“My” Recent Progress on CP Violation

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arXiv: 2301.05848, 2211.07332

Collaborated with Y.F.Shen, W.J.Song, J.P.Wang, F.S.Yu

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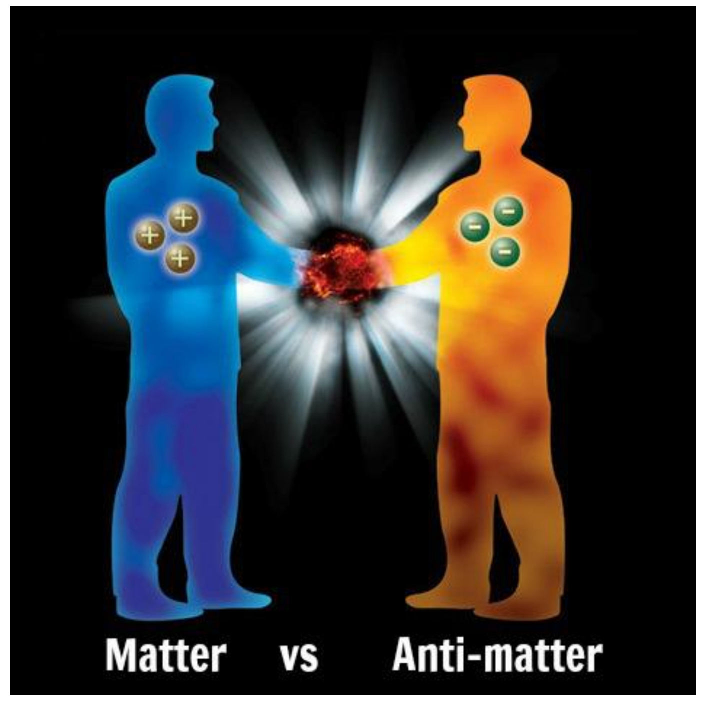
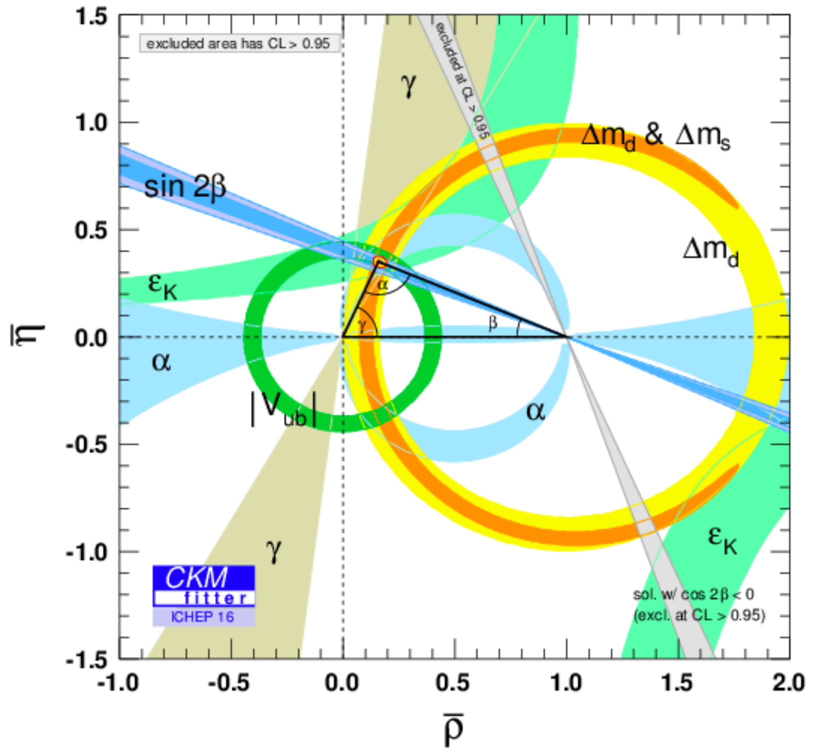
Why CP violation?



- One of the Sakharov's criteria of matter-anti-matter asymmetry

  ➡ Requires new source of CP violation

  [Sakharov, '67]



- Determination of CKM matrix phase angles

  ➡ To test the unitarity of the CKM matrix

- Open windows to new dynamics beyond the SM

CP violation in Flavor Physics

- **Discovery:** Mixing-induced CPV observed in Kaon decays

  [Christenson, Cronin, Fitch, Turlay, ’64]

- The Kobayashi-Maskawa mechanism

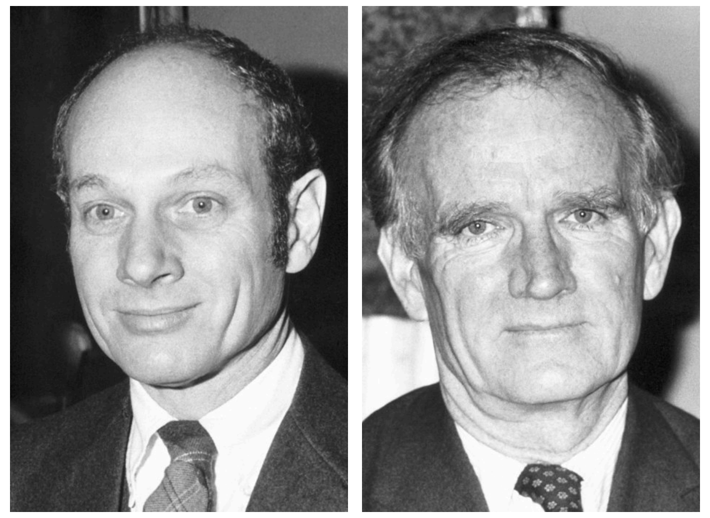
  [Kobayashi, Maskawa, ’73]

- Direct CPV discovered in B meson decays

  [BaBar & Belle, ’01]

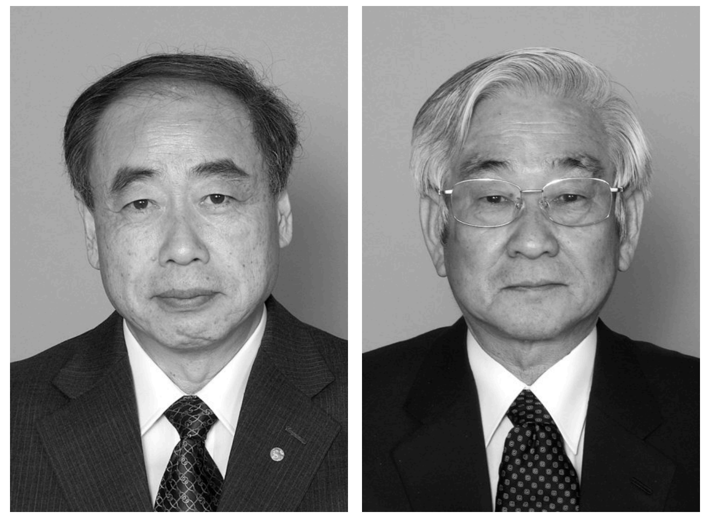
- What’s next?

  ➡ More precise! **<u>More observables!</u>**



Cronnin Fitch

[Nobel Prize for Physics in 1980]



Kobayashi Maskawa

[Nobel Prize for Physics in 2008]

More is better!

