# Baryon CP Violation by T-odd and T-even correlations

于福升

兰州大学

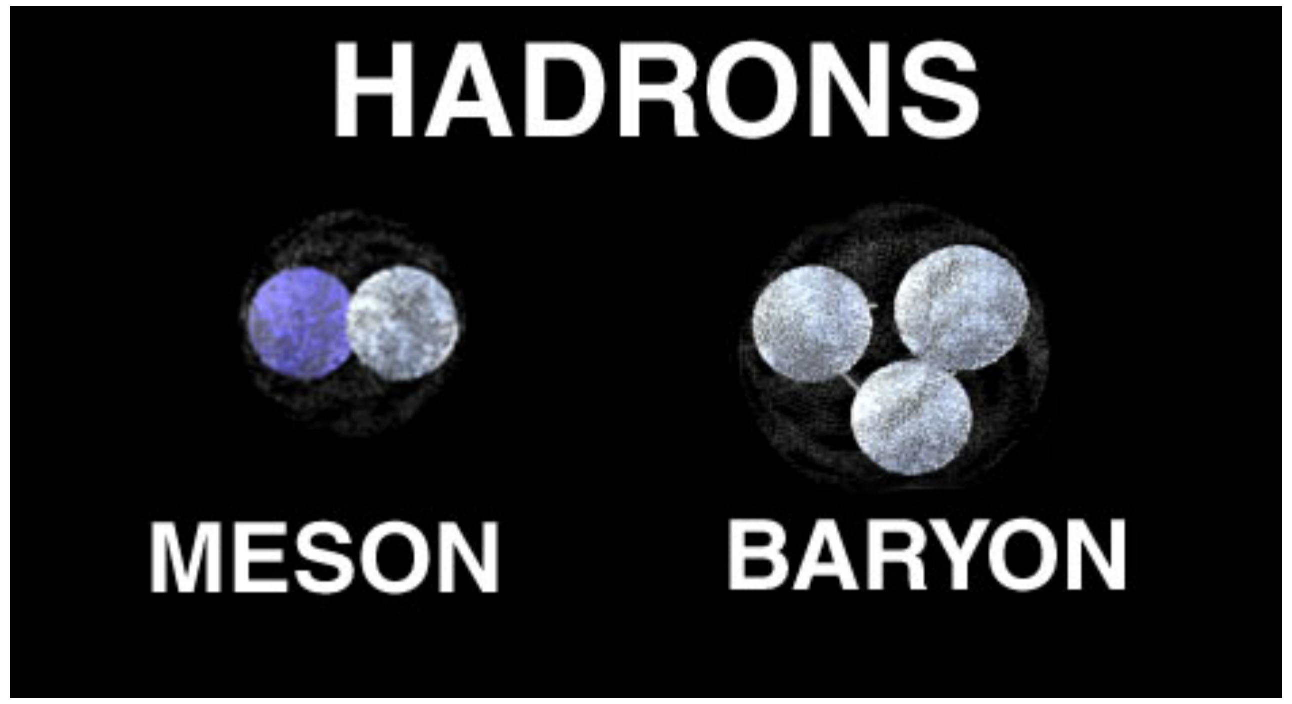
Based on [J.P.Wang, Q.Qin, FSY, arXiv:2211.07332]

