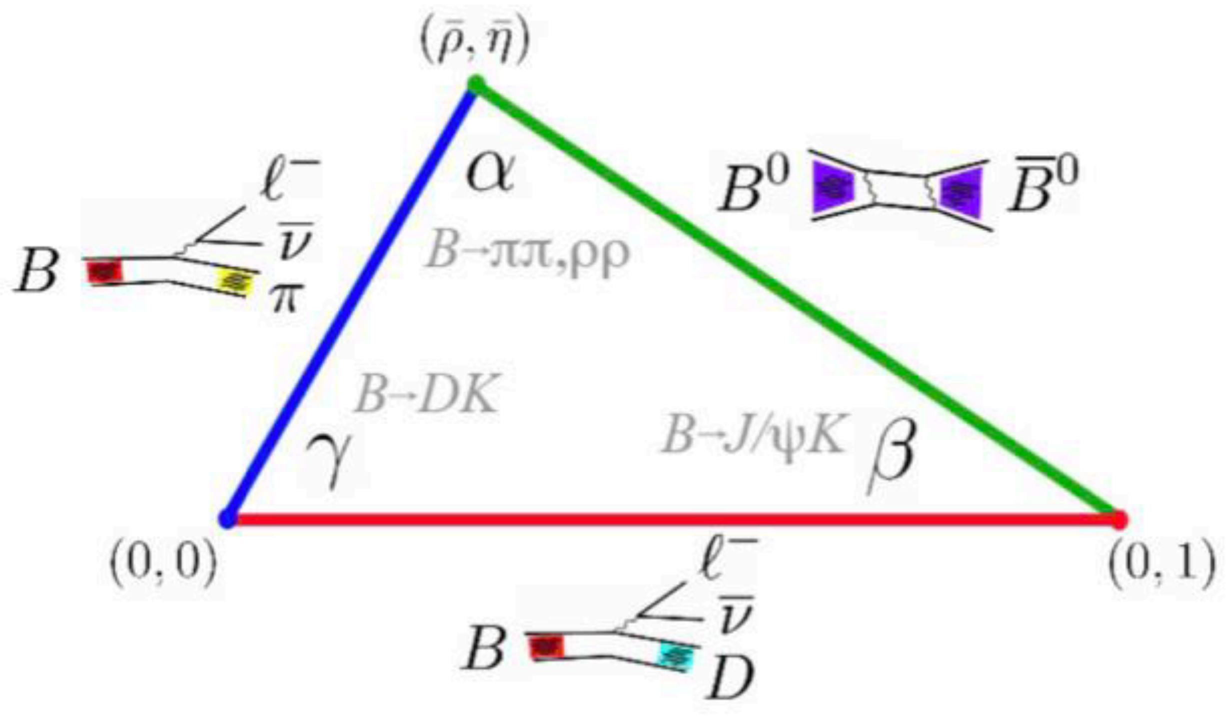
  ➡ Requires new source of CP violation

  [Sakharov, '67]

- Determination of CKM matrix phase angles

  ➡ To test the unitarity of the CKM matrix

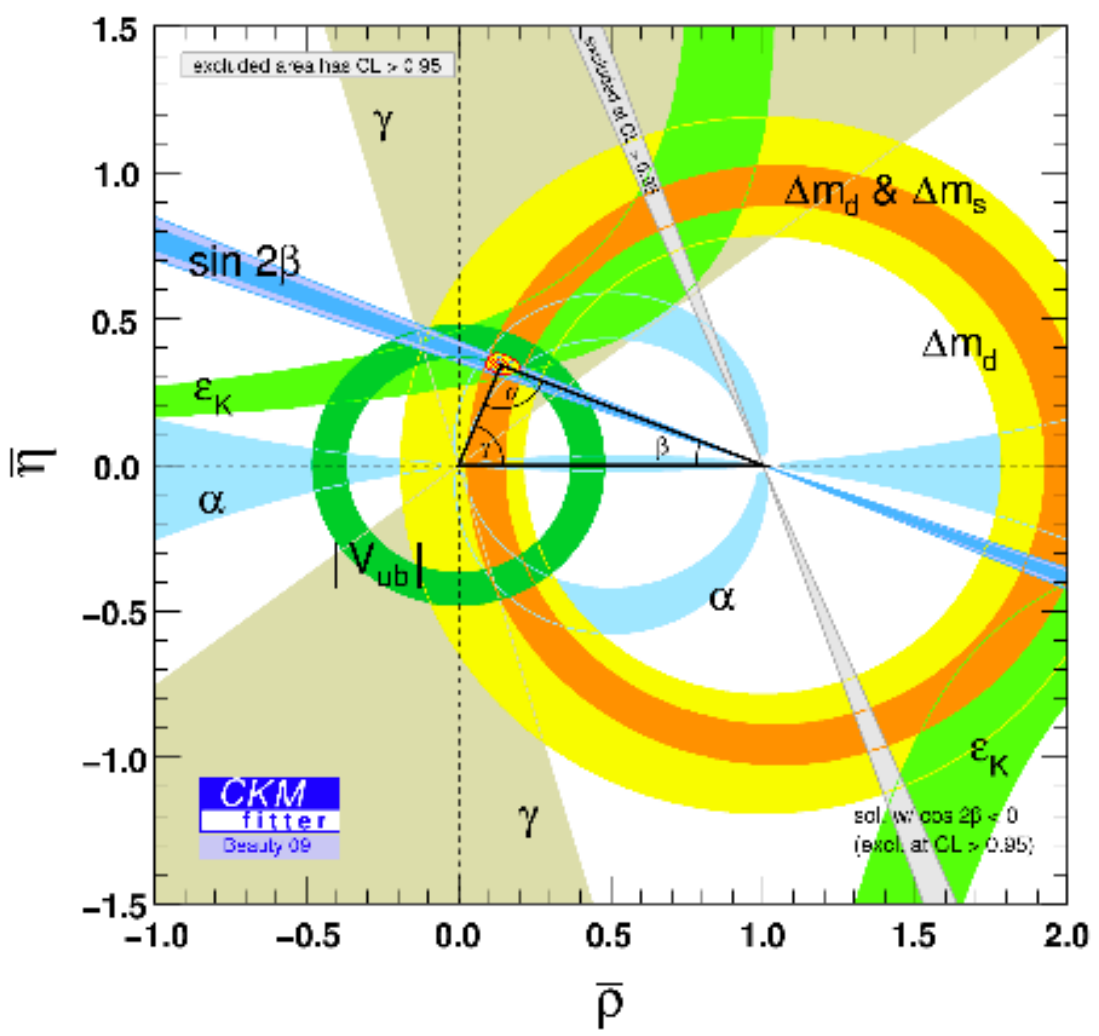
$$V_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}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

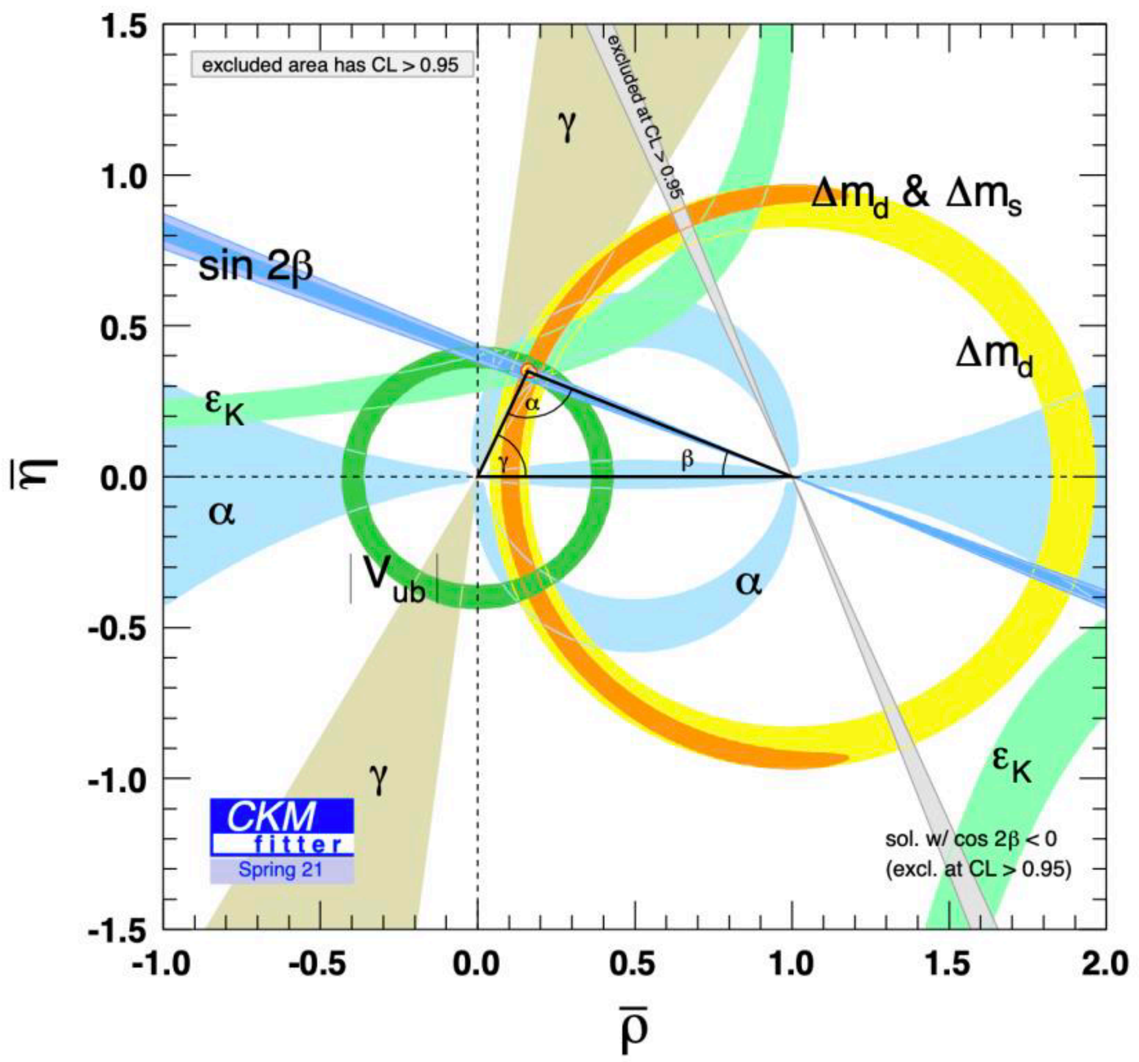


- Open windows to new dynamics beyond the SM

Status

- CP violation measured in
  - ➡ Decay, mixing, interference of decay w/ and w/o mixing
  - ➡ K, $B^{0,+}$, B_s^0, D mesons





- No evidence of new CPV source beyond the SM
- What should/can CEPC (and other future experiments) do?

