T-odd CP Violation

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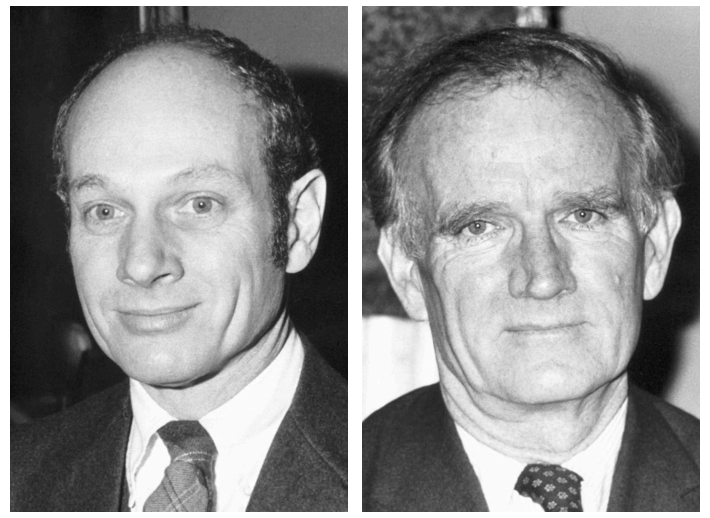
Highlights of Flavor Physics



Cronnin Fitch

[Nobel Prize for Physics in 1980]

- **CP violation**

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

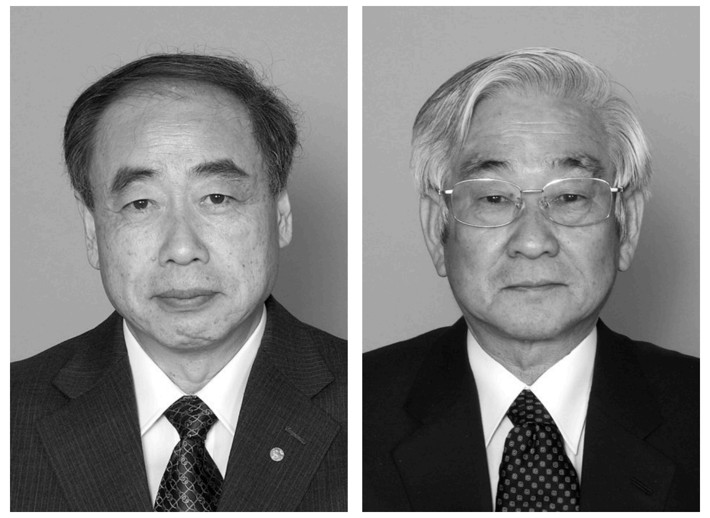
  [Christenson, Cronin, Fitch, Turlay, ’64]

  ➡ The Kobayashi-Maskawa mechanism

  [Kobayashi, Maskawa, ’73]