LHCb workshop，2023.4.15

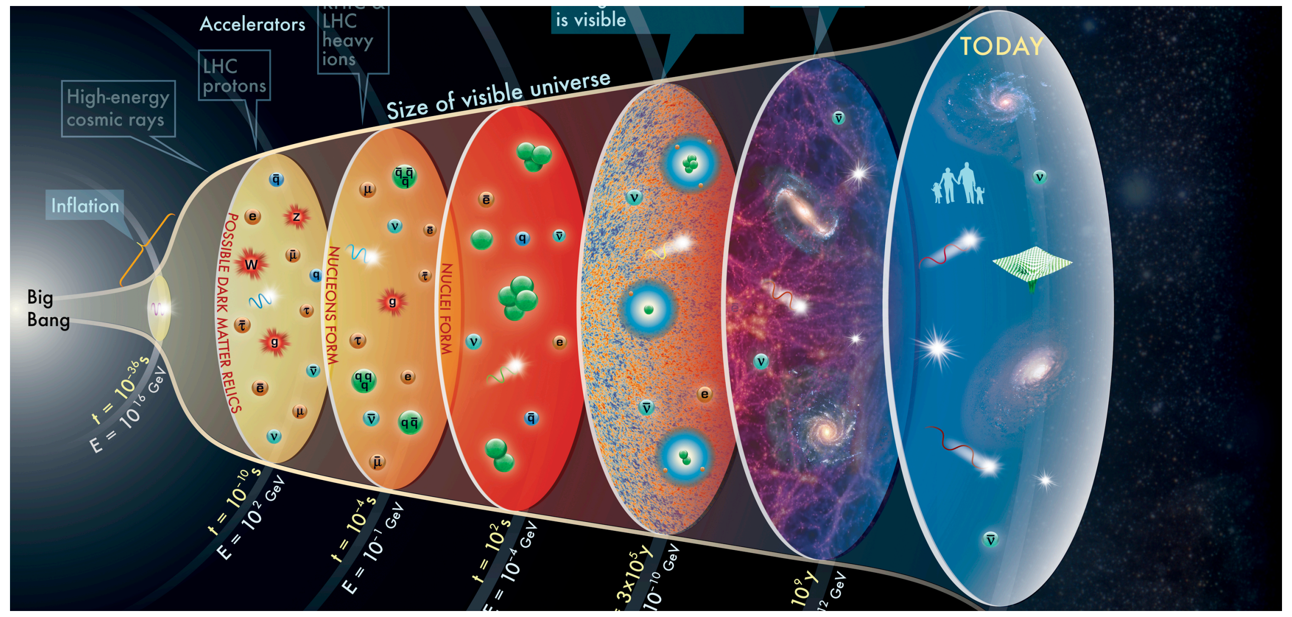
# Outline

- Why baryon physics? Opportunities.
- CP violation induced by T-odd and T-even correlations
- Complimentary observables
- Summary