Do something new

- **Lager statistics**
- **Better acceptance and detection**
- **Better time resolution**
- **Better flavor tagging**
- **……**

→

- **New precision**: $B_s \to J/\psi K$, $B^0 \to \pi^0\pi^0$
- **New channel**: $B^0 \to \gamma\gamma$
- **New observable**: double-mixing CPV
- **New methodology**: T-odd and -even CPV
- ……

New Precision

An example: $B_s \to J/\psi\,\phi$

- $B_s \to J/\psi\,\phi$: important for determination of the CKM phase $\phi_s = -2\beta_s$

$$\beta_s \equiv \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$$

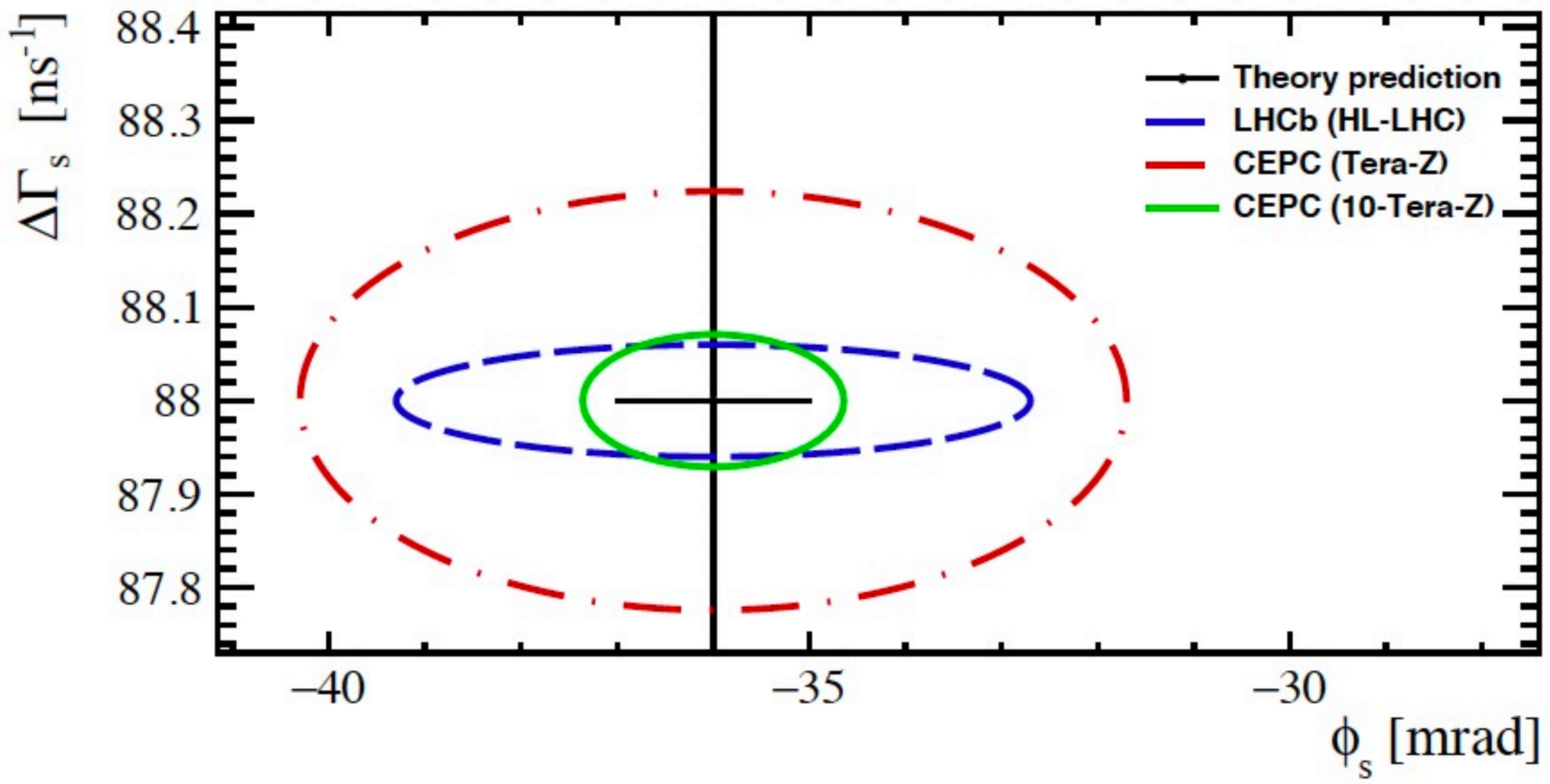
- All charged-particle final state: LHCb likes that.
- **CEPC**, as a Tera-Z, almost 2 orders fewer B mesons produced
- but has significantly better detection efficiency, flavor tagging, time resolution than LHCb

	LHCb (HL-LHC)	CEPC (Tera-Z)	CEPC/LHCb
$b\bar{b}$ statics	43.2×10^{12}	0.152×10^{12}	1/284
Acceptance×efficiency	7%	75%	10.7
Br	6×10^{-6}	12×10^{-6}	2
Flavour tagging*	4.7%	20%	4.3
Time resolution* $(\exp(-\frac{1}{2}\Delta m_s^2 \sigma_t^2)^2)$	0.52	1	1.92
scaling factor ξ	0.0014	0.0019	0.8
$\sigma(\phi_s)$	3.3 mrad	4.3 mrad	

(5 fs vs 20-30 fs)

[Li,Ruan,Zhao, 2205.10565]

An example: $B_s \to J/\psi\ \phi$



CEPC measurement of ϕ_s:

- Tera-Z, competitive with HL-LHC
- 10 Tera-Z, better than HL-LHC

[Li,Ruan,Zhao, 2205.10565]

Another example: $B^0 \to \pi^0\pi^0$

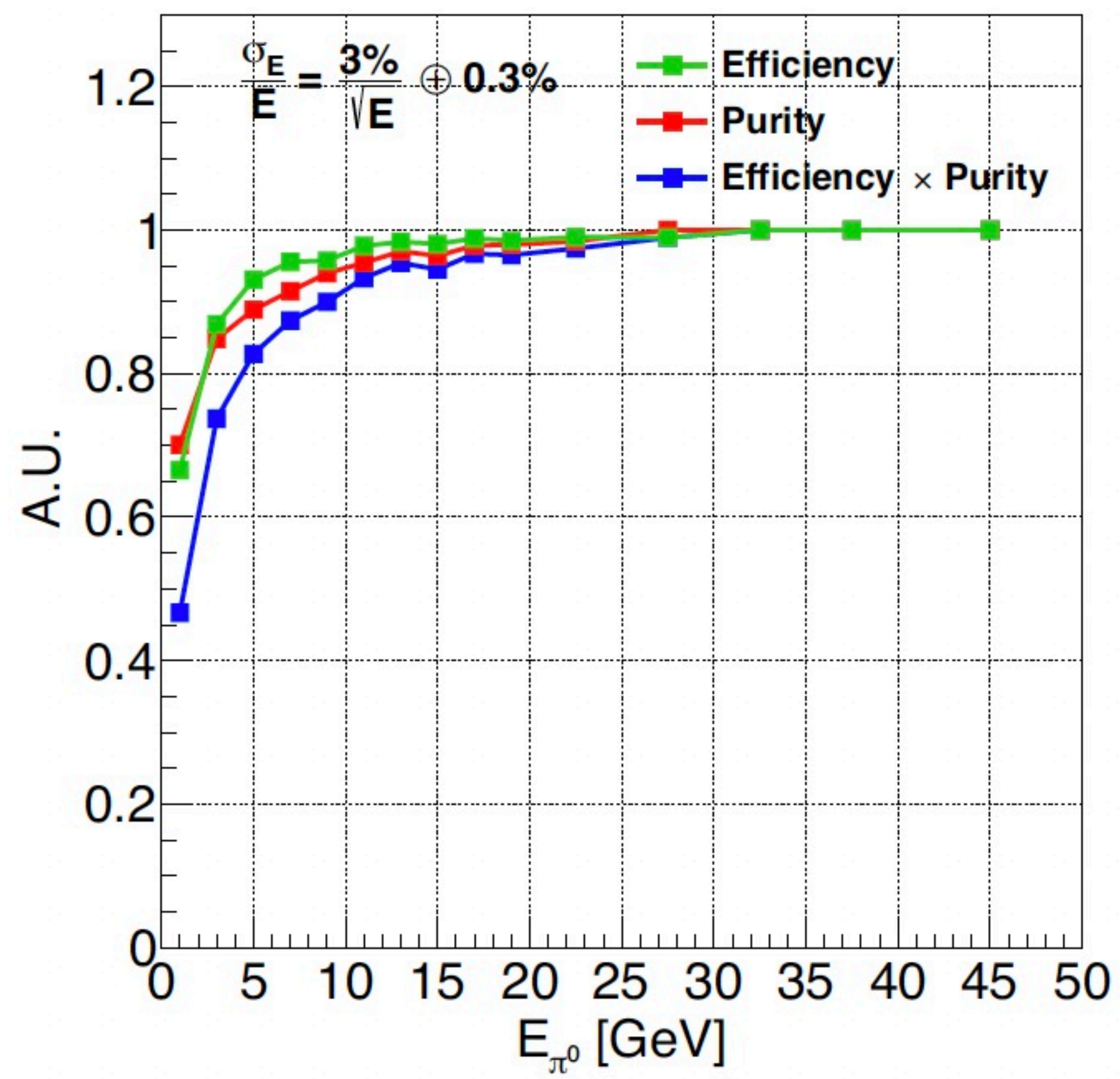
- $B^0 \to \pi^0\pi^0$**:** used to extract the CKM angle α, together with other isospin-partner channels $B^0 \to \pi^+\pi^-$ and $B^+ \to \pi^+\pi^0$

$$\alpha \equiv \arg[-(V_{td}V_{tb}^*)/(V_{ud}V_{ub}^*)]$$

- All neutral-particle final state: LHCb fails, CEPC wins Belle II (statistics)

b-hadrons	Belle II	LHCb $(300\,\mathrm{fb}^{-1})$	Tera-Z
$B^0,\ \bar{B}^0$	5.4×10^{10} $(50\ \mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}	1.2×10^{11}
$B^\pm$	5.7×10^{10} $(50\ \mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}	1.2×10^{11}
$B_s^0,\ \bar{B}_s^0$	6.0×10^{8} $(5\ \mathrm{ab}^{-1}$ on $\Upsilon(5S))$	1×10^{13}	3.1×10^{10}

- CEPC, perfect reconstruction of π^0 by $\gamma\gamma$

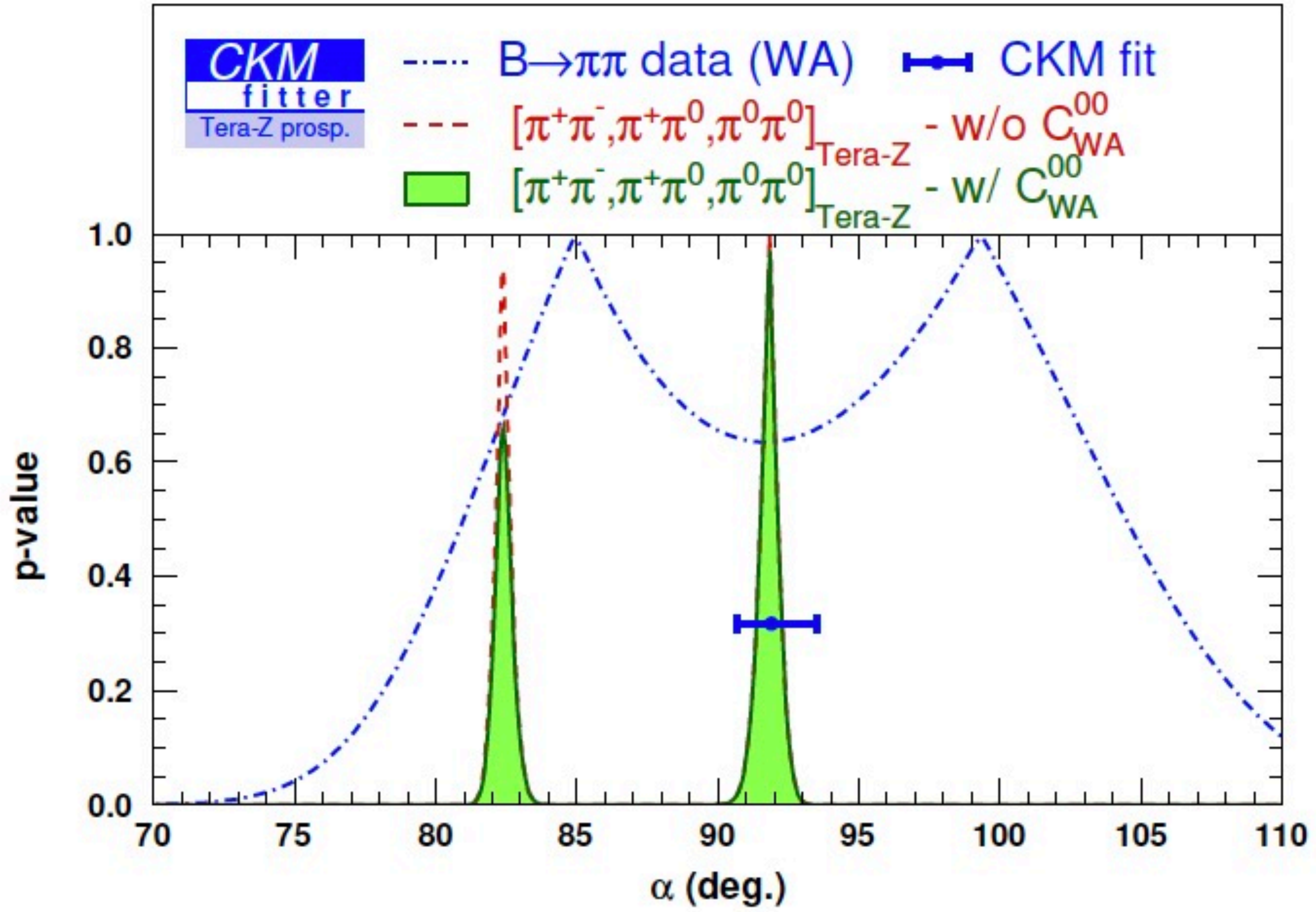


[Wang, Descotes-Genon, Deschamps, Li, Chen, Zhu, Ruan, JHEP, '22]