  ➡ Direct CPV discovered in B meson decays

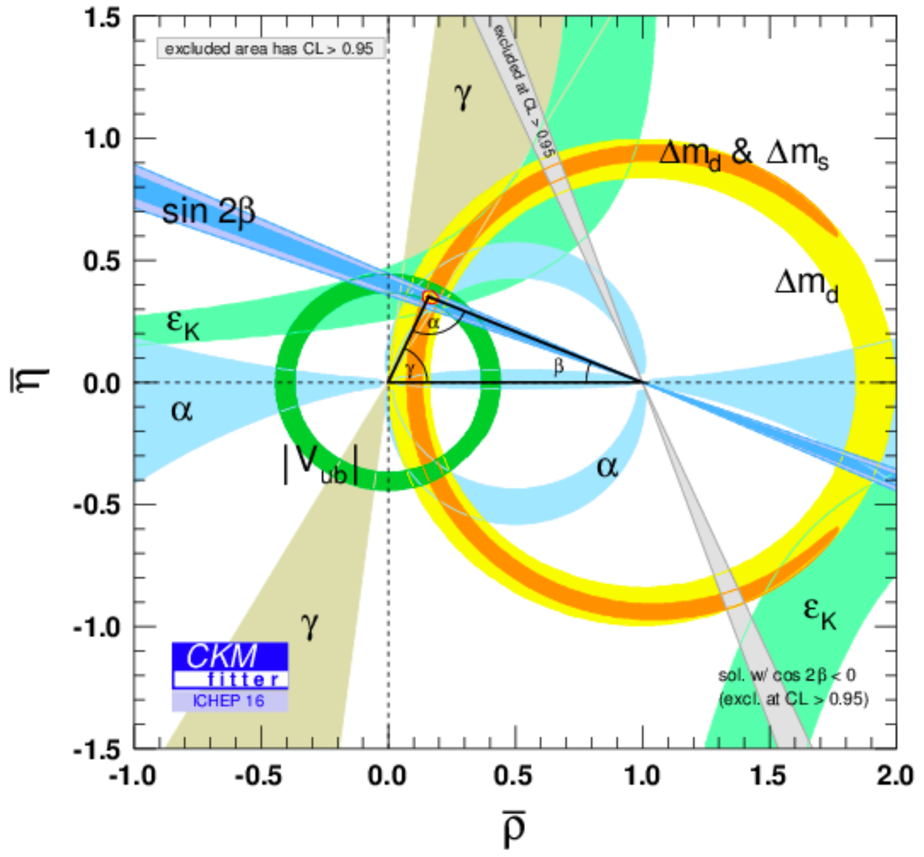
  [BaBar & Belle, ’01]



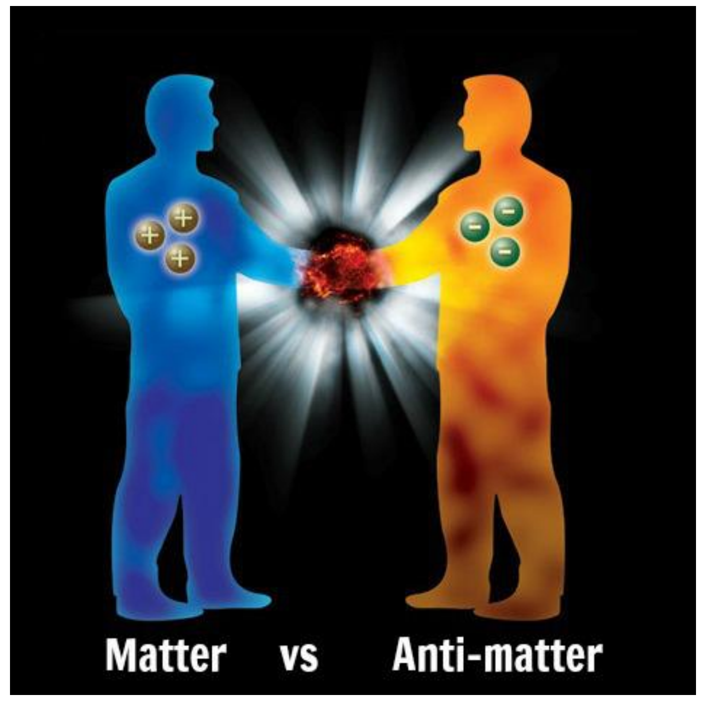
Kobayashi Maskawa

[Nobel Prize for Physics in 2008]

- **CKM**: Measurements of fundamental parameters of nature



Why still Flavor Physics?