# Baryon physics

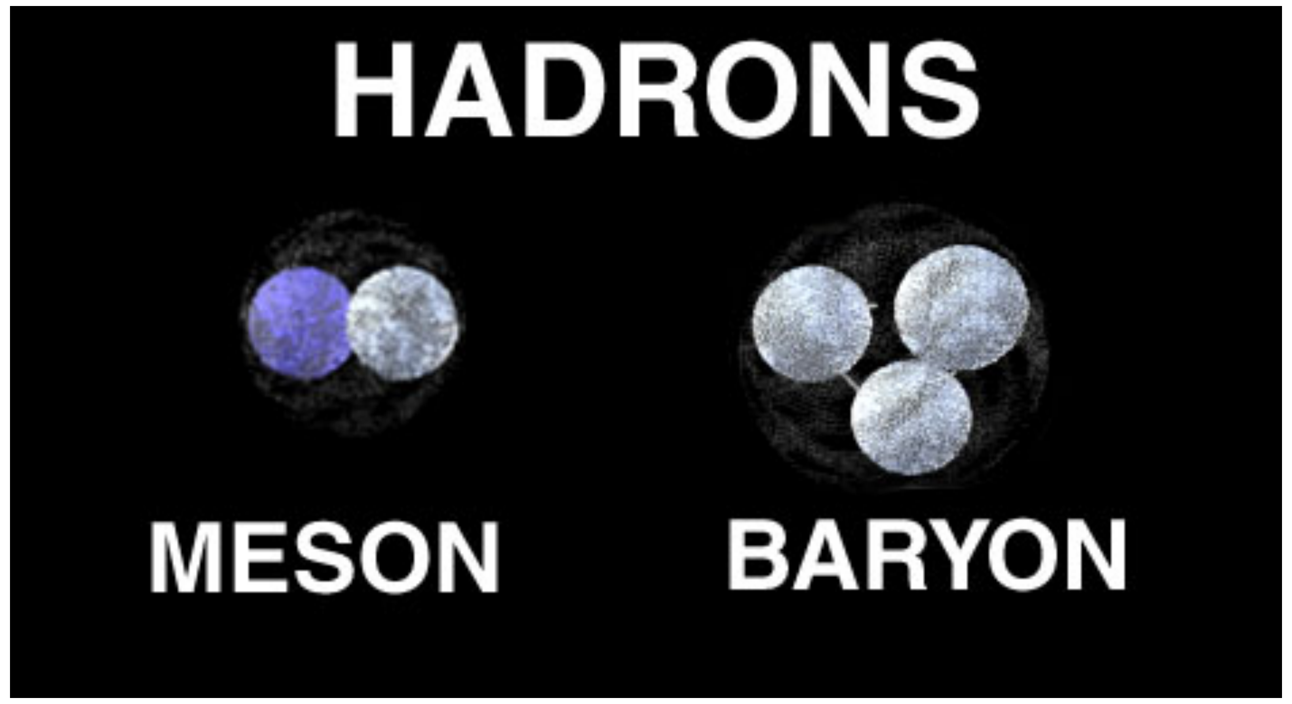


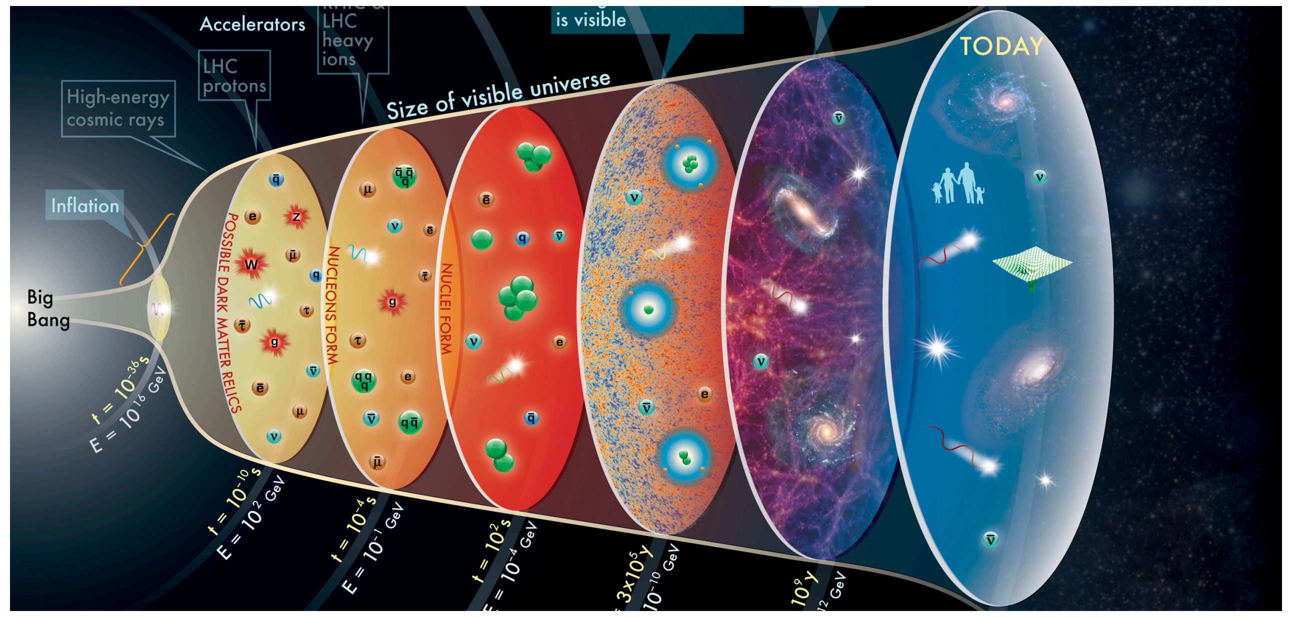

- The **visible matter** of the Universe is mainly made of baryons.
- Baryons play an important role in the **evolution of the Universe**, such as baryogenesis and big-bang nucleosynthesis.

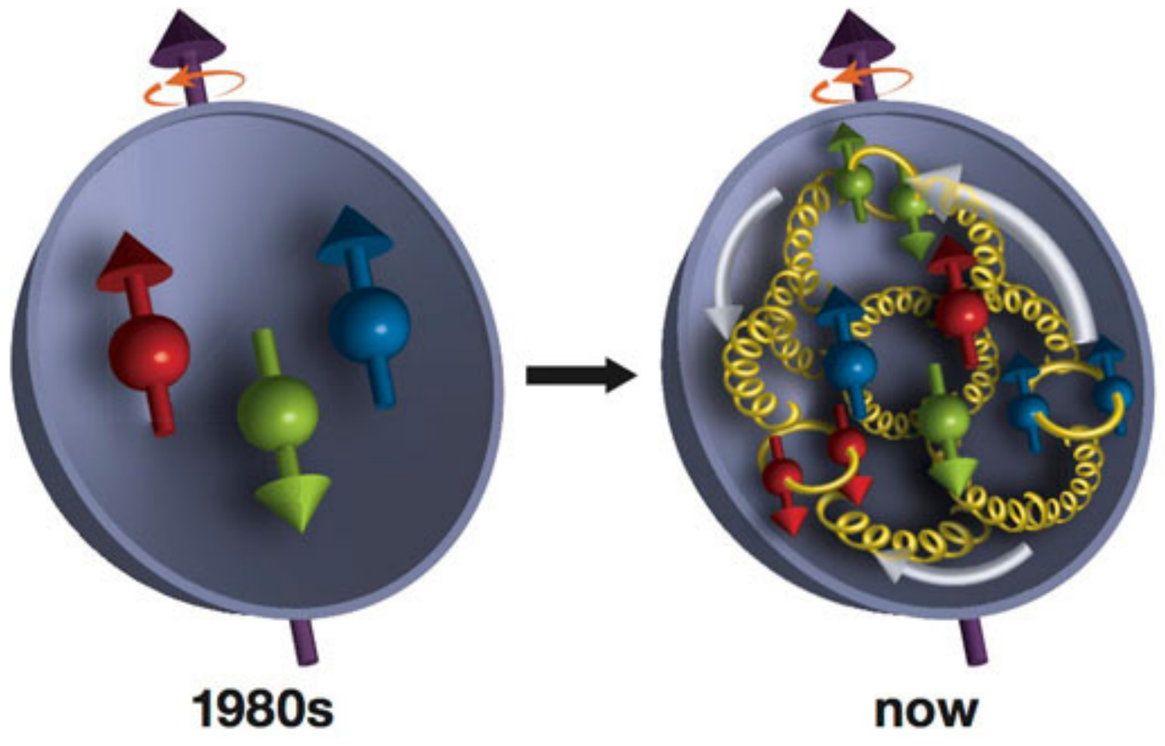


# Baryon physics

- The **visible matter** of the Universe is mainly made of baryons.
- Baryons play an important role in the **evolution of the Universe**, such as baryogenesis and big-bang nucleosythesis.
- However, our knowledge on the basic nucleon are even limited.
- The **mass and spin puzzles** of nucleons.
- Related to the **inner structures** of hadrons and **perturbative and non-perturbative QCD** dynamics.