Another example: $B^0 \to \pi^0\pi^0$

- **Tera-Z:** $\alpha(\pi\pi) = (91.8 \pm 0.4)^\circ$
- 40 times better than world average
- 5 times better than Belle II

Parameters	Tera-Z Projection
$\sigma_{\mathcal{B}^{00}}/\mathcal{B}^{00}$	0.45%
$\sigma_{\mathcal{B}^{+0}}/\mathcal{B}^{+0}$	0.19%
$\sigma_{\mathcal{B}^{+-}}/\mathcal{B}^{+-}$	0.18%
$\sigma_{a^{00}_{\rm CP}}$	$\pm$ (0.014–0.018)
$\sigma_{C^{+-}_{\rm CP}}$	$\pm$ (0.004–0.005)
$\sigma_{S^{+-}_{\rm CP}}$	$\pm$ (0.004–0.005)



[Wang, Descotes-Genon, Deschamps, Li, Chen, Zhu, Ruan, JHEP, '22]

New Channel

An example: $B^0 \to \gamma\gamma$

- $B^0 \to \gamma\gamma$: simplest decay of B meson, like $B_{d,s} \to \mu\mu$

  ➡ Sensitive to dynamics beyond the SM (FCNC), e.g. CP violation

  ➡ Clean environment to address the intricate strong interaction mechanism of the heavy-meson systems

- **Silver channel** of Belle II

Belle II

Physics Book

Process	Observable	Theory	Sys. limit (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
$B \to X_s l^+ l^-$	R_{X_s}	$\star\star\star$	>50	$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star\star$
$B \to K^{(*)} e^+ e^-$	$R(K^{(*)})$	$\star\star\star$	>50	$\star\star$	$\star\star\star$	$\star\star\star$	$\star\star\star$
$B \to X_s \gamma$	$Br.$	$\star\star$	1-5	$\star\star\star$	$\star$	$\star$	$\star\star$
$B_{d,(s)} \to \gamma\gamma$	$Br.$, A_{CP}	$\star\star$	$>50(5)$	$\star\star$	$\star\star$	-	$\star\star$
$B \to K^* e^+ e^-$	P_5'	$\star\star$	>50	$\star\star\star$	$\star\star$	$\star\star\star$	$\star\star\star$
$B \to K \tau l$	$Br.$	$\star\star\star$	>50	$\star\star$	$\star\star\star$	$\star\star$	$\star\star\star$

An example: $B^0 \to \gamma\gamma$

[Shen, Wang, Wei, JHEP, '20]

[**QQ**, Shen, Wang, Wang, PRL, '23]

- **Standard model prediction:**

$$\mathcal{B}(B^0 \to \gamma\gamma) = (1.9^{+1.1}_{-1.0}) \times 10^{-8} \qquad A_{\rm CP}(B^0 \to \gamma\gamma) \approx 24\,\%$$

- **BEllE II precision**

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B_d \to \gamma\gamma)$	$< 740\%$	30%	9.6%
$A_{CP}(B_d \to \gamma\gamma)$	–	78%	25%
$\mathrm{Br}(B_s \to \gamma\gamma)$	$< 250\%$	23%	–

- **Tera-Z precision:** (Assuming efficiency*purity = 50% (twice $B^0 \to \pi^0\pi^0$) with 10^{11} B^0)

$$\sigma(\mathcal{B})/\mathcal{B} \approx 3\,\%\,, \qquad \sigma(A_{\rm CP}) \approx 7.8\,\%$$

(Wild estimation)

Evidence of $A_{\rm CP}(B^0 \to \gamma\gamma)$ with Tera-Z.

Discovery of $A_{\rm CP}(B^0 \to \gamma\gamma)$ with 4 Tera-Z!

New Observable

Traditional CP violation observables

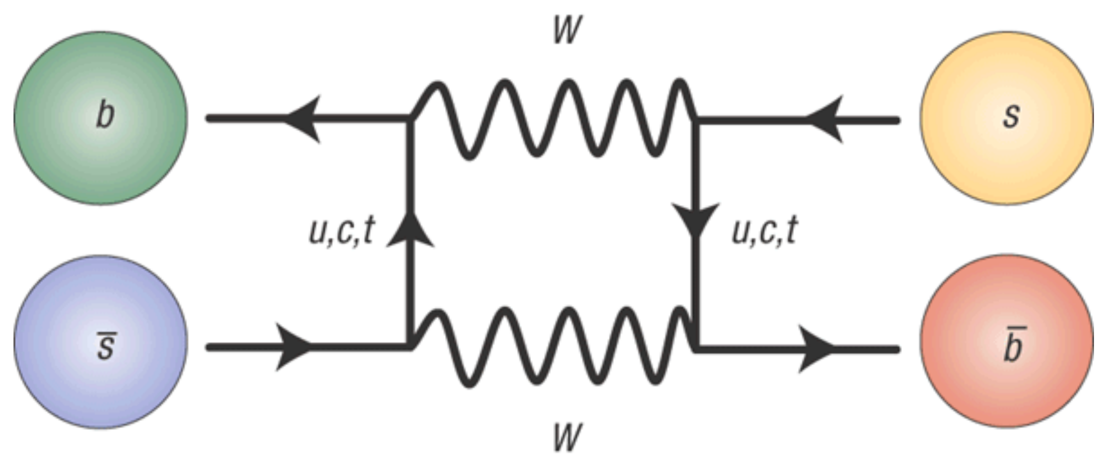
- Common CPV observables

✓ CPV in decay (direct CPV)

$$|M^0 \to f| \neq |\bar{M}^0 \to \bar{f}|$$

✓ CPV in mixing (indirect CPV)

$$|M^0 \to \bar{M}^0| \neq |\bar{M}^0 \to M^0| \quad (|q/p| \neq 1)$$



✓ CPV in interference between a decay without and with **initial** mixing

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

- CPV in interference between a decay without and with **final** mixing

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

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

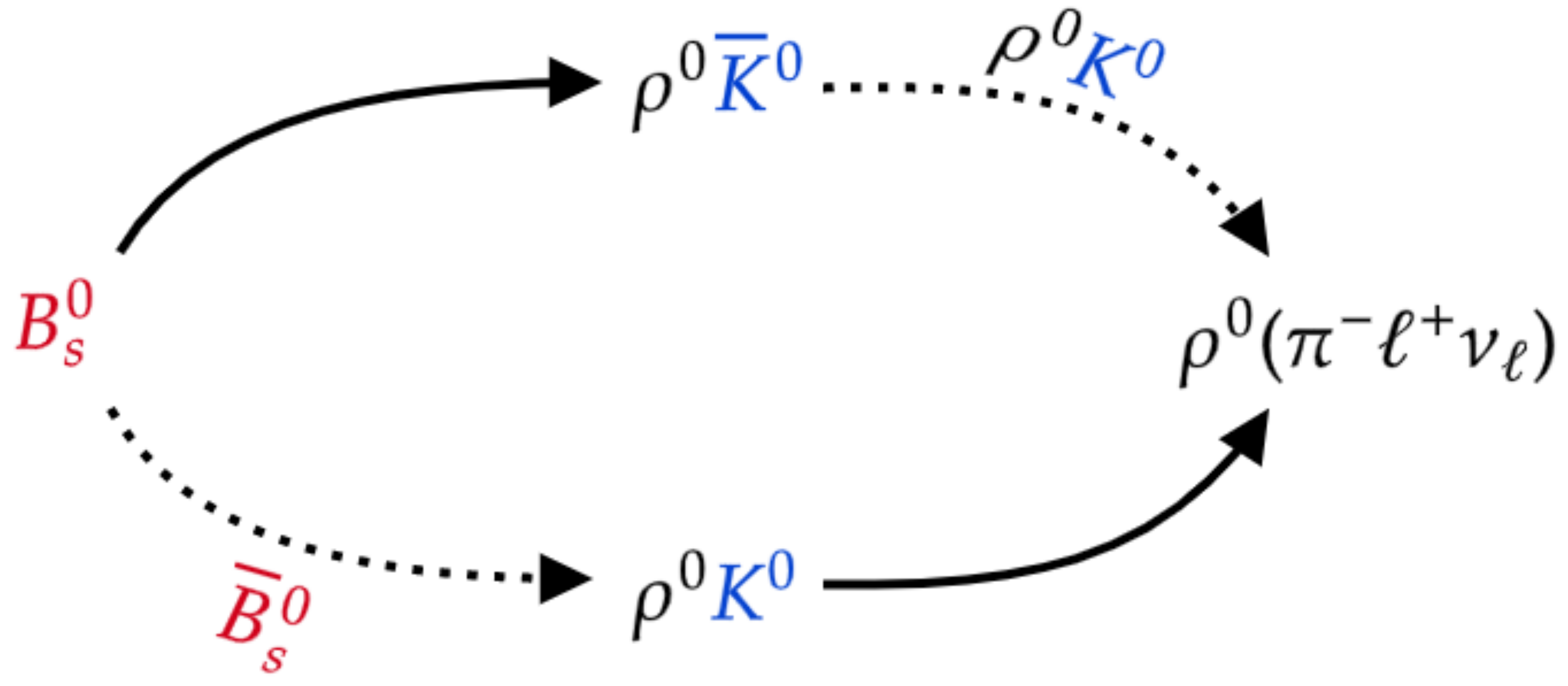
Double mixing CP violation

- **Double mixing CP violation**: induced by interference of different mixing paths of neutral mesons in cascade decays

- Consider $B_s^0 \to \rho^0 K \to \rho^0 \pi^- e^+ \nu$

  Upper path: $B_s^0 \to \rho^0 \bar{K}^0 \to \rho^0 K^0 \to \rho^0 \pi^- e^+ \nu$

  Lower path: $B_s^0 \to \bar{B}_s^0 \to \rho^0 K^0 \to \rho^0 \pi^- e^+ \nu$



- General Case:

$$(M_1^0 \to \bar{M}_2^0 \to M_2^0) \; + \; (M_1^0 \to \bar{M}_1^0 \to M_2^0)$$

It does not require nonzero strong phases!