CP violation observables

- Common CPV observables

  ✓ CPV in decay (direct CPV) $(M \to f) \neq (\bar{M} \to \bar{f})$

  ✓ CPV in mixing (indirect CPV) $(M^0 \to \bar{M}^0) \neq (\bar{M}^0 \to M^0)$

  ✓ 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

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

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

- We propose/investigate **two new types of CPV observables**

  ➡ CPV induced by interference between two meson mixing [Shen,Song,**QQ**,2301.05848]

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

  ➡ A special kind of time-reversal-odd (T-odd) observables $TQ\_ = -Q\_T$ [Wang,**QQ**,Yu,2211.07332]

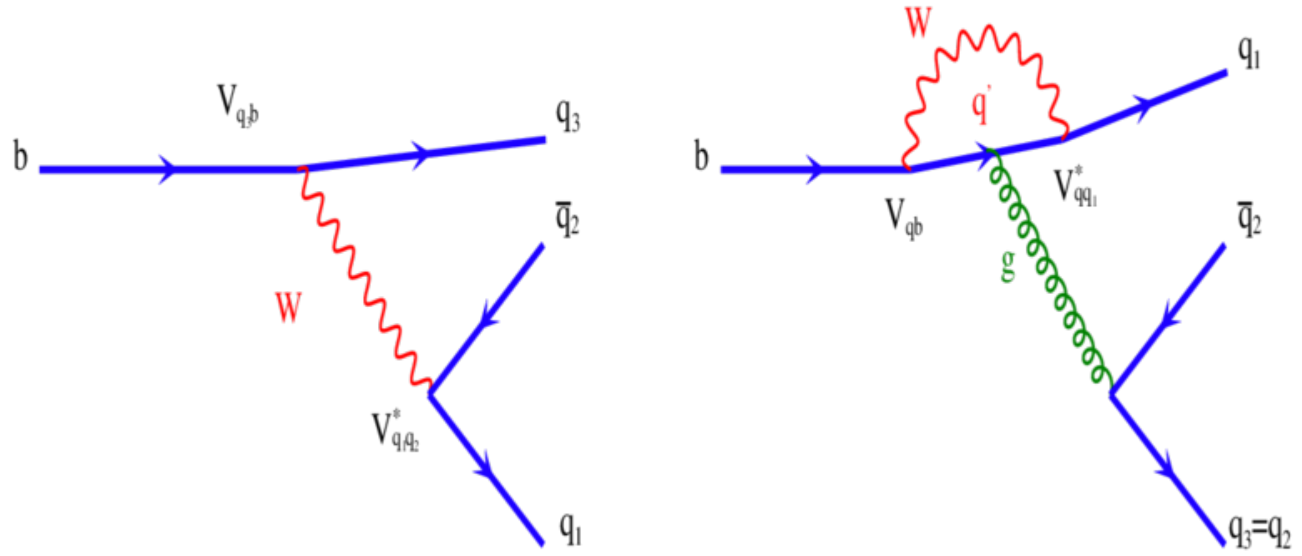
Part 1. Double mixing CP violation