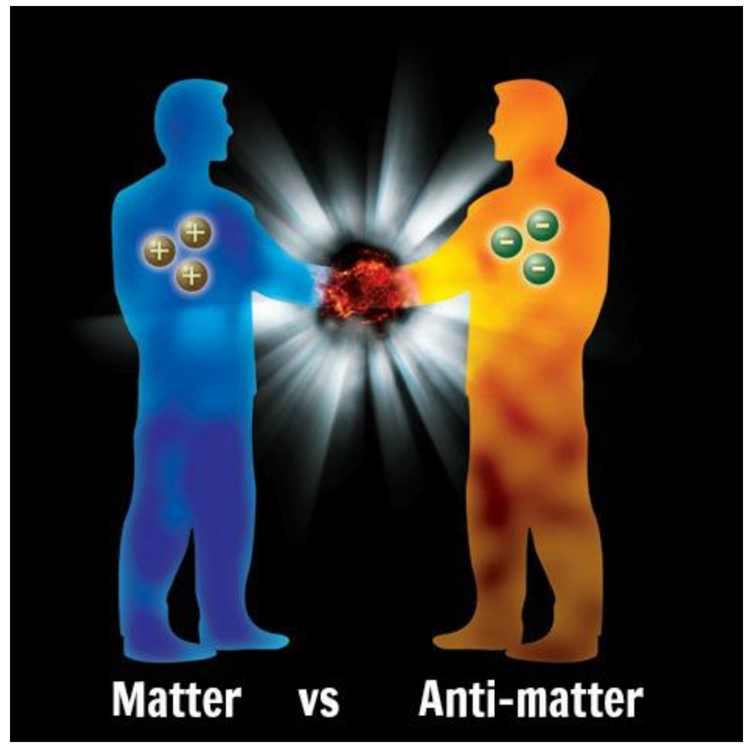


# CP violation in baryons

- Sakharov conditions for **Baryogenesis**:
  1) **baryon** number violation
  2) C and **CP violation**
  3) out of thermal equilibrium
- **CPV: SM < BAU. => new source of CPV, NP**
- CPV well established in K, B and D mesons,
  **but CPV never established in any baryon**
- **Comparison between precise prediction and measurement is helpful to test the SM and search for NP**




# Opportunities

- **LHCb is a baryon factory !!** **Large Production:** $\frac{f_{\Lambda_b}}{f_{u,d}} \sim 0.5 \rightarrow \frac{N_{\Lambda_b}}{N_{B^{0(-)}}} \sim 0.5$

# Opportunities

- **LHCb is a baryon factory !!** **Large Production:** $\frac{f_{\Lambda_b}}{f_{u,d}} \sim 0.5 \;\longrightarrow\; \frac{N_{\Lambda_b}}{N_{B^{0(-)}}} \sim 0.5$

- Precision of baryon CPV measurements has reached to the order of **1%** [LHCb, PLB2018]

$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (-3.5 \pm 1.7 \pm 2.0)\,\%\,, \quad A_{CP}(\Lambda_b^0 \to pK^-) = (-2.0 \pm 1.3 \pm 1.0)\,\%$$

- CPV in some B-meson decays are as large as **10%**:

$$A_{CP}(\overline{B}^0 \to \pi^+\pi^-) = -\,(32 \pm 4)\,\%\,, \quad A_{CP}(\overline{B}_s^0 \to K^+\pi^-) = +\,(21.3 \pm 1.7)\,\%$$

- **It can be expected that CPV in b-baryons might be observed soon !!**

# Opportunities

- **LHCb is a baryon factory !! Large Production:** $\frac{f_{\Lambda_b}}{f_{u,d}} \sim 0.5 \;\Rightarrow\; \frac{N_{\Lambda_b}}{N_{B^{0(-)}}} \sim 0.5$

- Precision of baryon CPV measurements has reached to the order of **1%** [LHCb, PLB2018]

$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (-3.5 \pm 1.7 \pm 2.0)\,\%\,, \quad A_{CP}(\Lambda_b^0 \to pK^-) = (-2.0 \pm 1.3 \pm 1.0)\,\%$$

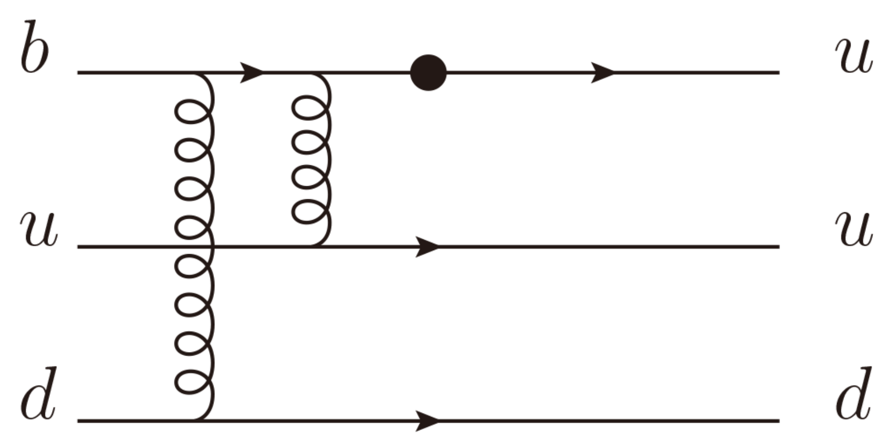
- CPV in some B-meson decays are as large as **10%**:

$$A_{CP}(\overline{B}^0 \to \pi^+\pi^-) = -\,(32 \pm 4)\,\%\,, \quad A_{CP}(\overline{B}_s^0 \to K^+\pi^-) = +\,(21.3 \pm 1.7)\,\%$$

- **It can be expected that CPV in b-baryons might be observed soon !!**

- Baryons have non-zero spin, with more kinematic information for measurements.