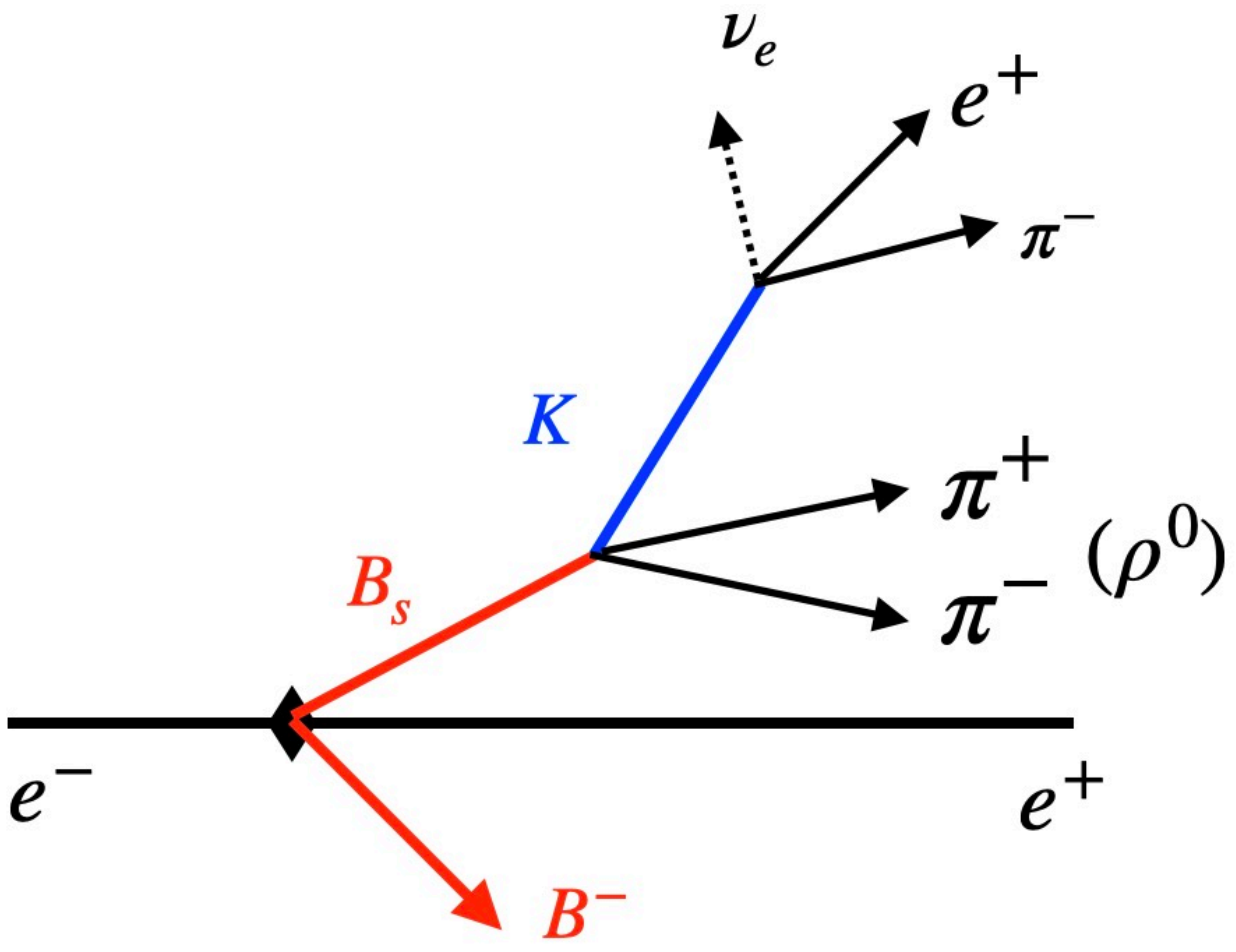
Strong phases can be extracted from experiment data without theoretical input.

A 2-D time dependence analysis can be performed.

[Shen,Song,**QQ**, 2301.05848]

Double mixing CP violation — Significance

- Benefiting from good time resolution, CEPC can do the 2D time dependence analysis



Double mixing CP violation — Significance

- Take $B_s^0(t_1) \to \rho^0 \bar{K}^0(t_2) \to \rho^0 \pi^- e^+ \nu$ as an example (penguin≈0)

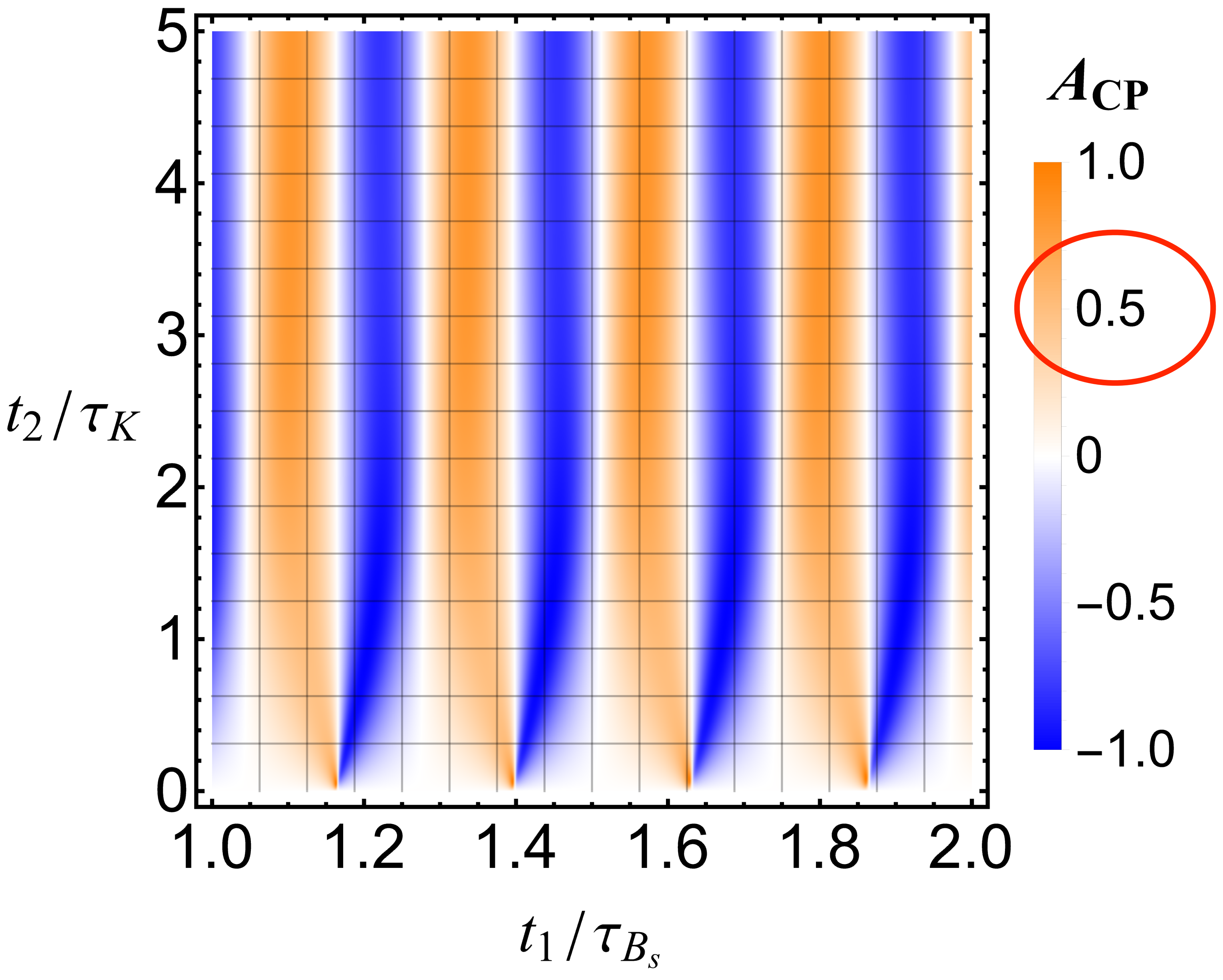
Time dependence:

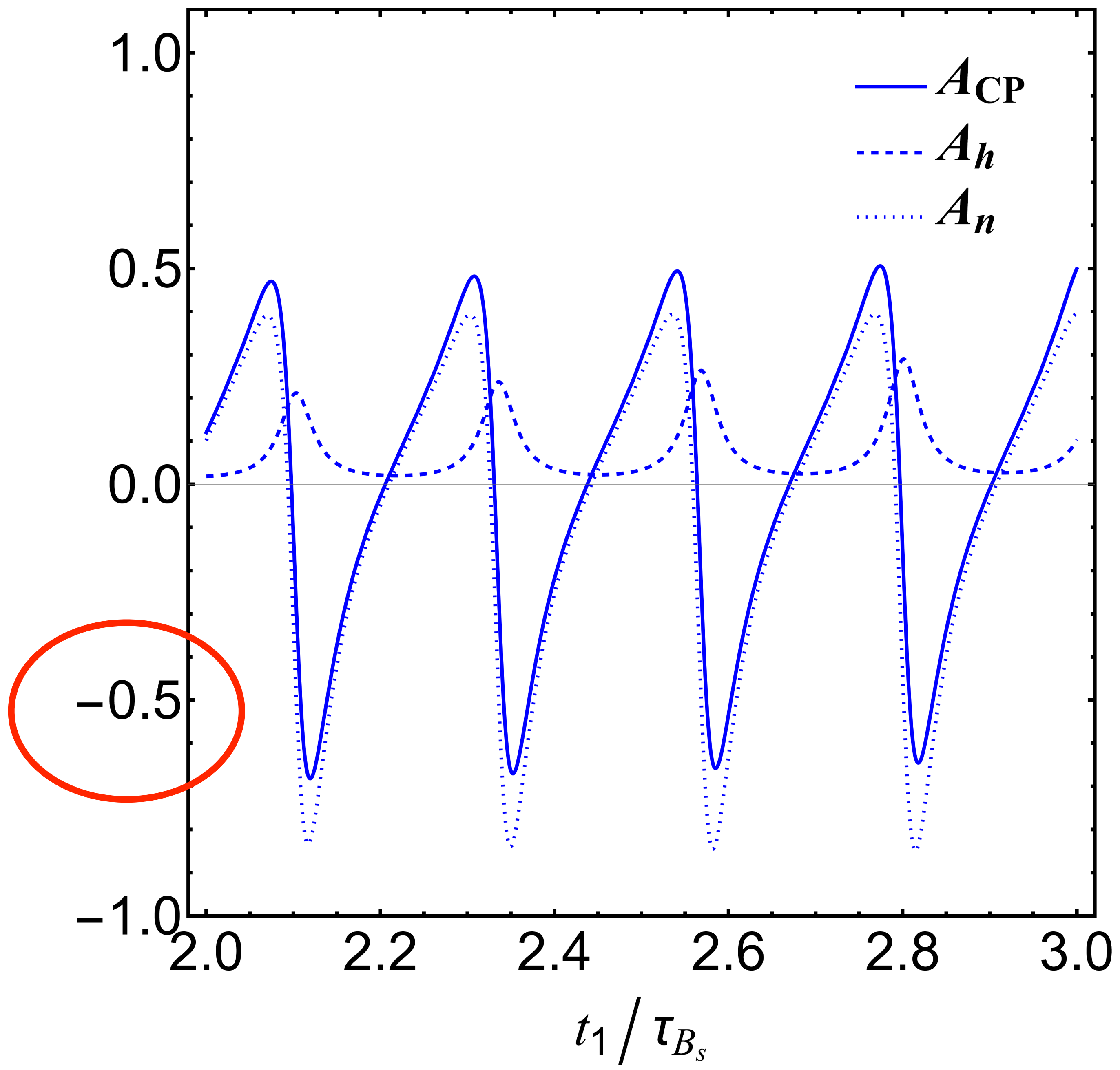
$$S_n \propto \sin(\Delta m_1 t_1)\ \sinh\frac{\Delta\Gamma_2 t_2}{2}\ \sin(\phi_1 + \phi_2 + 2\delta)$$