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

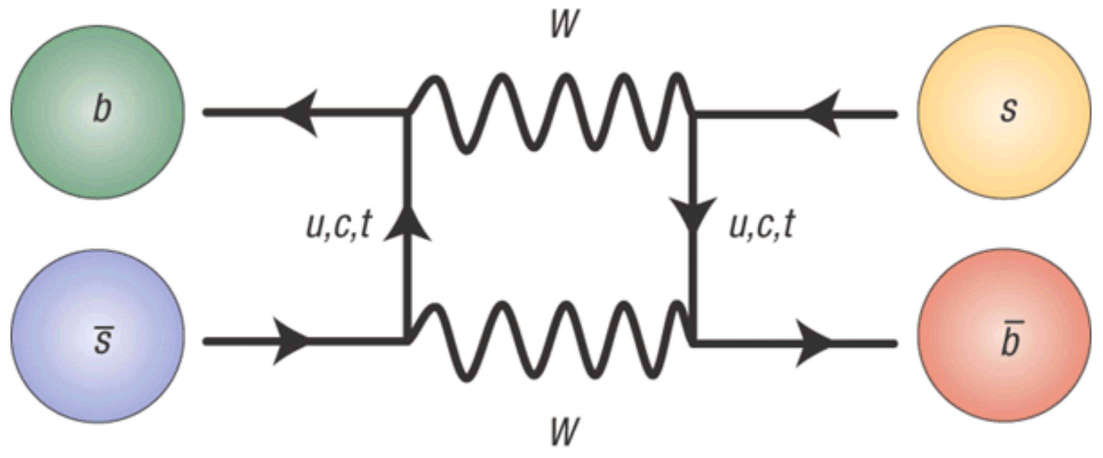
Double mixing CP violation

- Visualization of CPV requires **interference** between different amplitudes

  ✓ CPV in decay (direct CPV): tree and penguin amplitudes



  ✓ CPV in mixing: different quark mediating box amplitudes

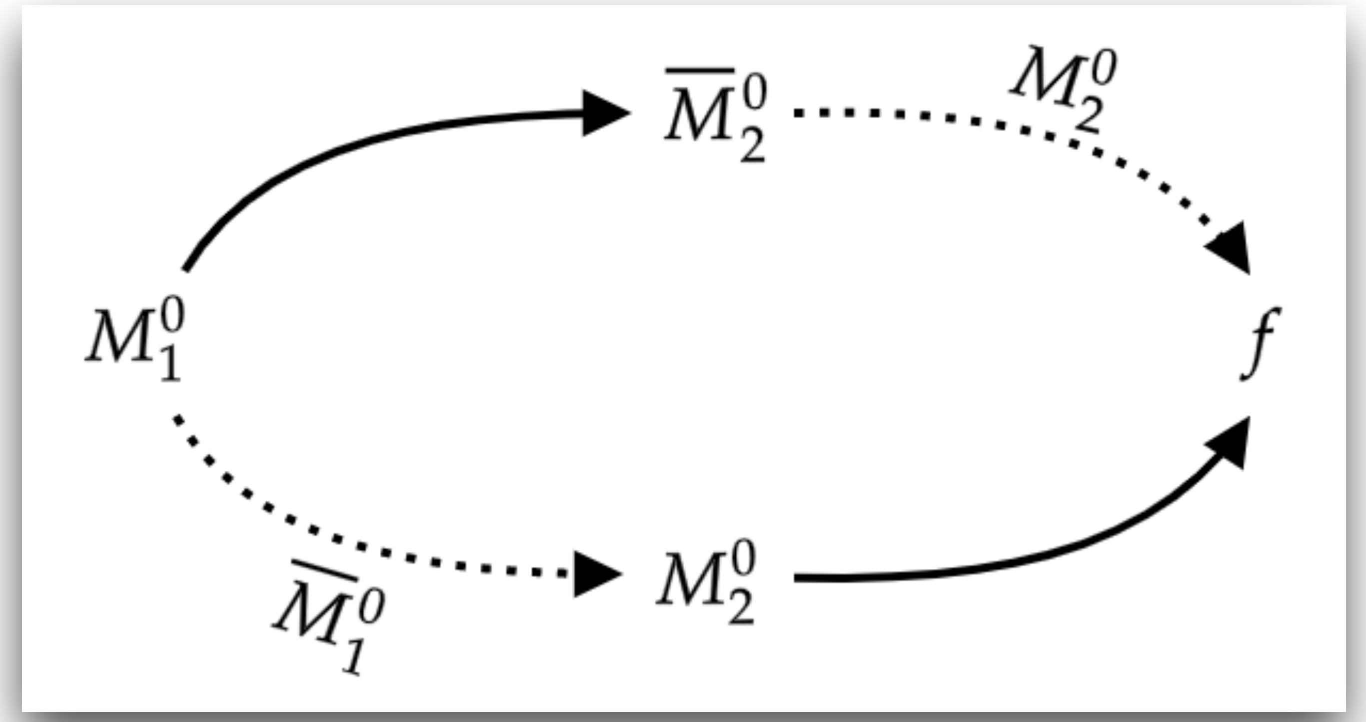


  ✓ CPV in interference between a decay without and with mixing

$M^0 \to f \qquad M^0 \to \bar{M}^0 \to f$

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

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

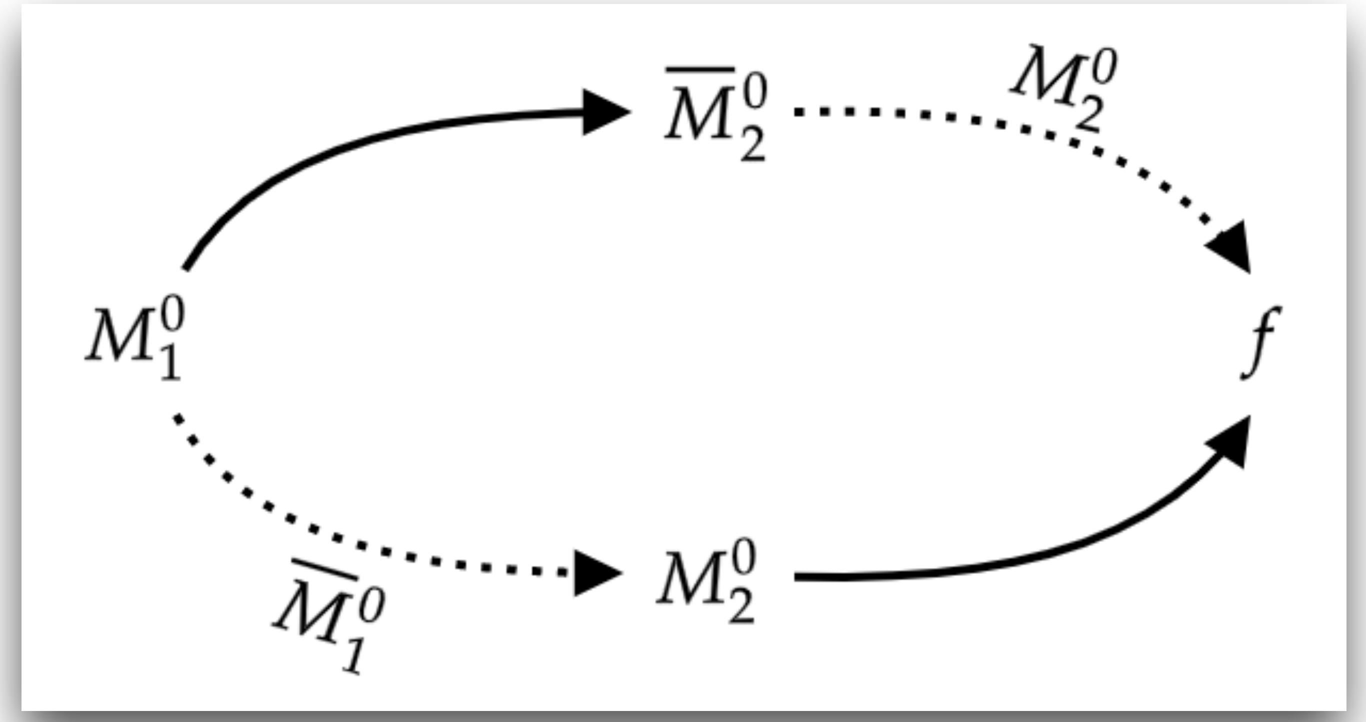


Double mixing CP violation

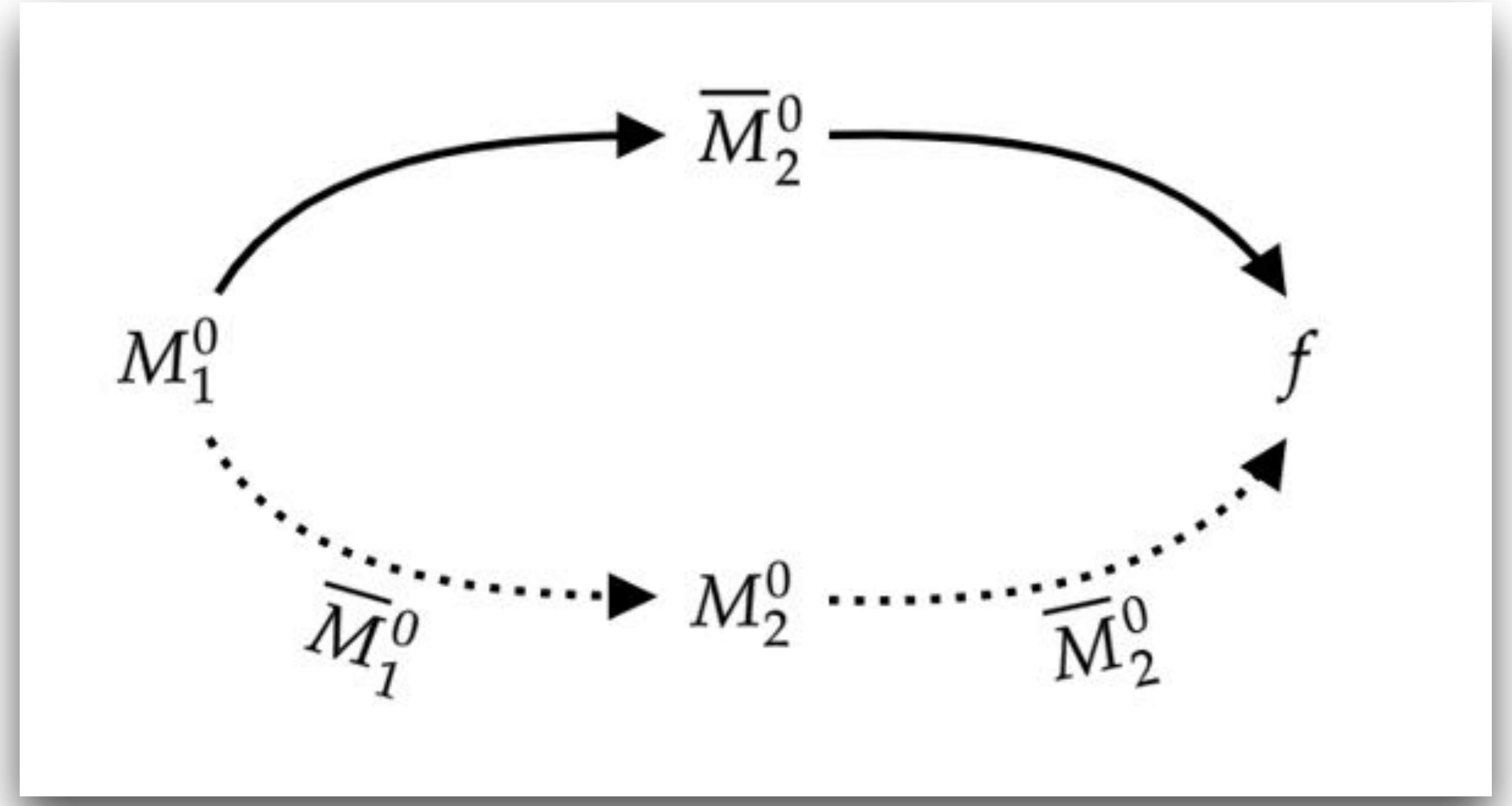
- **<u>Double mixing CP violation</u>**: induced by interference of different mixing paths of neutral mesons