# Challenges




## 1. QCD dynamics

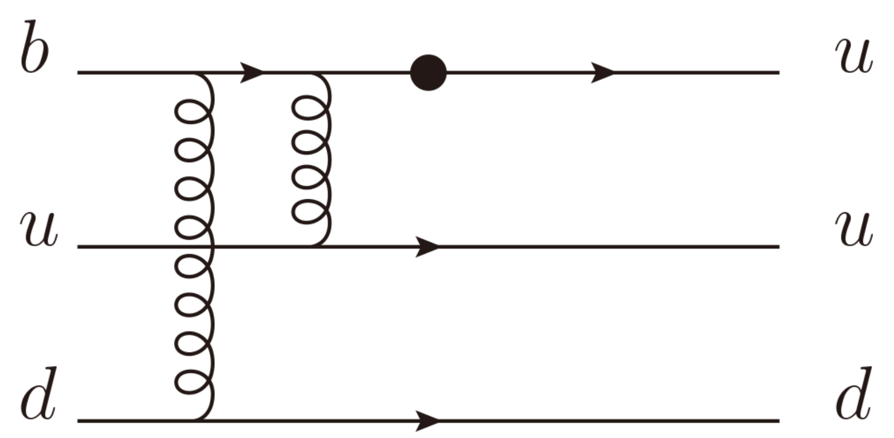
- One more energetic quark, one more hard gluon.

  Counting rule of power expansion is violated by $\alpha_s$ . More is different.

- Progresses have been made for PQCD.

## 2. Measurements

# Challenges



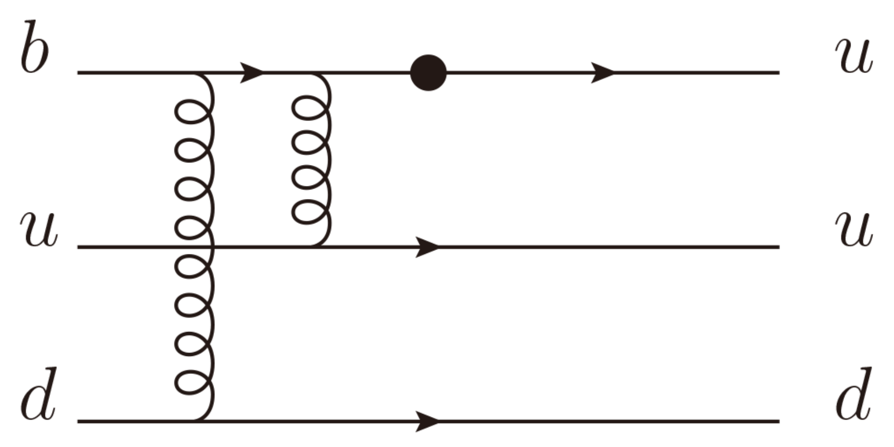

## 1. QCD dynamics

- One more energetic quark, one more hard gluon.
  Counting rule of power expansion is violated by $\alpha_s$ . More is different.
- Progresses have been made for PQCD.

## 2. Measurements

- Much less measurable processes, since only proton detectable for baryons.
  Low efficiency for hyperons whose lifetimes are too long.

# Challenges



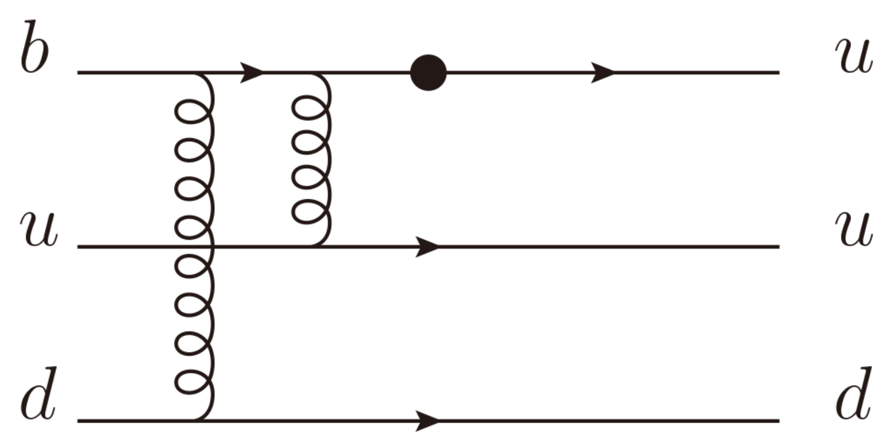

## 1. QCD dynamics

- One more energetic quark, one more hard gluon.
  Counting rule of power expansion is violated by $\alpha_s$ . More is different.
- Progresses have been made for PQCD.

## 2. Measurements

- Much less measurable processes, since only proton detectable for baryons.
  Low efficiency for hyperons whose lifetimes are too long.
- **Strong phases** is process dependent. $a_{CP}^{\rm dir} \propto \sin\delta_s \sin\phi_w$ is small if $\delta_s$ is small.

# Challenges




## 1. QCD dynamics

- One more energetic quark, one more hard gluon.
  Counting rule of power expansion is violated by $\alpha_s$ . More is different.
- Progresses have been made for PQCD.