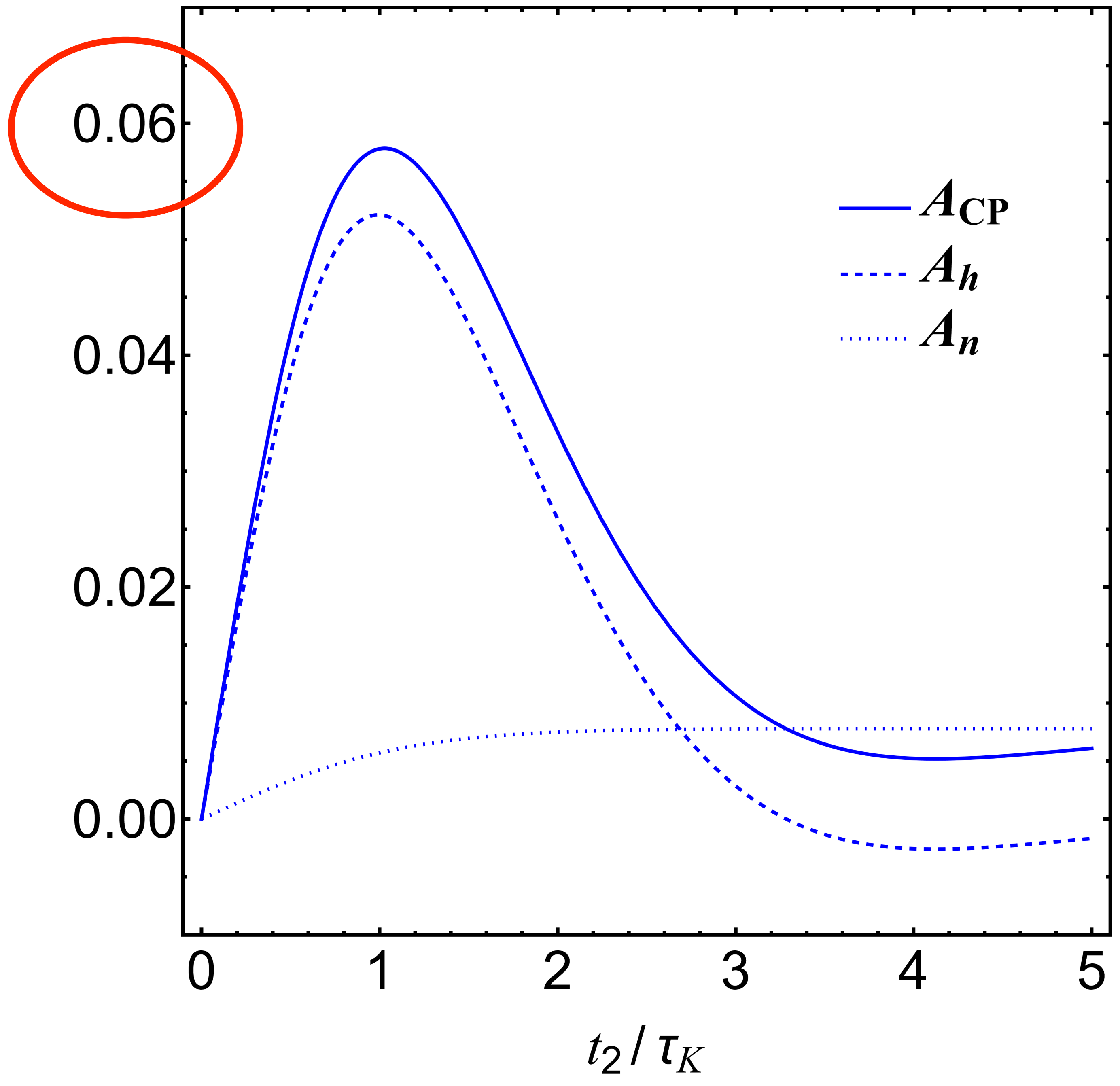
$K_S + K_L$

$$S_h \propto \sinh\frac{\Delta\Gamma_1 t_1}{2}\ \sin(\Delta m_2 t_2)\ \sin(\phi_1 + \phi_2 + 2\delta)]$$

K_S, K_L **interference**







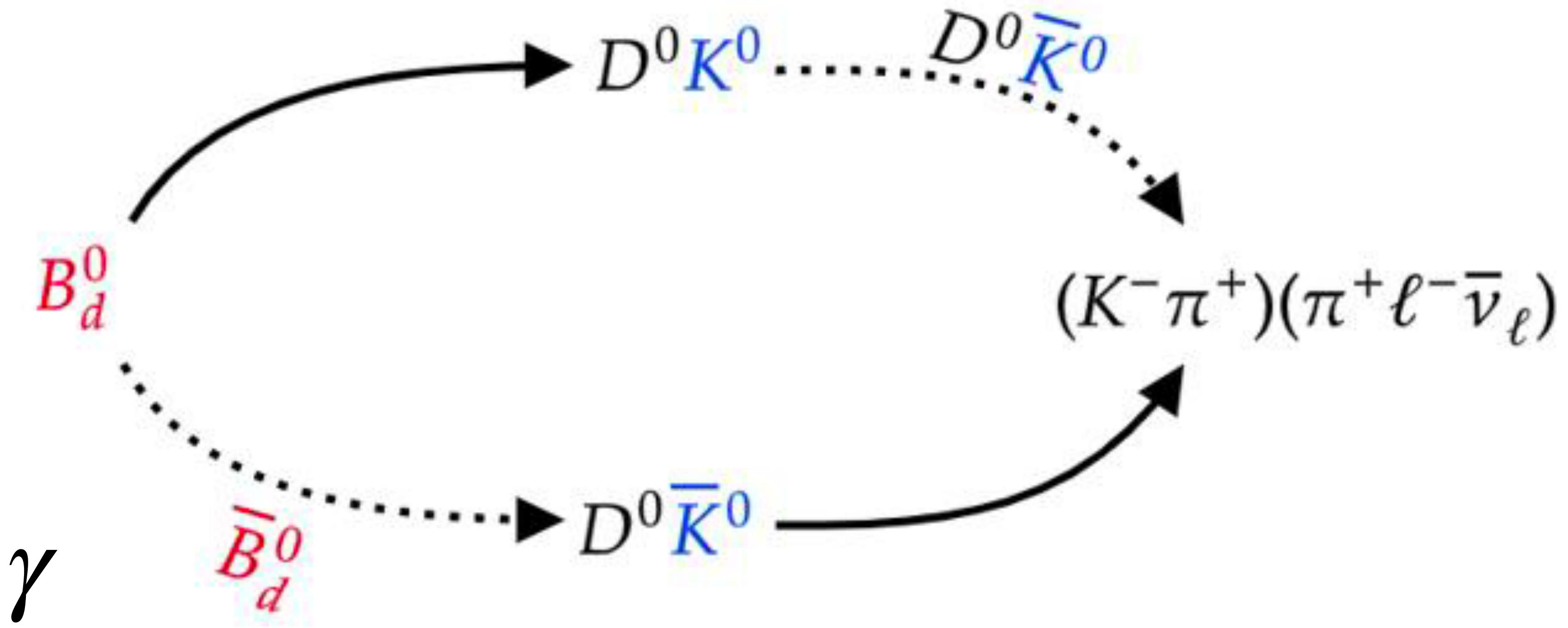
[Shen,Song,**QQ**, 2301.05848]

Double mixing CP violation — CKM phase

- Take $B_d^0(t_1) \to D^0K^0(t_2) \to (K^-\pi^+)(\pi^+e^-\bar{\nu})$ as an example

$$\langle D^0\bar{K}^0 | \bar{B}^0\rangle = \langle \bar{D}^0K^0 | B^0\rangle e^{i\delta_1}$$

$$\langle D^0K^0 | B^0\rangle = \langle \bar{D}^0K^0 | B^0\rangle r_B e^{i(\delta_s+\delta_2)}$$



3 Parameters: $r_B,\ \delta_s,\ \delta_w \equiv \phi_2 - \phi_1 + \delta_1 - \delta_2 \approx -2\beta - \gamma$

$$q_1/p_1 = |q_1/p_1| e^{-i\phi_1}$$
$$q_2/p_2 = |q_2/p_2| e^{-i\phi_2}$$

$$A_{CP}(t_1,t_2) = \frac{e^{-\Gamma_B t_1}\sin\Delta m_B t_1 S(t_2)}{e^{-\Gamma_B t_1}[C'(t_2)(1+\cos\Delta m_B t_1)+S'(t_2)\sin\Delta m_B t_1]}$$

$$S(t_2) = \frac{e^{-\Gamma_2 t_2}}{2} r_B[-2\sin\delta_w \cos\delta_s \sinh\frac{\Delta\Gamma_K}{2}t_2 + 2\sin\delta_w \sin\delta_s \sin\Delta m_K t_2]$$

$$C'(t_2) = \frac{e^{-\Gamma_2 t_2}}{2}[(1+r_B^2)\cosh\frac{\Delta\Gamma_K}{2}t_2 + (1-r_B^2)\cos\Delta m_K t_2]$$

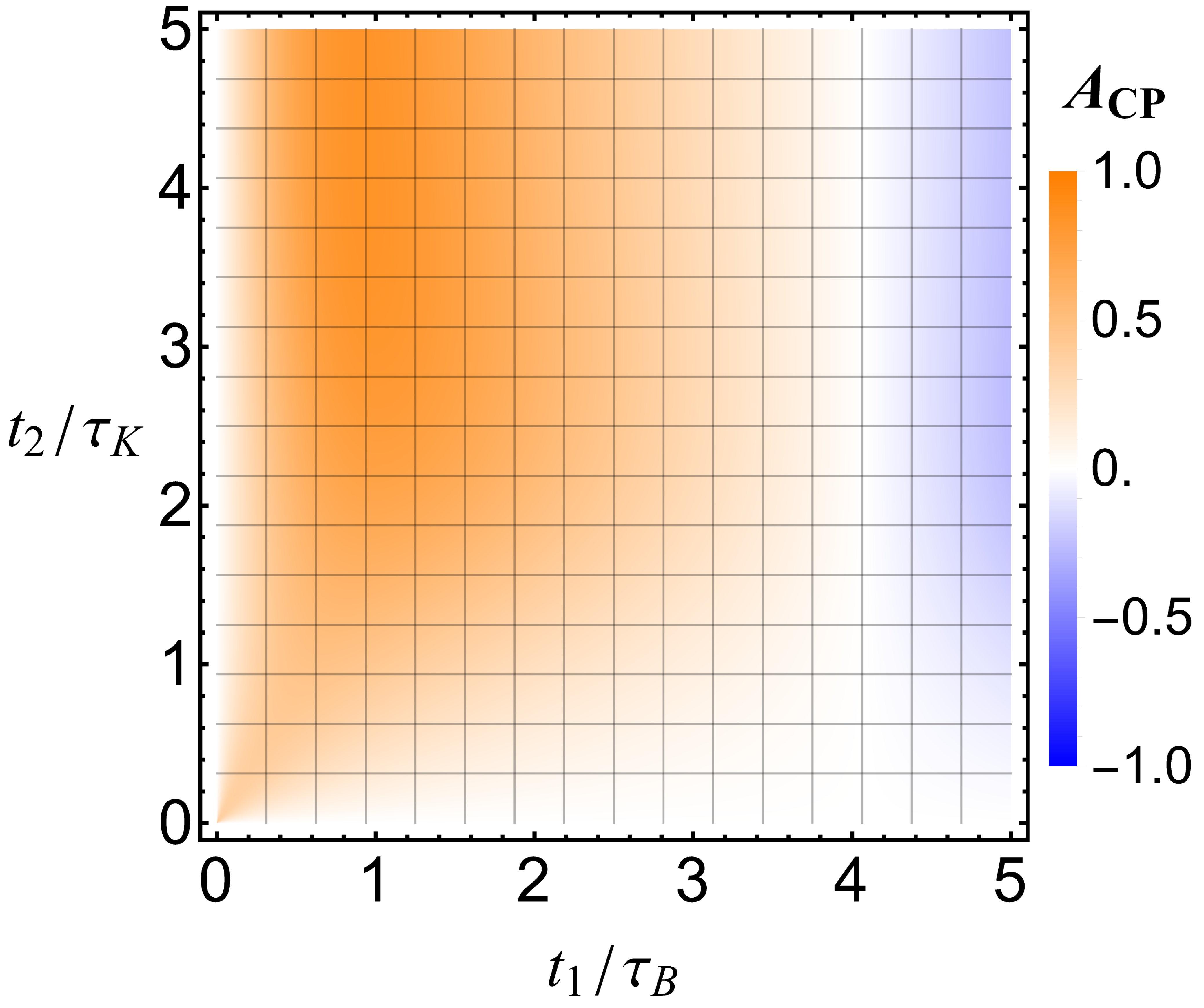
$$S'(t_2) = \frac{e^{-\Gamma_2 t_2}}{2} r_B[2\cos\delta_w \sin\delta_s \sinh\frac{\Delta\Gamma_K}{2}t_2 + 2\cos\delta_w \cos\delta_s \sin\Delta m_K t_2]$$