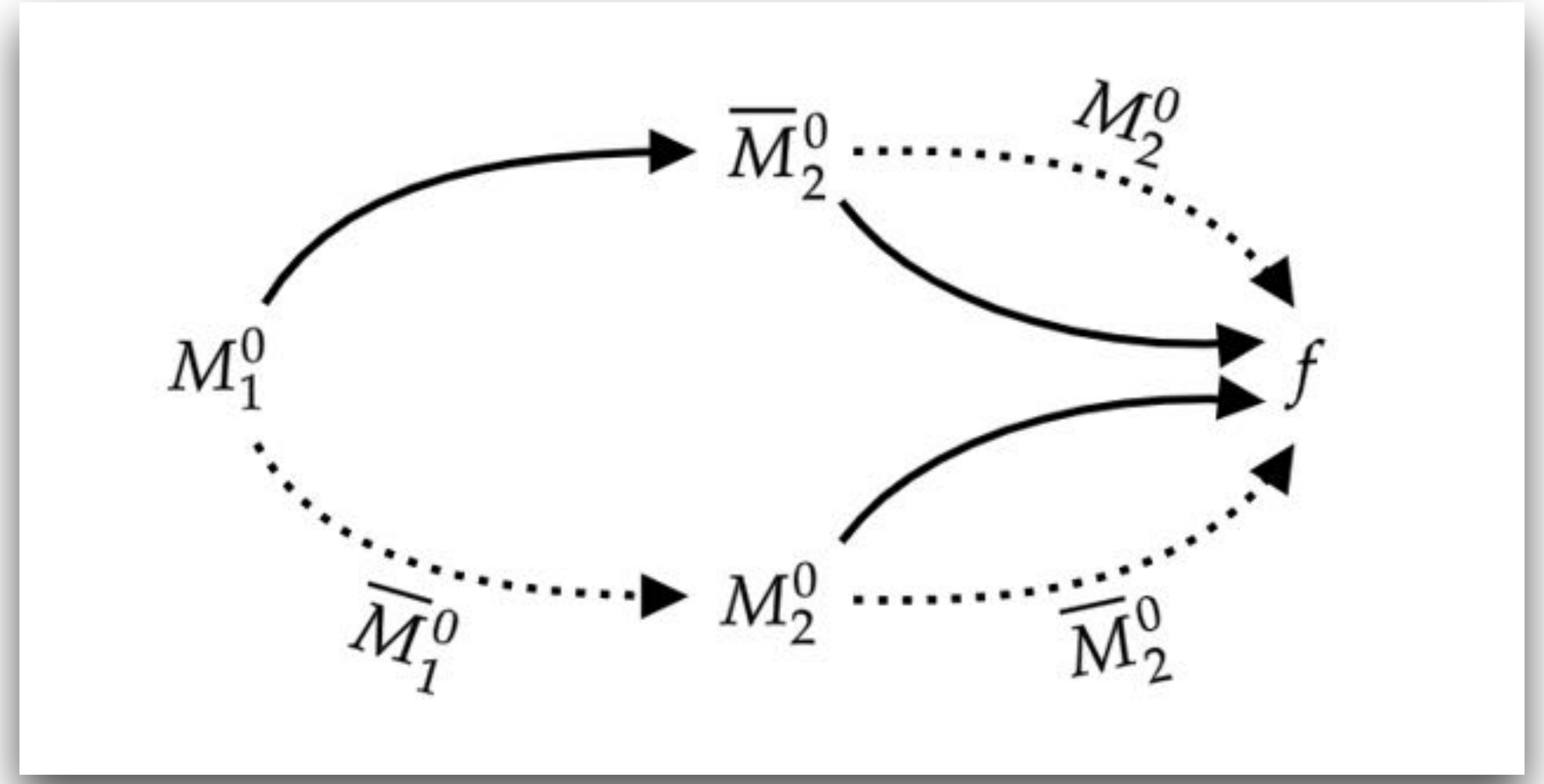
  ✓ At least two mixing mesons are involved

  ✓ At least two decays in the chain —— cascade decay

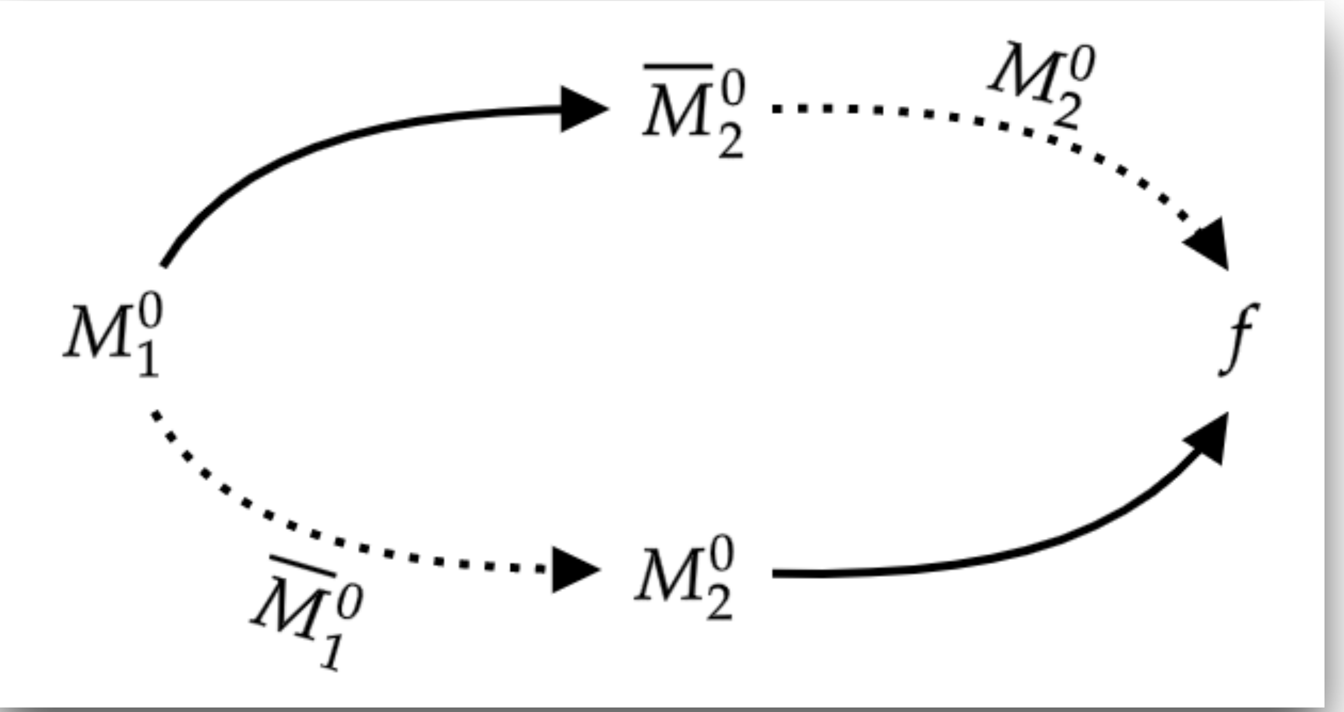


- More complicated cases





Double mixing CP violation



- 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)