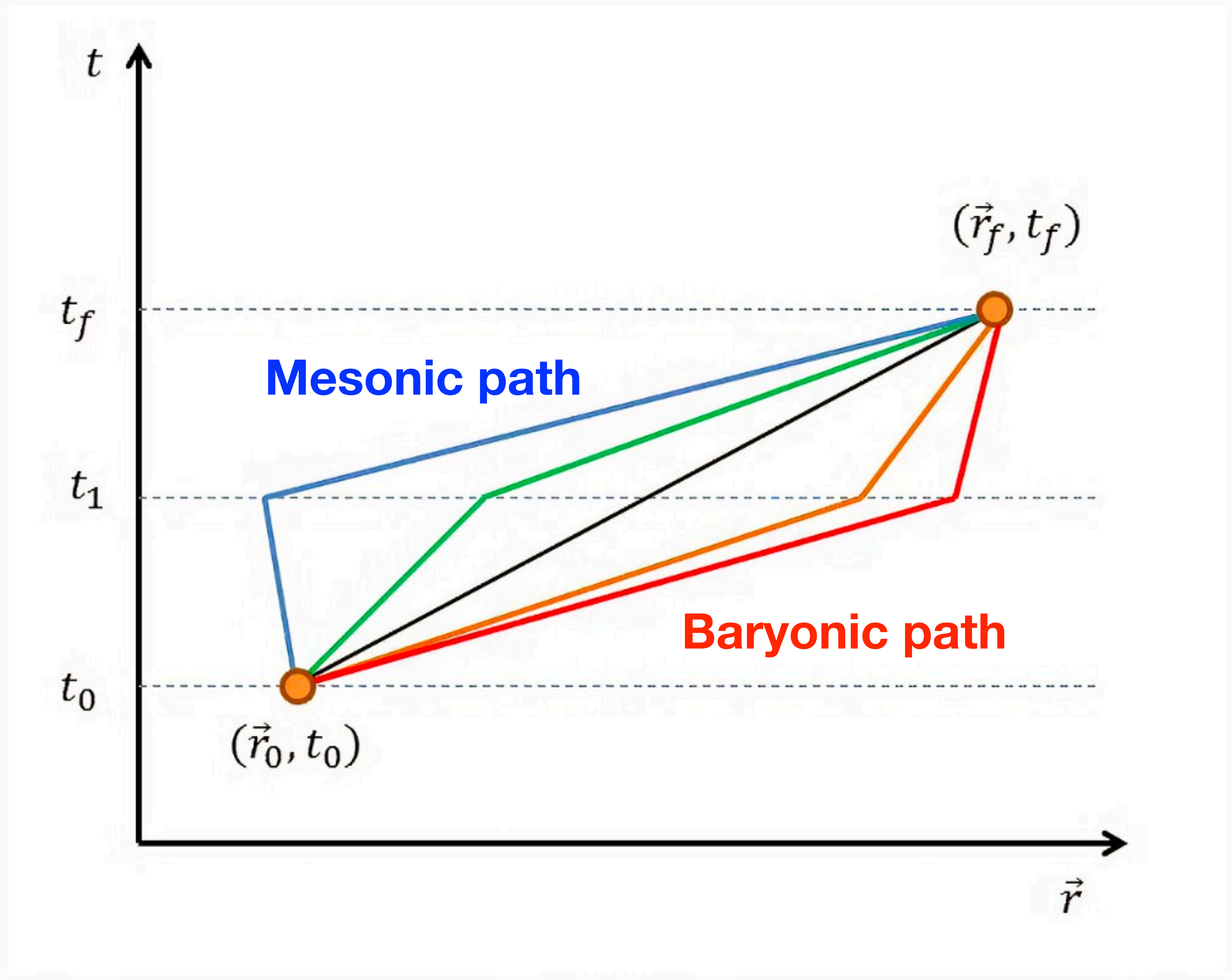


- Unanswered questions.
- **Precision test of the standard model ⇒ new dynamics**
- **What else can be do except improve the precision?**
- New facilities (BESIII, Belle II, upgrading LHCb, CEPC)! New opportunities!

  ➡ Release **new channels & new observables**

- Never forget a bunch of new particles —— **baryons!**

Mesonic flavor physics → Mesonic & Baryonic flavor physics!


t
$(\vec{r}_f, t_f)$
t_f
Mesonic path
t_1
Baryonic path
t_0
$(\vec{r}_0, t_0)$
$\vec{r}$

Huge opportunities for baryon

Particle	BESIII	Belle II	LHCb (300 fb^{-1})	CEPC (4×Tera-Z)
B^0, $\bar{B}^0$	-	5.4×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
$B^{\pm}$	-	5.7×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
B_s^0, $\bar{B}_s^0$	-	6.0×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	1.2×10^{11}
$B_c^{\pm}$	-	-	1×10^{11}	7.2×10^{8}
Λ_b^0, $\bar{\Lambda}_b^0$	-	-	2×10^{13}	1×10^{11}
D^0, $\bar{D}^0$	1.2×10^{8}			5.2×10^{11}
$D^{\pm}$	1.2×10^{8}			2.2×10^{11}
$D_s^{\pm}$	1×10^{7}			8.8×10^{10}
$\Lambda_c^{\pm}$	0.3×10^{7}			5.5×10^{10}
$\tau^{\pm}$	3.6×10^{8}	4.5×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)		1.2×10^{11}

No reason to spare the prairie!