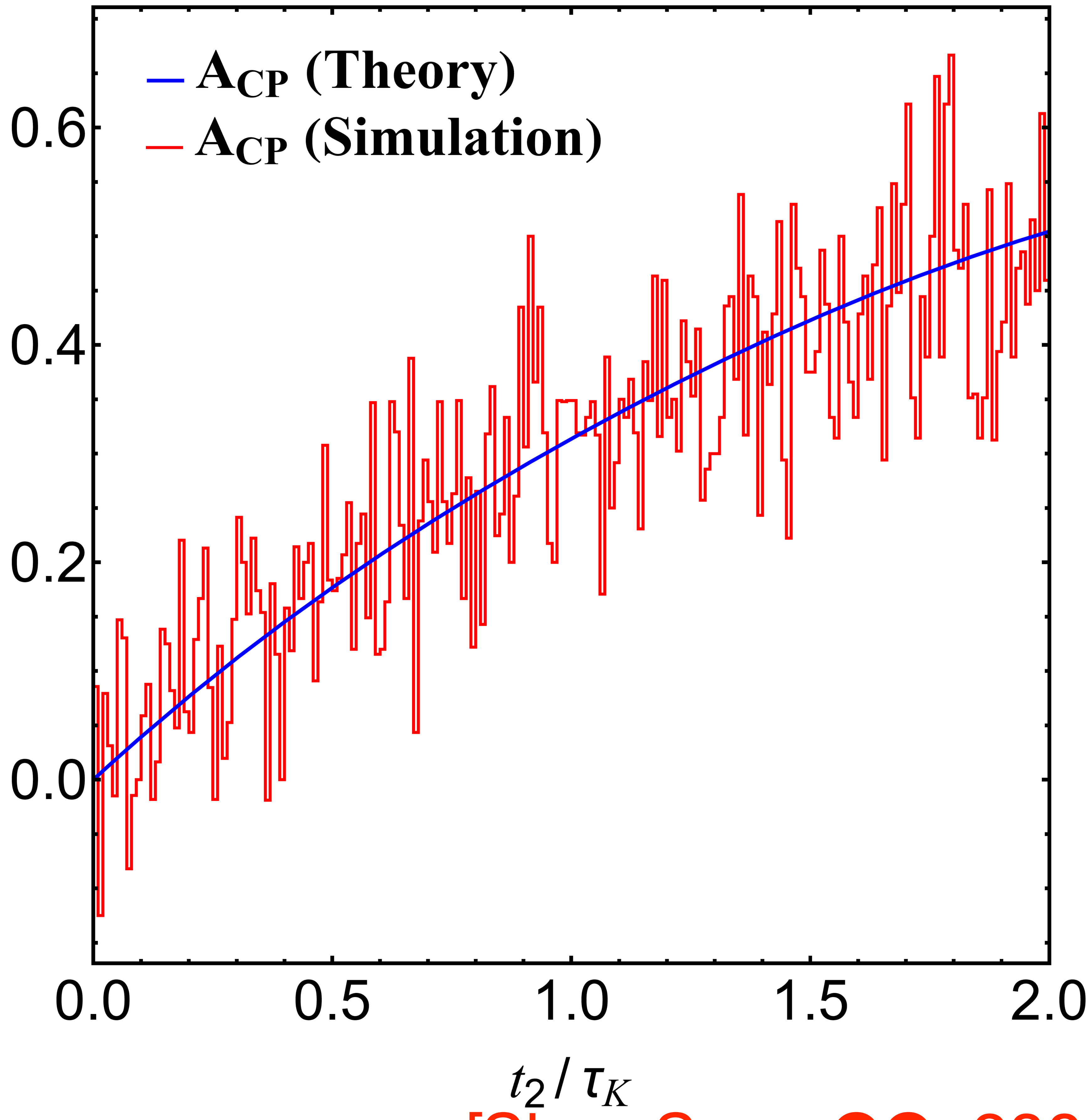
Strong phase

[Shen,Song,**QQ**, 2301.05848]

Double mixing CP violation — CKM phase

- Take $B_d^0(t_1) \to D^0 K^0(t_2) \to (K^- \pi^+)(\pi^+ e^- \bar{\nu})$ as an example





[Shen,Song,**QQ**, 2301.05848]

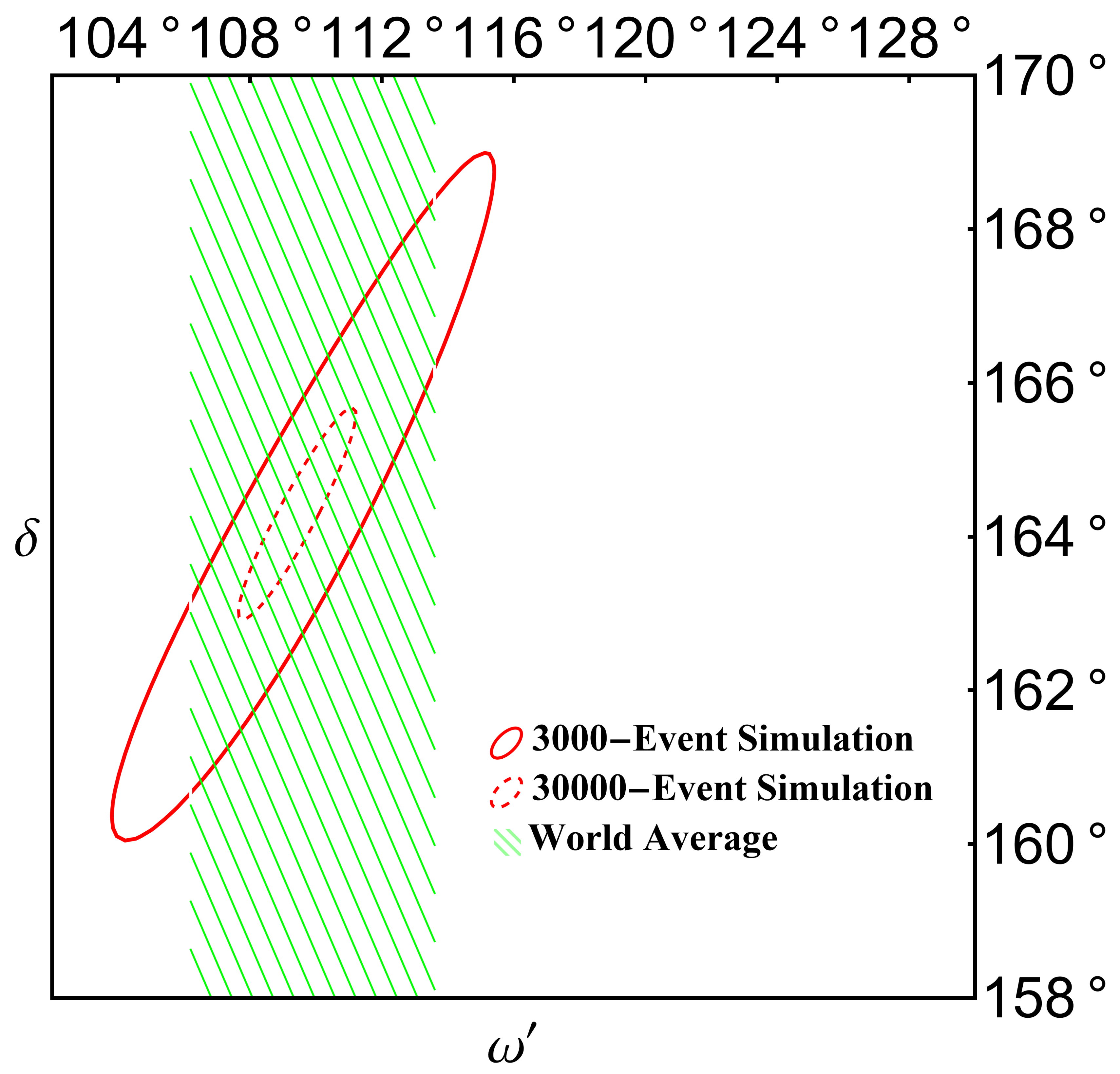
Double mixing CP violation — CKM phase

- Take $B_d^0(t_1) \to D^0 K^0(t_2) \to (K^-\pi^+)(\pi^+ e^- \bar{\nu})$ as an example

Assuming 3000 events (Belle II):

Parameters	Central value	Uncertainty
r_B	0.367	± 0.014
δ_s	164	± 4
δ_w	109	± 5

Input: $2\beta + \gamma = (109.9 \pm 3.7)°$



[Shen,Song,**QQ**, 2301.05848]

New methodology

(Baryon)

b-hadrons	Belle II	LHCb $(300\,\mathrm{fb}^{-1})$	Tera-Z
$B^0,\ \bar{B}^0$	5.4×10^{10} $(50\ \mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}	1.2×10^{11}
$B^{\pm}$	5.7×10^{10} $(50\ \mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}	1.2×10^{11}
$B_s^0,\ \bar{B}_s^0$	6.0×10^{8} $(5\ \mathrm{ab}^{-1}$ on $\Upsilon(5S))$	1×10^{13}	3.1×10^{10}
$B_c^{\pm}$	-	1×10^{11}	1.8×10^{8}
$\Lambda_b^0,\ \bar{\Lambda}_b^0$	-	2×10^{13}	2.5×10^{10}

Baryon factories!

[Wang, Descotes-Genon, Deschamps,
Li, Chen, Zhu, Ruan, JHEP, ‘22]

Baryon is NOT meson!

Difference between meson and baryon

- Meson has two quarks.
- Baryon has three quarks.

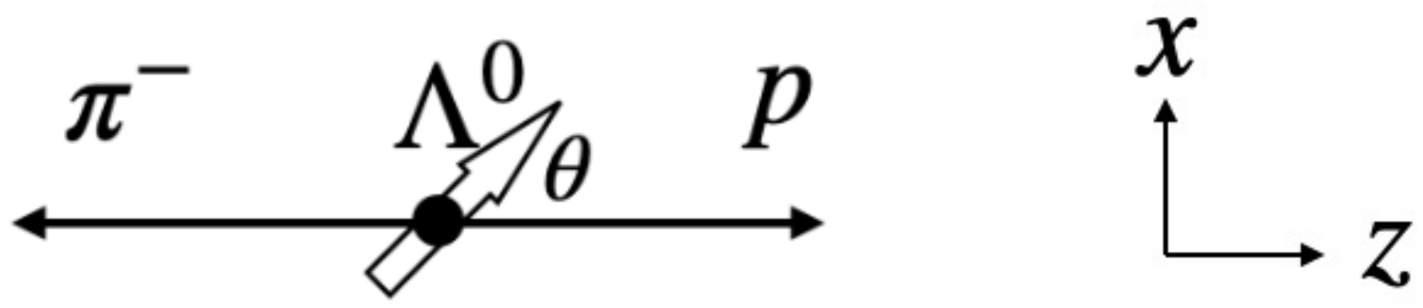
→ More is different!