$$M_1(t_1, t_2) \propto g_{1,+}(t_1)\left[-\frac{p}{q} g_{2,-}(t_2)\right]$$

$\bar{K}^0 \to K^0$

$$M_2(t_1, t_2) \propto \left[-\frac{q}{p} g_{1,-}(t_1)\right] g_{2,-}(t_2)$$

$B_s^0 \to \bar{B}_s^0$

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

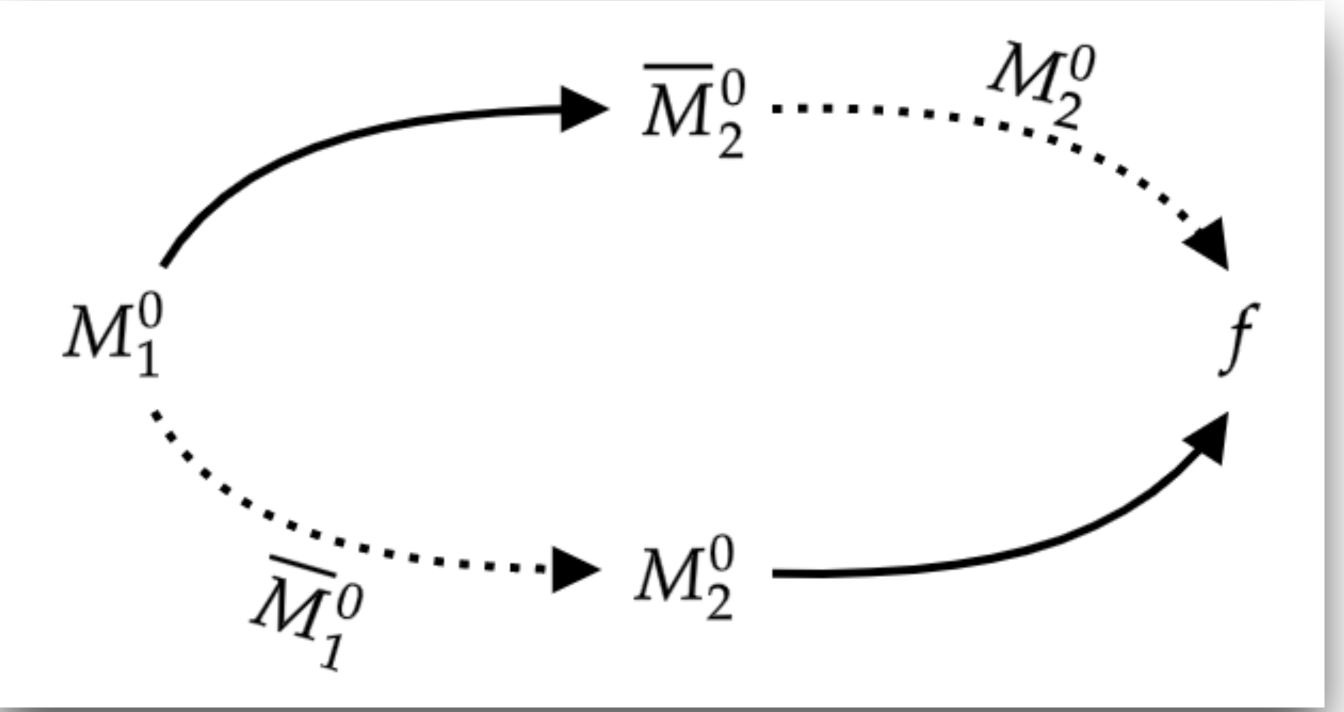
- Two-time dependent CPV: $A_{CP}(t_1, t_2) = (|M|^2 - |\bar{M}|^2)/(|M|^2 + |\bar{M}|^2)$ $M \equiv M_1 + M_2$

Sources: 1. $|M_1|^2$; → CP violation in K^0 mixing

2. $|M_2|^2$; → CP violation in B_s^0 mixing

3. $M_1^* M_2 + M_1 M_2^*$ → CP violation in interference between K^0, B_s^0 mixing

Double mixing CP violation



- 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)

$$A_{CP}(t_1, t_2) \propto \underbrace{|g_{1,+}(t_1)|^2 C_+(t_2)}_{|M_1|^2} + \underbrace{|g_{1,-}(t_1)|^2 C_-(t_2)}_{|M_2|^2} + \underbrace{e^{-\Gamma_1 t_1} \sinh \frac{\Delta\Gamma_1 t_1}{2} S_h(t_2) + e^{-\Gamma_1 t_1} \sin(\Delta m_1 t_1)\, S_n(t_2)}_{M_1^* M_2 + M_1 M_2^*}$$

$$C_+(t_2) = |g_{2,-}(t_2)|^2 \left(\left|\frac{p}{q}\right|_2^2 - \left|\frac{q}{p}\right|_2^2 \right),$$

$$C_-(t_2) = |g_{2,+}(t_2)|^2 \left(\left|\frac{q}{p}\right|_1^2 - \left|\frac{p}{q}\right|_1^2 \right),$$

$$S_h(t_2) = \frac{e^{-\Gamma_2 t_2}}{2}[-2 \sin \Delta m_2 t_2 \sin(\phi_1 + \phi_2 + 2\delta)]$$

$$S_n(t_2) = \frac{e^{-\Gamma_2 t_2}}{2} 2 \sinh \frac{\Delta\Gamma_2 t_2}{2} \sin(\phi_1 + \phi_2 + 2\delta)$$