Huge opportunities for baryon

- Same heavy quark: Remeasurements and retests of the mesonic version

  ➡ Important but not fully satisfactory

- Different spectator ⇒ **Principle differences**

  ➡ Three quarks ➡ Different power counting in baryon decays (to probe QCD)

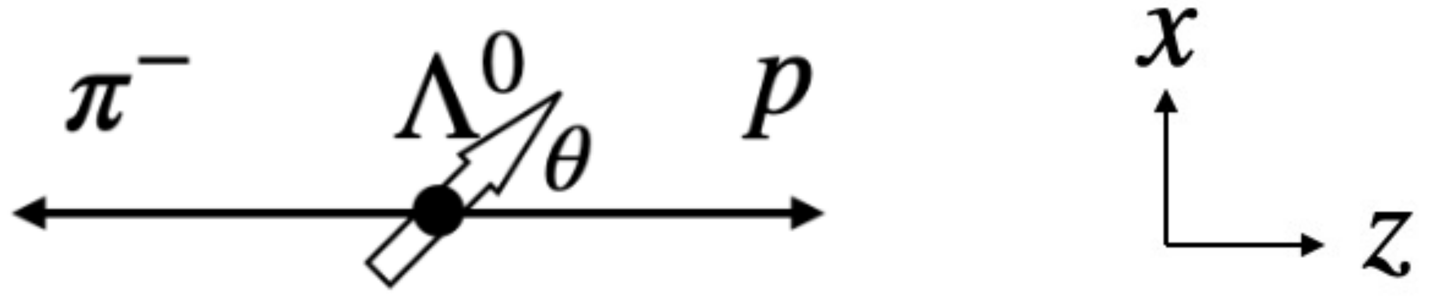
  ➡ Nonzero baryon number ➡ Sensitive to different (non-)standard operators

  ➡ Nonzero spin ➡ ……

Polarization induced observables

- **Spins/Polarizations/Helicities** of baryons provide fruitful observables.

- Lee-Yang parameters: α, β, γ



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

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!

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

Polarization induced observables

- **Build spin-dependent CP violation observables, e.g., $\alpha + \bar{\alpha}$, $\gamma - \bar{\gamma}$.**

- 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! ←

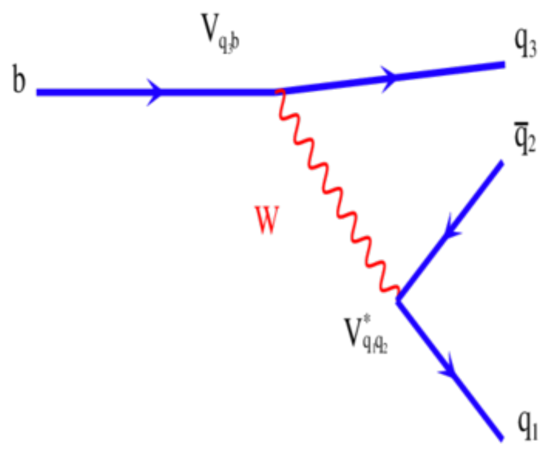
$$\Delta\phi_{\mathrm{CP}} \approx \frac{\langle\alpha\rangle}{\sqrt{1-\langle\alpha\rangle^2}}\left(\frac{\beta+\bar{\beta}}{\alpha-\bar{\alpha}}\right)_{\Xi} = (-5 \pm 15) \times 10^{-3}$$