- All baryons has non-zero **spins**.

Polarization induced observables

- **Polarizations/helicities** of particle provide fruitful information to build more observables.

- Lee-Yang parameters: $\alpha,\ \beta,\ \gamma$



$$A(\Lambda^0 \to p\pi) = \bar{u}_p(S + P\gamma_5)u_\Lambda$$

General Partial Wave Analysis of the Decay of a Hyperon of Spin $\frac{1}{2}$

T. D. Lee* and C. N. Yang

Institute for Advanced Study, Princeton, New Jersey

(Received October 22, 1957)

Theoretically, they are expressed by **partial wave amplitudes** (helicity amplitudes $h_\pm = S \pm P$) as:

$$\alpha = \frac{2Re(S^*P)}{|S|^2 + |P|^2}, \quad \beta = \frac{2Im(S^*P)}{|S|^2 + |P|^2}, \quad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha\cos\theta$$

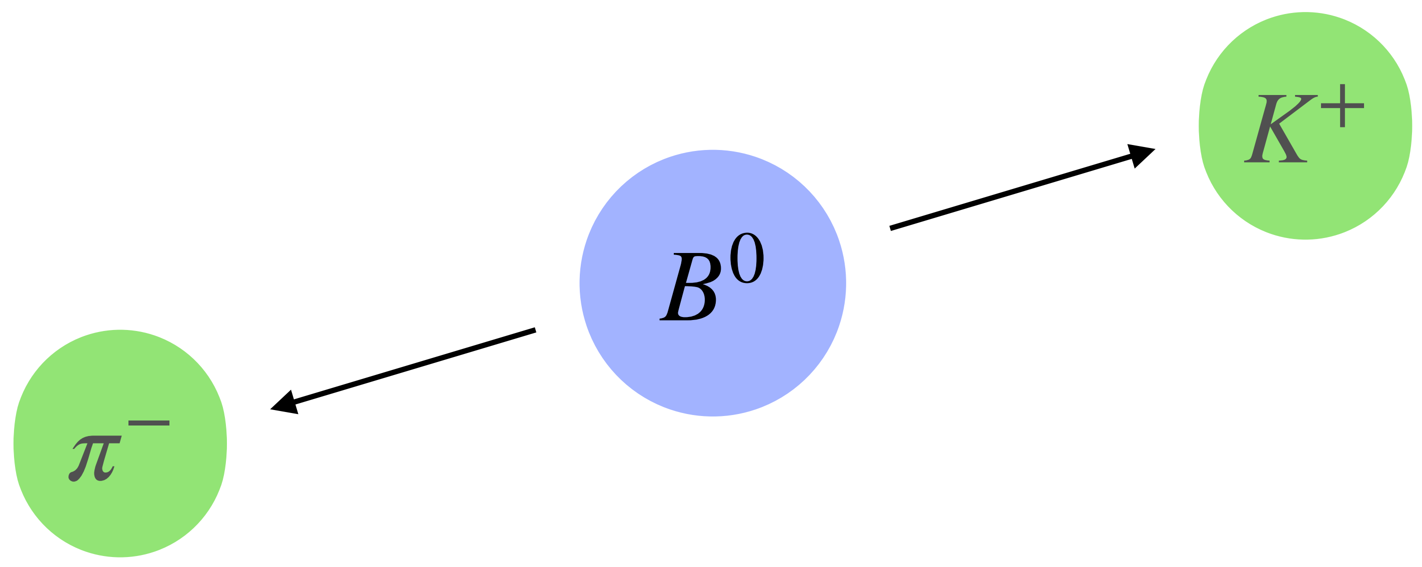
Experimentally, they are measured by **proton polarizations:**

$$P_p = \frac{(\alpha + \cos\theta)\hat{p} + \beta\hat{p}\times\hat{s} + \gamma(\hat{p}\times\hat{s})\times\hat{p}}{1 + \alpha\cos\theta}$$

Polarization induced CP violation

- **Meson case:**

Direct CP violation



$$A_{CP} = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}} \propto \sin\omega \, \sin\delta$$

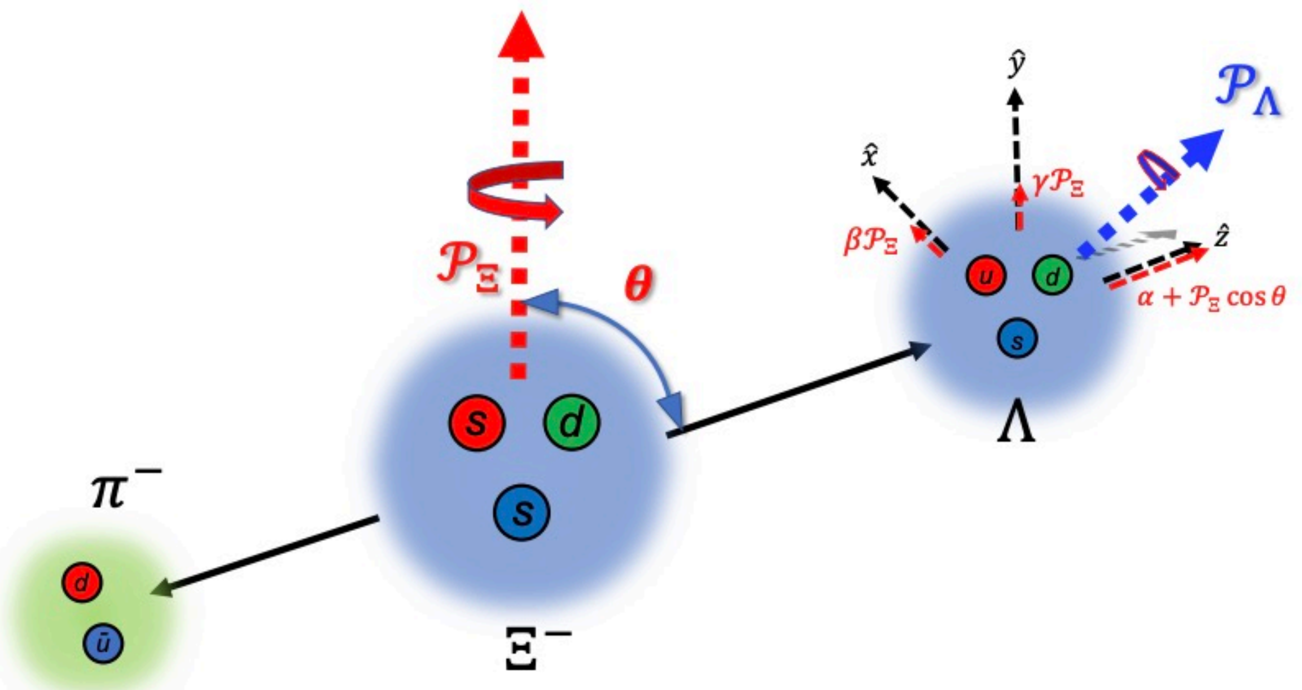
Weak phase

Strong phase

<u>**Disaster for theory!**</u>

- **Baryon case:**

e.g., BESIII measure the Lee-Yang parameters in $\Xi^- \to \Lambda\pi^- \to p2\pi^-$ and the induced CPV



$$\left(\frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}}\right)_\Xi \approx \omega_P - \omega_S$$

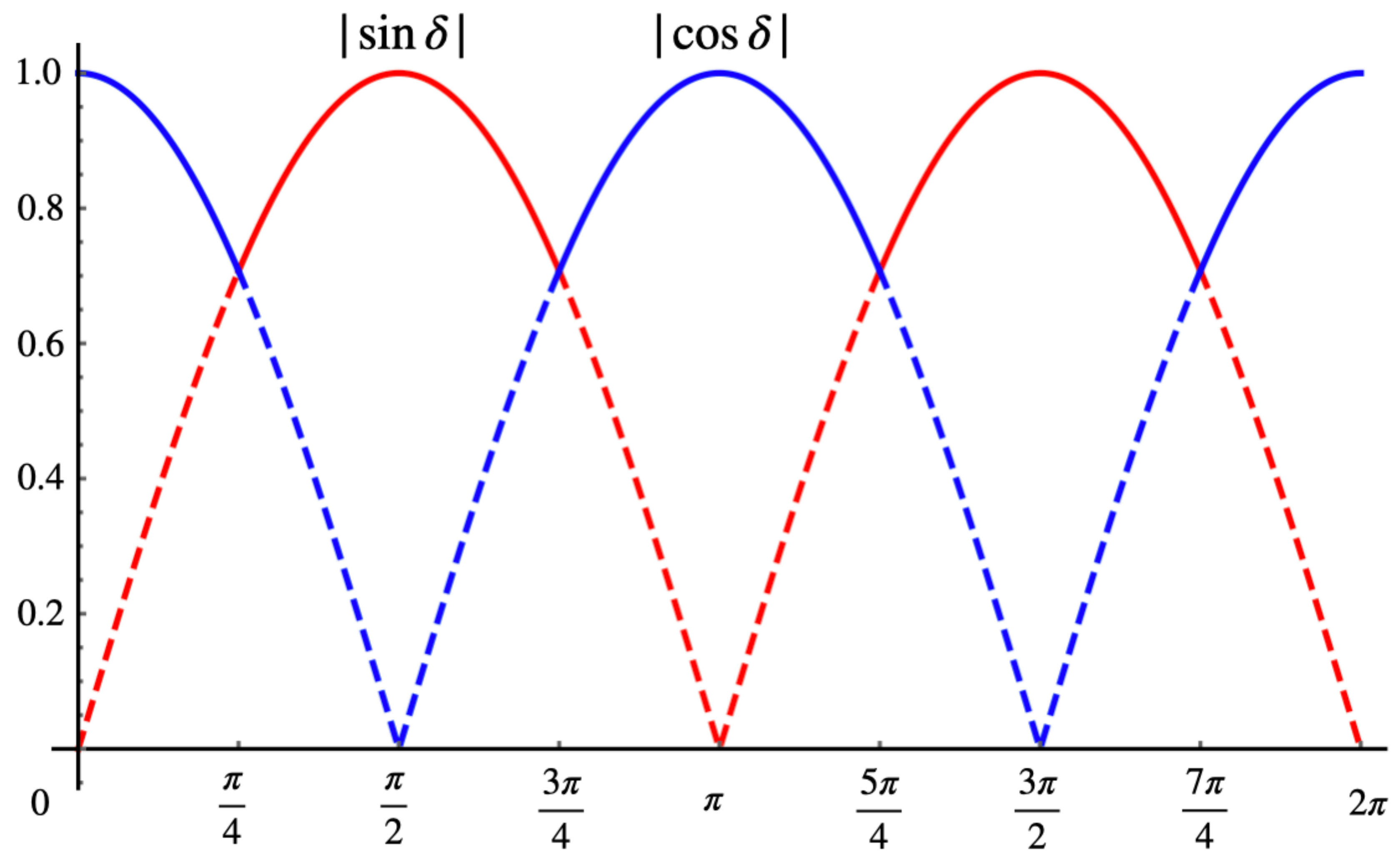
Purely weak phase!

Disaster disappears!

[BESIII, Nature, '22]

Polarization induced CP violation

- The reason is the $A_{\rm CP}^{\alpha}$ and $A_{\rm CP}^{\beta}$ **strong phase dependence:** $\sin\delta_s$ **vs** $\cos\delta_s$



- Whatever the strong phase is, either $|\sin\delta|$ or $|\cos\delta|$ would be larger than 0.7.
- If both of CPVs are measured, the strong phase can be determined.