Weak Phase

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

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

$$< \rho\bar{K} | B_s > = < \rho K | \bar{B}_s > e^{2i\delta}$$

B_s & K mixing interference

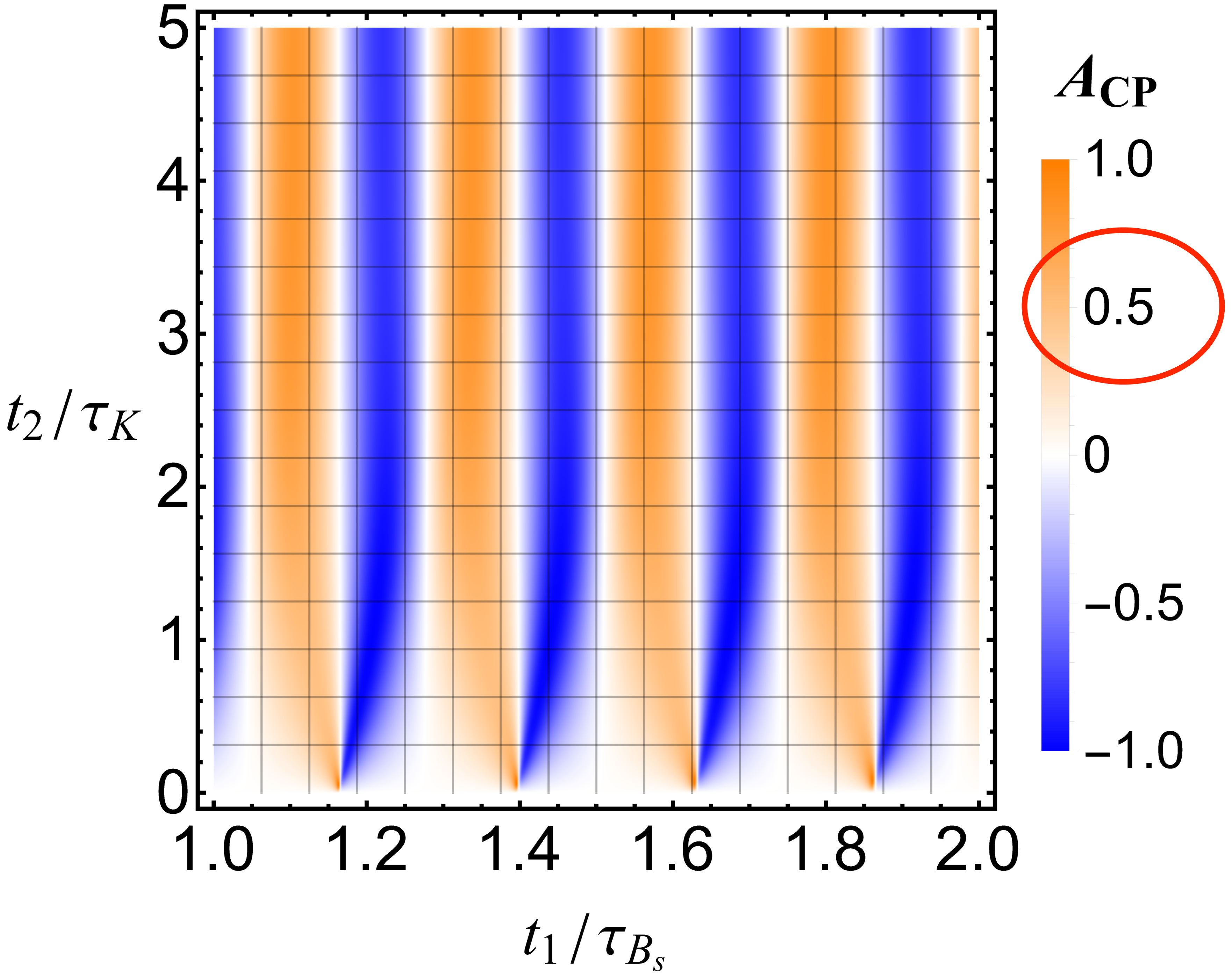
Double mixing CP violation

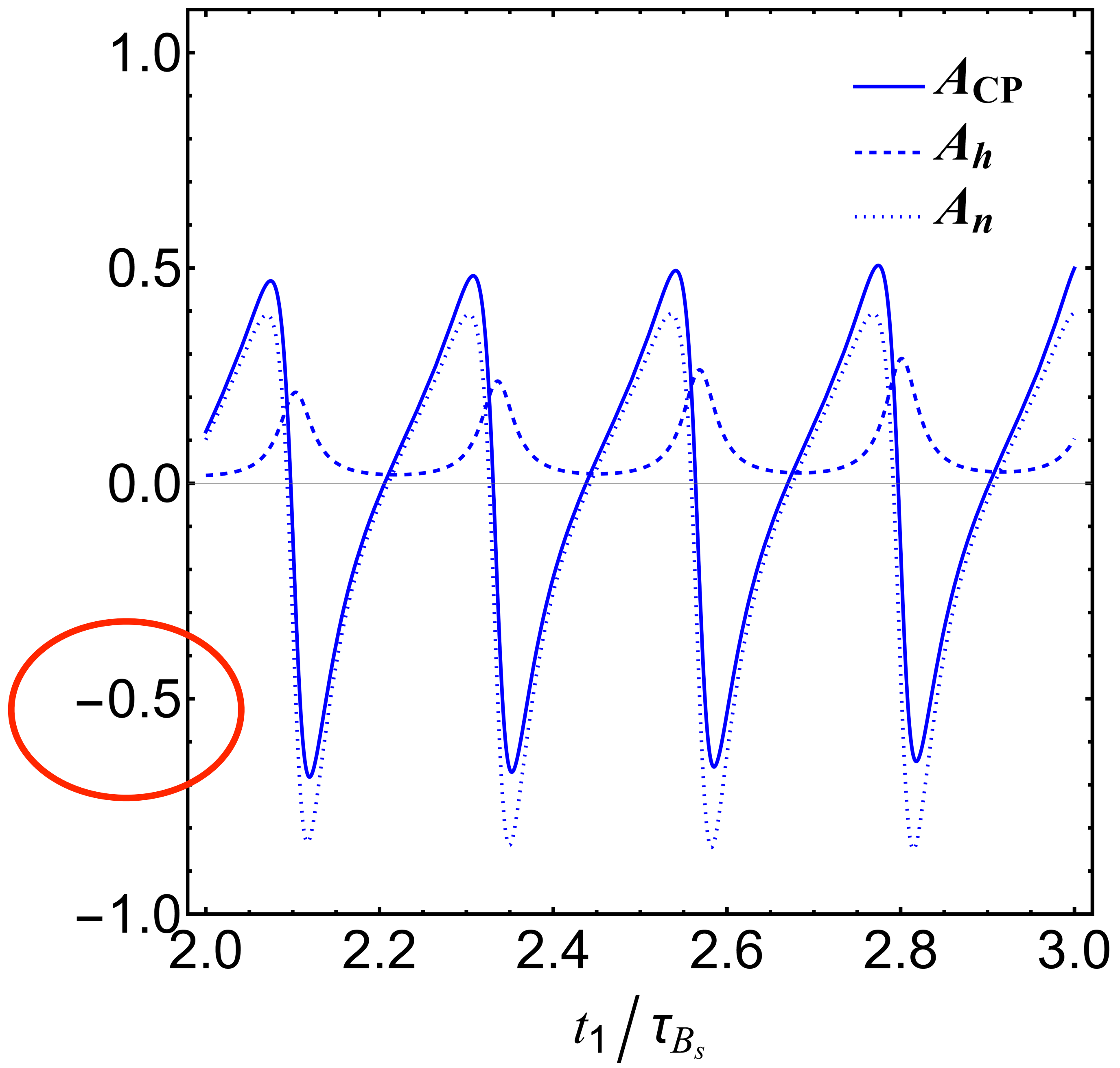
- Take $B_s^0(t_1) \to \rho^0 \bar{K}^0(t_2) \to \rho^0 \pi^- e^+ \nu$ as an example (penguin≈0)

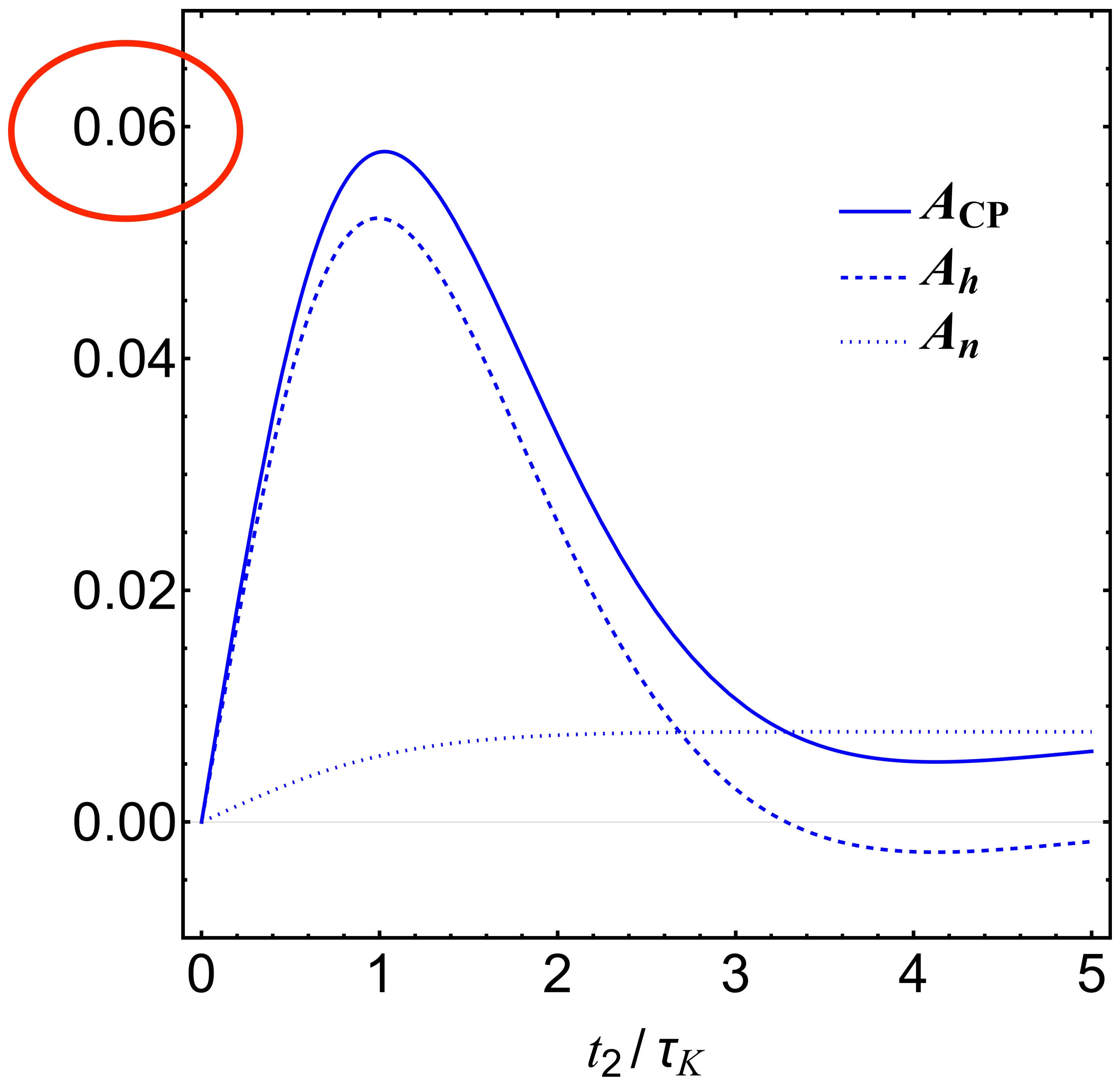
Time dependence:

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

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







Measurable at Z-factories like CEPC!