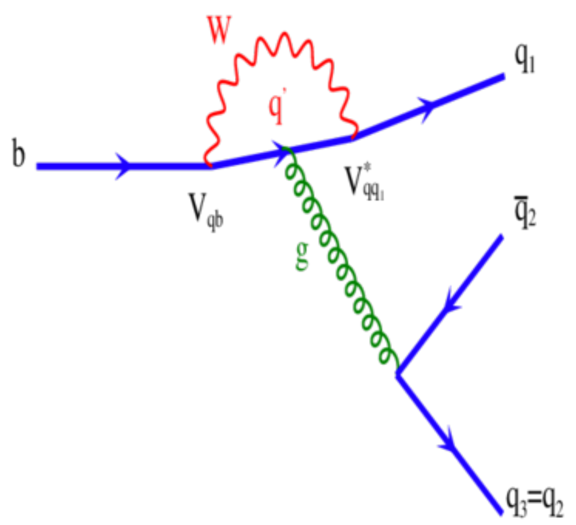
- Traditional direct CP asymmetry: <u>sine dependence</u> on strong phase.

$$A_{CP} \equiv \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2},$$

$$A = A_1 e^{i\phi_1} e^{i\delta_1} + A_2 e^{i\phi_2} e^{i\delta_2} = A_1 e^{i\phi_1} e^{i\delta_1}(1 + r e^{i\phi} e^{i\delta})$$

$$\bar{A} = A_1 e^{-i\phi_1} e^{i\delta_1} + A_2 e^{-i\phi_2} e^{i\delta_2} = A_1 e^{-i\phi_1} e^{i\delta_1}(1 + r e^{-i\phi} e^{i\delta})$$





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

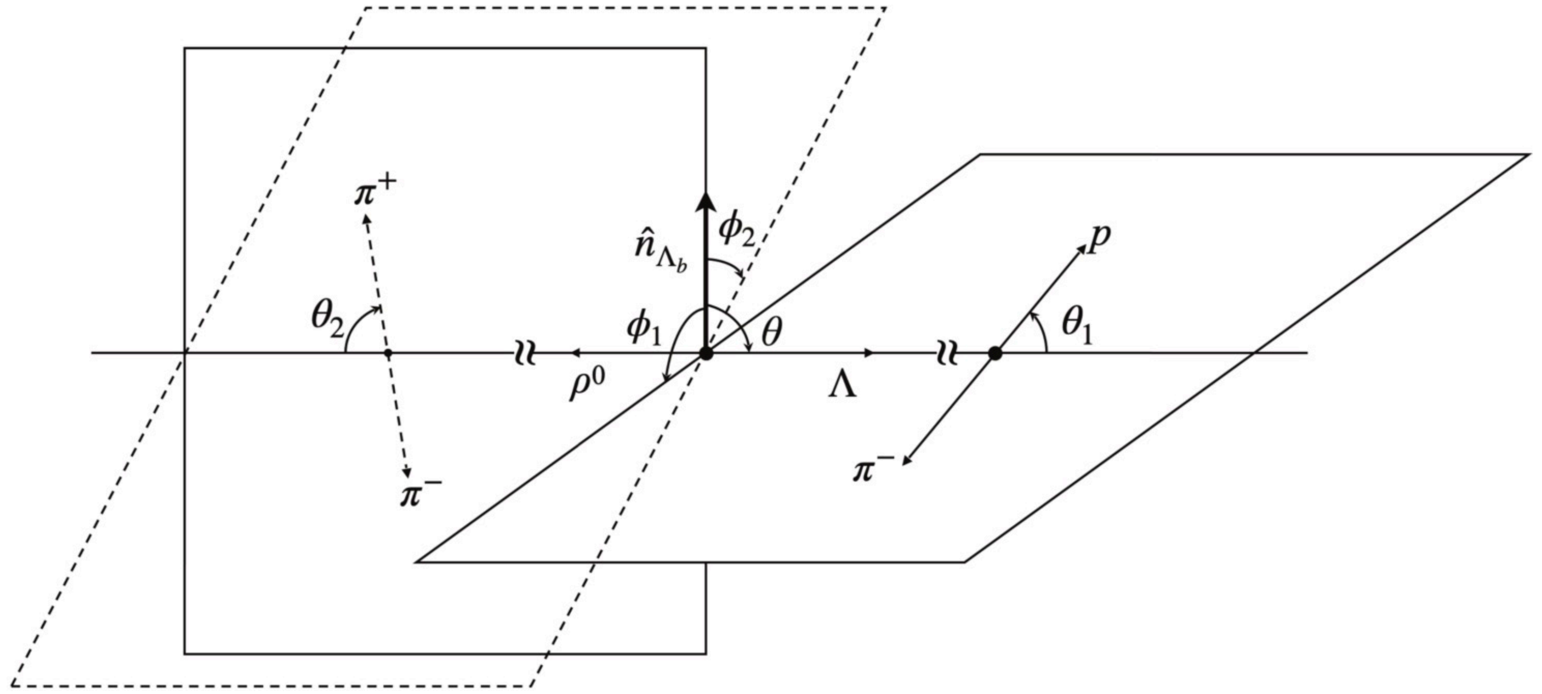
Angular distribution ⇒ spin/helicity ⇒ strong phase!