- **Question:** does this complementarity generally exist?
- **Question:** if yes, how to find them systematically?

T-odd correlation induced CP asymmetry

- **General conclusion**: Time-reversal-odd correlation Q_- induces CPV with cosine dependence on strong phases

$$TQ_- = -Q_- T, \qquad A_{CP}^{Q_-} \equiv \frac{\langle Q_- \rangle - \langle \bar{Q}_- \rangle}{\langle Q_- \rangle + \langle \bar{Q}_- \rangle} \propto \cos\delta_s$$

if it satisfies two conditions: (i) for the final-state basis $\{|\psi_n\rangle$, n =1,2,…}, there is a unitary transformation U, s.t. $UT|\psi_n\rangle = e^{-i\alpha}|\psi_n\rangle$; (2) $UQ_-U^\dagger = Q_-$.

Proof:

$$\begin{aligned}\langle f|Q_-|f\rangle &= \langle i|S^\dagger Q_- S|i\rangle \\ &= \sum_{m,n}\langle\psi_i|S^\dagger|\psi_m\rangle\langle\psi_m|Q_-|\psi_n\rangle\langle\psi_n|S|\psi_i\rangle \\ &= \sum_{m,n} A_m^* A_n \langle\psi_m|Q_-|\psi_n\rangle \,.\end{aligned}$$

$$\begin{aligned}\langle\psi_m|Q_-|\psi_n\rangle &= \langle\psi_m|\mathcal{T}^\dagger\mathcal{T}\, Q_-|\psi_n\rangle^* \\ &= -\langle\psi_m|\mathcal{T}^\dagger Q_-\mathcal{T}|\psi_n\rangle^* \\ &= -\langle\psi_m|\mathcal{T}^\dagger\, \mathcal{U}^\dagger\mathcal{U}\, Q_-\, \mathcal{U}^\dagger\mathcal{U}\, \mathcal{T}|\psi_n\rangle^* \\ &= -\langle\psi_m|\mathcal{T}^\dagger\mathcal{U}^\dagger\, Q_-\, \mathcal{U}\mathcal{T}|\psi_n\rangle^* \\ &= -\langle\psi_m|Q_-|\psi_n\rangle^* \,,\end{aligned}$$

$\longrightarrow$ $\langle f|Q_-|f\rangle \ni \mathrm{Im}(A_m^* A_n)$ $\longrightarrow$ $A_{CP}^{Q_-} \propto \sin\delta_w \cos\delta_s$

[Wang, **QQ**, Yu, 2211.07332]

$A_{CP}^{Q_+} \propto \sin\delta_w \sin\delta_s$

T-odd correlation induced CP asymmetry

- Example 1. Triple product $Q_1 \equiv (\vec{s}_1 \times \vec{s}_2) \cdot \hat{p}$ in $P \to P_1 P_2$

$T: \vec{p} \to -\vec{p}, h \to h; \qquad U = R(\pi): -\vec{p} \to \vec{p}, h \to h \quad \longrightarrow \quad$ condition (i)

$T: Q_1 \to -Q_1; \qquad U = R(\pi): Q_1 \to Q_1 \quad \longrightarrow \quad$ condition (ii)

- Example 2. Triple product $Q_p \equiv (\hat{p}_1 \times \hat{p}_2) \cdot \hat{p}_3$ in $P \to P_1 P_2 P_3 P_4$

$T: \vec{p} \to -\vec{p}; \qquad U = P: -\vec{p} \to \vec{p} \quad \longrightarrow \quad$ condition (i)

$T: Q_p \to -Q_p; \qquad U = P: Q_p \to -Q_p \quad \not\longrightarrow \quad$ condition (ii)

[Wang, **QQ**, Yu, 2211.07332]

Complementarity: T-odd and -even CPV

- For the decay $\Lambda_b \to N^*(1520)K^*$, three such T-odd correlations

Triple product

$$Q_1 \equiv (\vec{s}_1 \times \vec{s}_2)\cdot\hat{p} = \frac{i}{2}(s_1^+ s_2^- - s_1^- s_2^+)$$

Hepta product

$$Q_2 \equiv (\vec{s}_1\cdot\hat{p})(\vec{s}_2\cdot\hat{p})Q_1 + Q_1(\vec{s}_1\cdot\hat{p})(\vec{s}_2\cdot\hat{p}) = \frac{i}{2}s_1^z s_2^z(s_1^+ s_2^- - s_1^- s_2^+) + \frac{i}{2}(s_1^+ s_2^- - s_1^- s_2^+)s_1^z s_2^z$$

Penta product

$$Q_3 \equiv (\vec{s}_1\cdot\vec{s}_2)Q_1 + Q_1(\vec{s}_1\cdot\vec{s}_2) - Q_2 = \frac{i}{2}(s_1^+ s_1^+ s_2^- s_2^- - s_1^- s_1^- s_2^+ s_2^+)$$

- Their expectations are imaginary helicity amplitude interferences

$$\langle Q_3\rangle = 2\sqrt{3}\,\mathrm{Im}\,(H_{+1,+\frac{3}{2}}H^*_{-1,-\frac{1}{2}} + H^*_{-1,-\frac{3}{2}}H_{+1,+\frac{1}{2}})$$

$\cos\delta_s$ **vs** $\sin\delta_s$

Exactly Complementary!

- Moreover, complementary T-even correlations are found

$$P_1 \equiv \vec{s}_1\cdot\vec{s}_2 - (\vec{s}_1\cdot\hat{p})(\vec{s}_2\cdot\hat{p}),\; P_2 \equiv (\vec{s}_1\cdot\hat{p})(\vec{s}_2\cdot\hat{p})P_1 + P_1(\vec{s}_1\cdot\hat{p})(\vec{s}_2\cdot\hat{p}),$$

$$P_3 \equiv P_1^2 - [\vec{s}_1^{\,2} - (\vec{s}_1\cdot\hat{p})^2][\vec{s}_2^{\,2} - (\vec{s}_2\cdot\hat{p})^2] - [(\vec{s}_1\times\vec{s}_1)\cdot\hat{p}][(\vec{s}_2\times\vec{s}_2)\cdot\hat{p}]$$

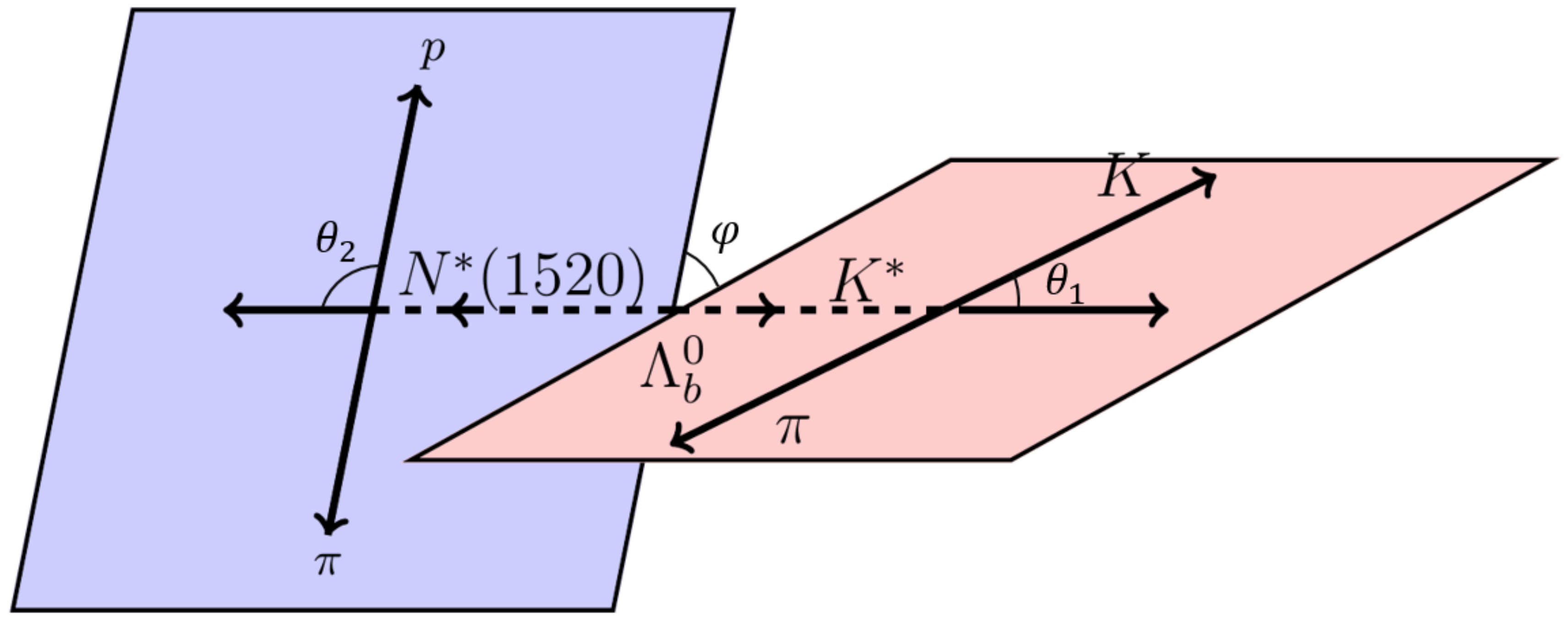
Real part

$$\langle P_3\rangle \propto \mathrm{Re}\,(H_{+1,+\frac{3}{2}}H^*_{-1,-\frac{1}{2}} + H^*_{-1,-\frac{3}{2}}H_{+1,+\frac{1}{2}})$$

[Wang, **QQ**, Yu, 2211.07332]

Complementarity: T-odd and -even CPV

- The expectations of the complementary T-odd and T-even correlations are both encoded in angular distribution of secondary decays of $N^*(1520)K^*$



$$
\begin{aligned}
\frac{d\Gamma}{dc_1\, dc_2\, d\varphi} \propto\ & s_1^2 s_2^2 \left(\left|\mathcal{H}_{+1,+\frac{3}{2}}\right|^2 + \left|\mathcal{H}_{-1,-\frac{3}{2}}\right|^2\right) \\
& + s_1^2(\frac{1}{3} + c_2^2)\left(\left|\mathcal{H}_{+1,+\frac{1}{2}}\right|^2 + \left|\mathcal{H}_{-1,-\frac{1}{2}}\right|^2\right) \\
& + 2c_1^2(\frac{1}{3} + c_2^2)\left(\left|\mathcal{H}_{0,-\frac{1}{2}}\right|^2 + \left|\mathcal{H}_{0,+\frac{1}{2}}\right|^2\right) \\
& - \frac{s_1^2 s_2^2}{\sqrt{3}} \mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin 2\varphi \qquad \langle Q_3 \rangle \\
& + \frac{s_1^2 s_2^2}{\sqrt{3}} \mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos 2\varphi \qquad \langle P_3 \rangle \\
& - \frac{4 s_1 c_1 s_2 c_2}{\sqrt{6}} \mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin\varphi \qquad \langle Q_1 + 2Q_2 \rangle \\
& + \frac{4 s_1 c_1 s_2 c_2}{\sqrt{6}} \mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos\varphi \qquad \langle P_1 + 2P_2 \rangle
\end{aligned}
$$

- Complementary CP asymmetries can thereby be measured, which depend on $\cos\delta_s$ & $\sin\delta_s$.

[Wang, **QQ**, Yu, 2211.07332]

Meson can be baryon!

$$(B \to VV)$$

Summary

Summary

- New facilities provide more opportunities to probe CP violation in favor physics.

- Not only **more precise** measurements can be performed because of larger statistics, better detector performance (e.g. CEPC),

- but also it open doors for **new CPV observables, new channels, new methodology.**

Thank you!