Double mixing CP violation

- The double-mixing CP asymmetry depends on two time variables and thus a **two-dimensional time dependence analysis** can be performed.

- It does not require nonzero strong phases, providing opportunities to directly **extract weak phases without strong pollution**.

- **Significant** in some channels, to be measured in experiments.

- To be investigated in **more channels** and to include **more accurate calculation**.

Part 2. T-odd CP violation

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

Baryonic CPV

- T-odd CP violation is motivated in investigation of baryonic CPV.

- Is direct CP asymmetry the correct observable for baryonic CPV?

$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2}\,, \qquad \begin{aligned} A &= A_1 e^{i\phi_1} e^{i\delta_1} + A_2 e^{i\phi_2} e^{i\delta_2} = A_1 e^{i\phi_1} e^{i\delta_1}(1 + r e^{i\phi} e^{i\delta}) \\ \bar{A} &= A_1 e^{-i\phi_1} e^{i\delta_1} + A_2 e^{-i\phi_2} e^{i\delta_2} = A_1 e^{-i\phi_1} e^{i\delta_1}(1 + r e^{-i\phi} e^{i\delta}) \end{aligned}$$

$$\Rightarrow \quad \boxed{A_{CP} \propto 2r \sin\phi \sin\delta}$$

Requirements:

1. r is large
2. weak phase ϕ is large
3. strong phase δ is large

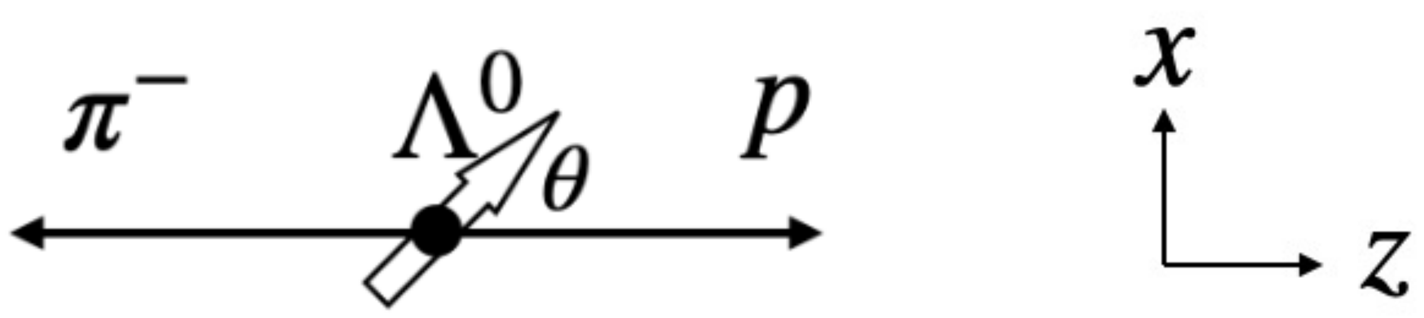
Far beyond control!

- Alternative observables to **satisfy** or **relax** the requirements?

Polarization induced observables

- **Polarizations/helicities** of baryons provide fruitful 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:**

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

Spin measurements are difficult!

Polarization induced observables

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

- **Key point: particle spins are encoded in their decay products.**

- With entangled $\Xi^-\bar{\Xi}^+$ and $\Xi^- \to \Lambda\pi^- \to p2\pi^-$, BESIII measure the Lee-Yang parameters and their induced CPV

[BESIII, Nature 2022]

Strong phase independent! ←

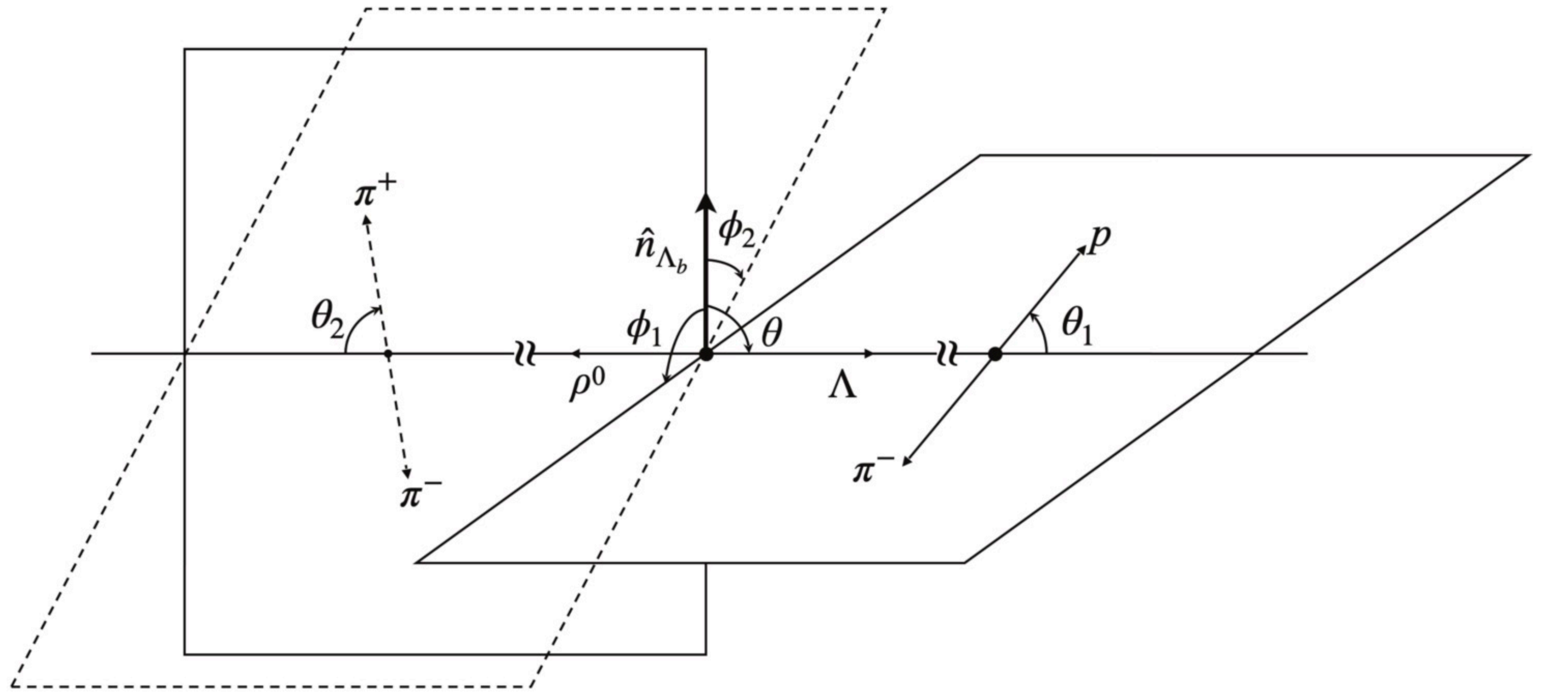
$$\Delta\phi_{\rm CP} \approx \frac{\langle\alpha\rangle}{\sqrt{1-\langle\alpha\rangle^2}}\left(\frac{\beta+\bar{\beta}}{\alpha-\bar{\alpha}}\right)_{\Xi} = (-5 \pm 15)\times 10^{-3}$$

- Application to more channels with Cascade decays (e.g. $\Lambda_b \to \Lambda V \to p3\pi$)