Polarization induced observables

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

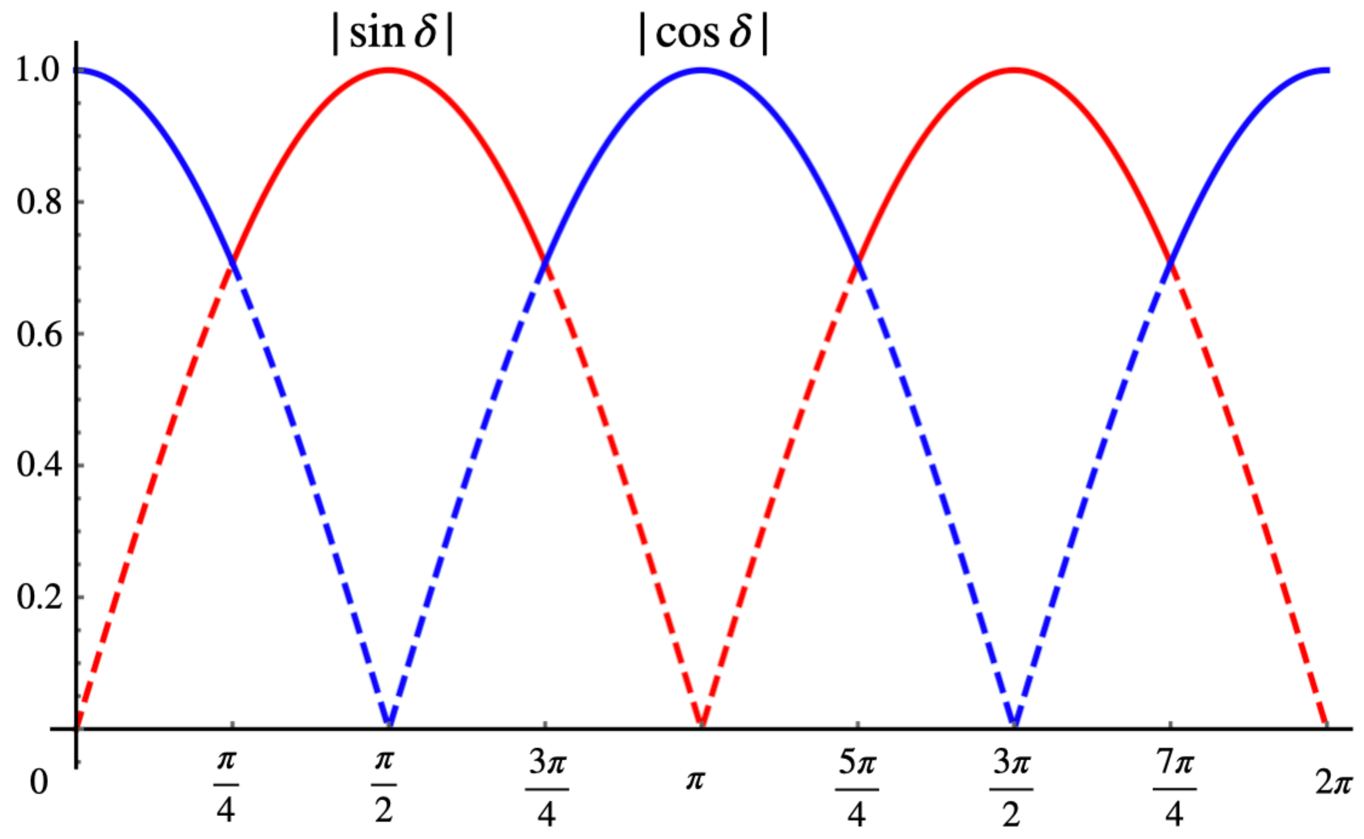
    1. Angular distribution encodes the **helicity amplitudes**
    2. They induce CPVs with **different strong phase dependences**

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



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

- **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.