## 2. Measurements

- Much less measurable processes, since only proton detectable for baryons.
  Low efficiency for hyperons whose lifetimes are too long.
- **Strong phases** is process dependent. $a_{CP}^{\mathrm{dir}} \propto \sin\delta_s \sin\phi_w$ is small if $\delta_s$ is small.
- **Observables:** T-odd triple products $(\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_3$ , $3\sigma$ signal in $\Lambda_b \to p\pi\pi\pi$[LHCb2017].
  Defined by kinematics, but unclear relation to the decay amplitudes.
  No way for theoretical explanations and predictions.

# T-odd triple-product asymmetries

- **T violation**
  - T violation implies CP violation, under CPT theorem.
  - However, time reversal cannot be really measured in a decay process in practice.

# T-odd triple-product asymmetries

- **T violation**
  - T violation implies CP violation, under CPT theorem.
  - However, time reversal cannot be really measured in a decay process in practice.
- **T-odd operators are still helpful**
  - Momentum $\vec{p}$ and spin $\vec{s}$ are odd under T operation. T-odd triple product: $(\vec{s}_1 \times \vec{s}_2) \cdot \vec{p}$
  - Example (1): $\vec{s}_i \times \vec{s}_f \cdot \vec{p}$ measures the $\beta$ parameter in $\Lambda \to p\pi$ [Lee, Yang, 1957]

    It was found that $a_{CP}^{\beta} \propto \beta + \bar{\beta} \propto \cos\delta_s \sin\phi_w$ [Donoghue, Pakvasa, 1985]

# T-odd triple-product asymmetries

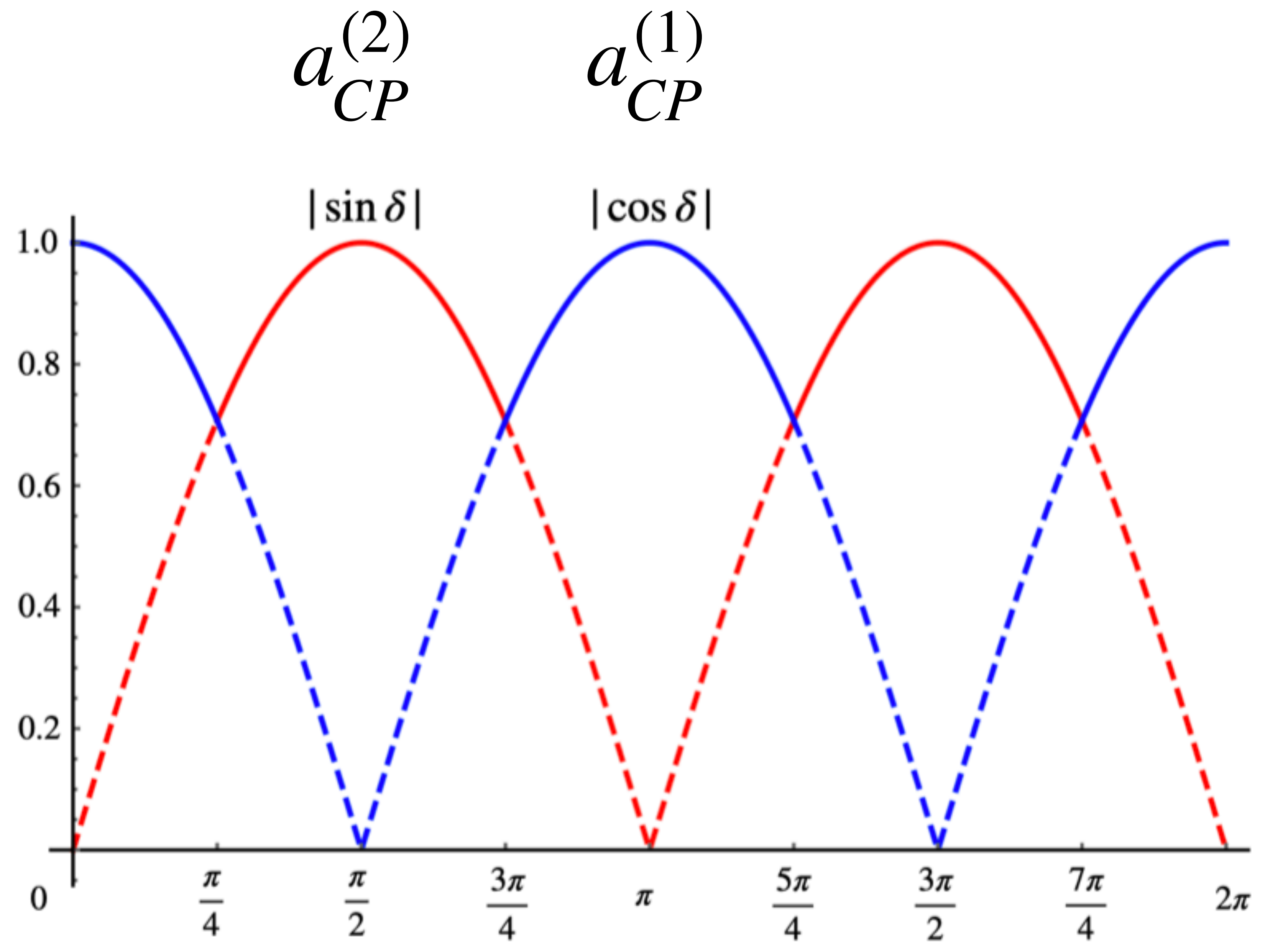
- **T violation**
  - T violation implies CP violation, under CPT theorem.
  - However, time reversal cannot be really measured in a decay process in practice.
- **T-odd operators are still helpful**
  - Momentum $\vec{p}$ and spin $\vec{s}$ are odd under T operation. T-odd triple product: $(\vec{s}_1 \times \vec{s}_2) \cdot \vec{p}$
  - Example (1): $\vec{s}_i \times \vec{s}_f \cdot \vec{p}$ measures the $\beta$ parameter in $\Lambda \to p\pi$ [Lee, Yang, 1957]