  1. Angular distribution encodes the **helicity amplitudes**

  2. They induce CPVs with **different strong phase dependences**

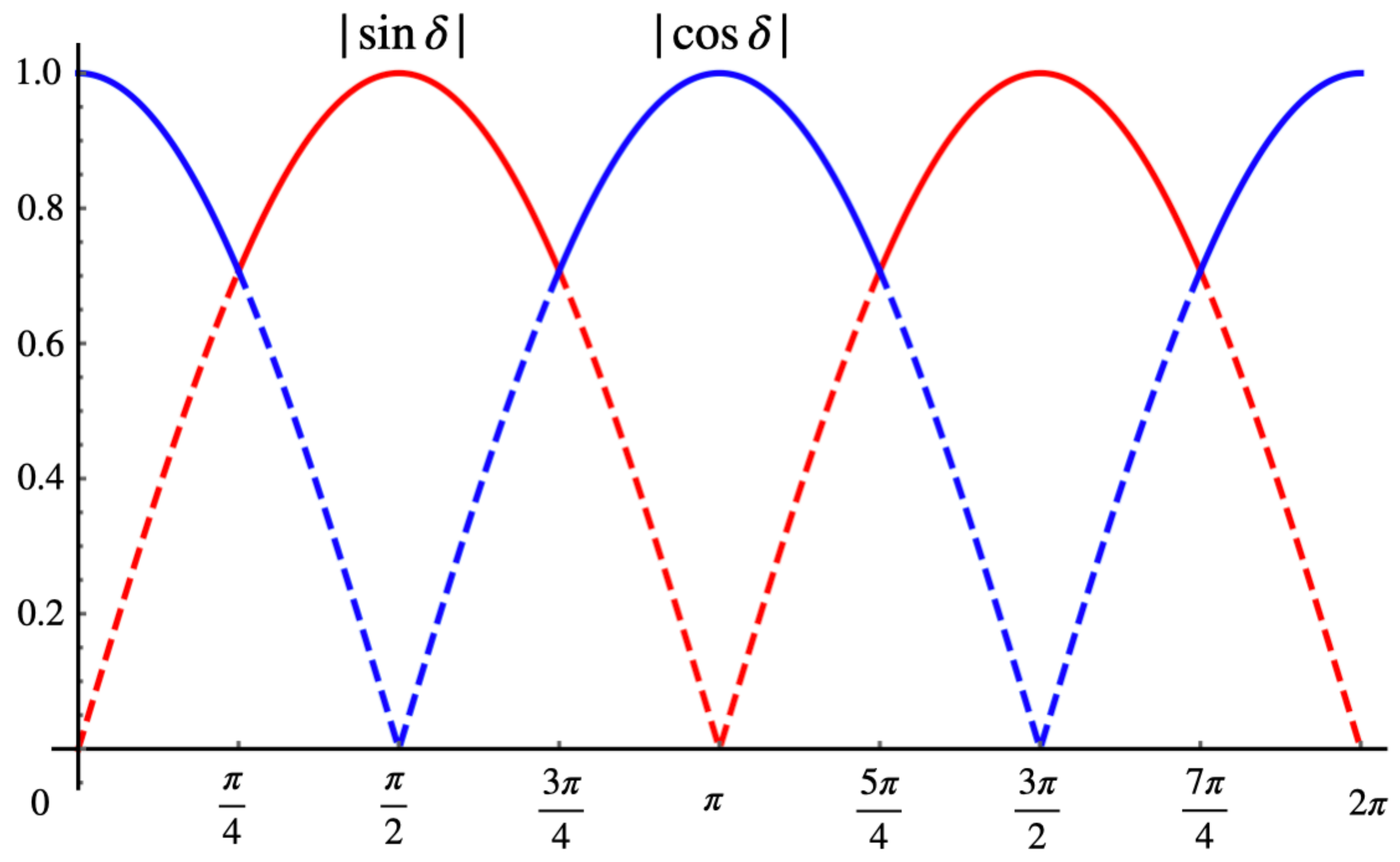
$\sin\delta_s$ **vs** $\cos\delta_s$



[Geng, Liu, Wei, et al, 2106.10628,2109.09524,2206.00348;Zhou, et al, 2210.15357]

Polarization induced observables

- **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.

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

T-odd correlation induced CP asymmetry

- T-odd correlation Q_- induced CPV have 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:

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

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

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

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

T-odd correlation induced CP asymmetry

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

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

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

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

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

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

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

T-odd correlation induced CP asymmetry

- 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

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

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

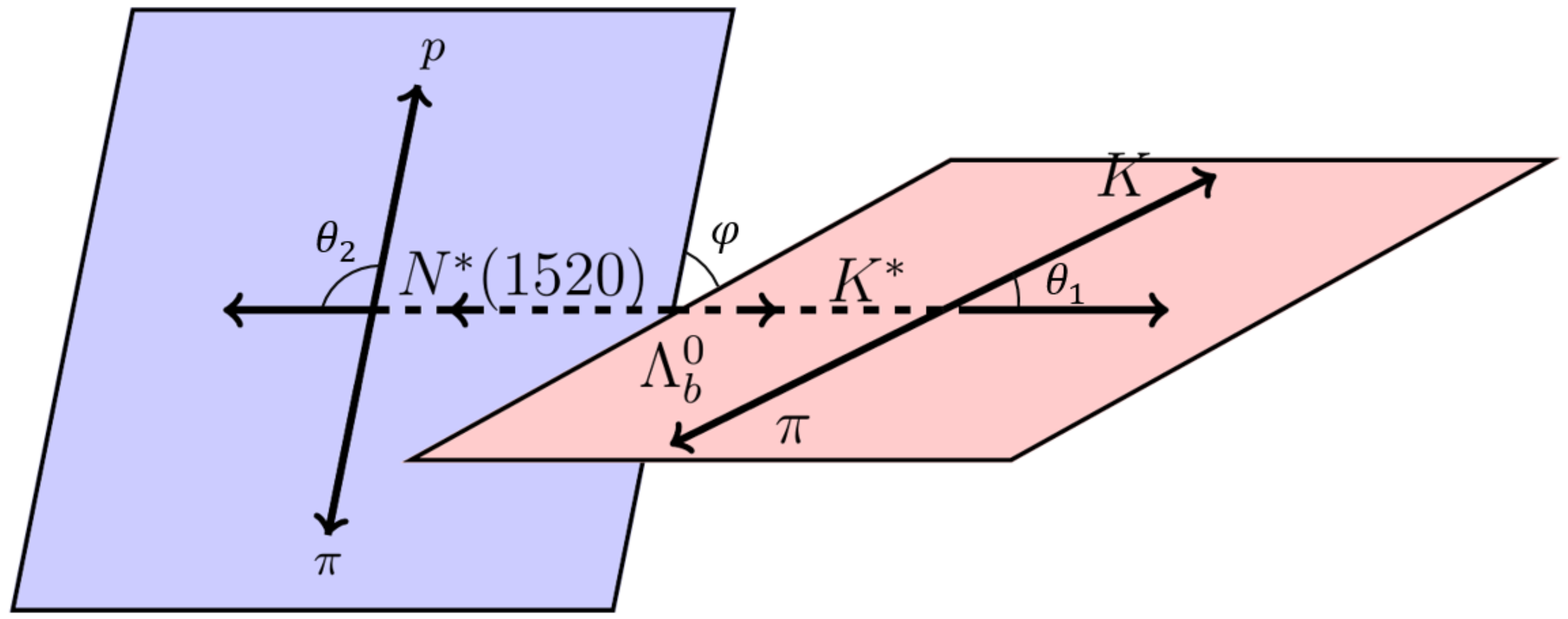
Real part →

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

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

T-odd correlation induced CP asymmetry

- 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]

Summary

Summary

- **New CPV observables** are proposed

- including **double mixing CPV**, which could avoid strong pollution,

- and a type of **complementary T-odd CPV**, which would help discover **baryonic CPV**.

- Both of them awaits more investigation. **Collaboration is always welcome!**

Thank you!