T-odd correlation induced CP asymmetry

- **General conclusion**: T-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:

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

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

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

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

[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

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

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

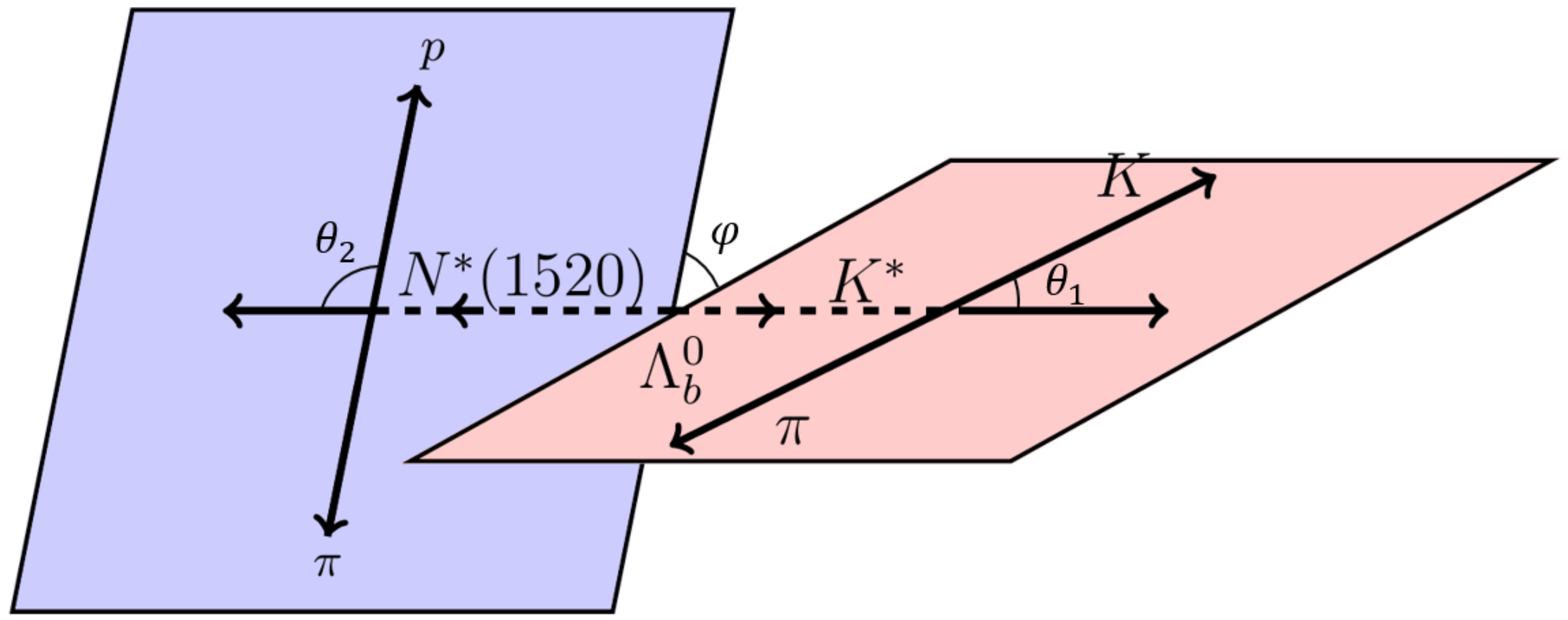
Real part →

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

[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

- **Baryonic flavor physics** has become more and more important
- Based on the spin/helicity information of baryons, CPV observables can be built with different dependences on strong phases
- We prove that a subset of **T-odd and T-even CPVs**, are proportional to **cos** δ_s **and sin** δ_s.
- They can be extracted from angular distributions of Cascade baryon decays.
- It may help **discover the baryonic CPV**, and afterwards help **determine the strong phase** and hence the weak phase.

Thank you!