    It was found that $a_{CP}^{\beta} \propto \beta + \bar{\beta} \propto \cos\delta_s \sin\phi_w$ [Donoghue, Pakvasa, 1985]
  - Example (2): It was proposed to measure $A_B \propto N(\vec{p} \cdot \vec{\epsilon}_1 \times \vec{\epsilon}_2 > 0) - N(\vec{p} \cdot \vec{\epsilon}_1 \times \vec{\epsilon}_2 < 0)$

    in $B \to VV$, whose CPV is $A_B + A_{\overline{B}} \propto \cos\delta_s \sin\phi_w$ [Valencia, 1989]

# Complementary: $\cos\delta_s$ vs $\sin\delta_s$

- Precise prediction on strong phases is far beyond control currently
- Complimentary CPV observables proportional to $\sin\delta$ or $\cos\delta$ cover all the $(0,\ 2\pi)$ region
- Whatever the strong phase is, either $|\sin\delta|$ or $|\cos\delta|$ would be larger than 0.7 which is large enough for measurements




- It might reduce the sensitivity of CPV on the strong phase, avoid the theoretical uncertainties on strong phases, and then increase the possibility of observation of baryon CPV

$$a_{CP}^{(1)} \propto \cos\delta_s \sin\phi_w$$

$$a_{CP}^{(2)} \propto \sin\delta_s \sin\phi_w$$

# Why $\cos\delta_s$ ? What conditions?

- To find the complementary observables, we should know
  - why are some CPV observables proportional to $\cos\delta_s$?
  - what are the conditions to construct such observables?

# Why $\cos\delta_s$ ? What conditions?

- To find the complementary observables, we should know
  - why are some CPV observables proportional to $\cos\delta_s$?
  - what are the conditions to construct such observables?
- **Why $\cos\delta_s$?**
  - T-odd operator $Q_-$: $TQ_-T^{-1} = -Q_-$
  - T is anti-unitary, $T = UK$ with $U$ a unitary operator and $K$ a complex conjugation

# Why $\cos \delta_s$ ? What conditions?

- To find the complementary observables, we should know
  - why are some CPV observables proportional to $\cos \delta_s$?
  - what are the conditions to construct such observables?
- **Why $\cos \delta_s$?**
  - T-odd operator $Q\_$: $TQ\_T^{-1} = -Q\_$
  - T is anti-unitary, $T = UK$ with $U$ a unitary operator and $K$ a complex conjugation
- **Two conditions:**

  (1) For a basis of final states and a unitary transformation so that $UT|\psi_n\rangle = e^{i\alpha}|\psi_n\rangle$

  (2) $Q\_$ is invariant under this unitary transformation, $UQ\_U^\dagger = Q\_$

# Why $\cos\delta_s$ ? What conditions?

- **Proof:**

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

pure imaginary

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

# Why $\cos\delta_s$ ? What conditions?

- **Proof:**

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

pure imaginary

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

$$\langle f|Q_-|f\rangle \propto \sum_{m,n} Im(A_m^* A_n)$$

# Why $\cos\delta_s$ ? What conditions?

- **Proof:**

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

pure imaginary

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

$$\langle f|Q_-|f\rangle \propto \sum_{m,n} Im(A_m^* A_n)$$

$$A_{\rm CP}^{Q_-} \equiv \frac{\langle f|Q_-|f\rangle - \langle\bar f|\bar Q_-|\bar f\rangle}{\langle f|Q_-|f\rangle + \langle\bar f|\bar Q_-|\bar f\rangle} \propto \sum_{m,n} Im(A_m^* A_n - \bar A_m^* \bar A_n) \propto \cos\delta_s \sin\phi_w$$

*Quod erat demonstrandum.*

# Complementary: $\cos\delta_s$ vs $\sin\delta_s$

$$A_{\rm CP}^{Q_-} \equiv \frac{\langle f|Q_-|f\rangle - \langle \bar{f}|\bar{Q}_-|\bar{f}\rangle}{\langle f|Q_-|f\rangle + \langle \bar{f}|\bar{Q}_-|\bar{f}\rangle} \propto \sum_{m,n} Im(A_m^* A_n - \bar{A}_m^* \bar{A}_n) \propto \cos\delta_s \sin\phi_w$$

- Compared to the direct CPV

$$A_{CP}^{\rm dir} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \propto Re(A_1^* A_2 - \bar{A}_1^* \bar{A}_2) \propto \sin\delta_s \sin\phi_w$$

$$A = A_1 + A_2$$

# Complementary: $\cos\delta_s$ vs $\sin\delta_s$

$$A_{\rm CP}^{Q_-} \equiv \frac{\langle f|Q_-|f\rangle - \langle \bar{f}|\bar{Q}_-|\bar{f}\rangle}{\langle f|Q_-|f\rangle + \langle \bar{f}|\bar{Q}_-|\bar{f}\rangle} \propto \sum_{m,n} Im(A_m^* A_n - \bar{A}_m^* \bar{A}_n) \propto \cos\delta_s \sin\phi_w$$

- Compared to the direct CPV

$$A_{CP}^{\rm dir} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \propto Re(A_1^* A_2 - \bar{A}_1^* \bar{A}_2) \propto \sin\delta_s \sin\phi_w$$

$$A = A_1 + A_2$$

- T-even operator, $TQ_+T^{-1} = Q_+$

$$A_{CP}^{Q_+} \propto \sum_{m,n} Re(A_m^* A_n - \bar{A}_m^* \bar{A}_n) \propto \sin\delta_s \sin\phi_w$$

**Complementary!!**

# CPV induced by T-odd and T-even

$$a_{CP}^{\text{T-odd}} \propto \sum_{m,n} Im(A_m^* A_n - \bar{A}_m^* \bar{A}_n) \propto \cos\delta_s \sin\phi_w$$

$$a_{CP}^{\text{T-even}} \propto \sum_{m,n} Re(A_m^* A_n - \bar{A}_m^* \bar{A}_n) \propto \sin\delta_s \sin\phi_w$$

- Example: $\Lambda \to p\pi$, Lee-Yang decay-asymmetry parameter

T-even: $\vec{s}_i \cdot \vec{p}$ $\qquad \alpha \propto Re[S^*P]$ $\qquad a_{CP}^{\alpha} = \dfrac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}} \propto \sin\delta$

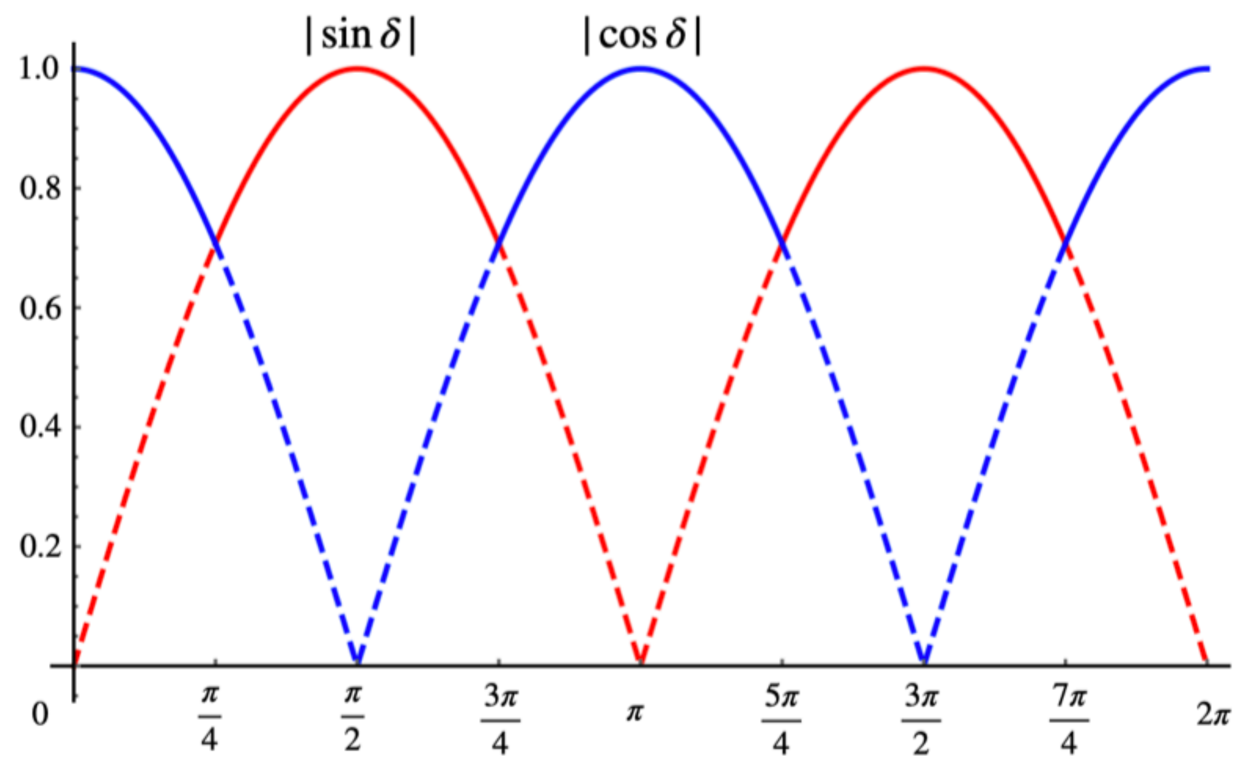
T-odd: $(\vec{s}_i \times \vec{s}_f) \cdot \vec{p}$ $\qquad \beta \propto Im[S^*P]$ $\qquad a_{CP}^{\beta} = \dfrac{\beta + \overline{\beta}}{\beta - \overline{\beta}} \propto \cos\delta$

complimentary

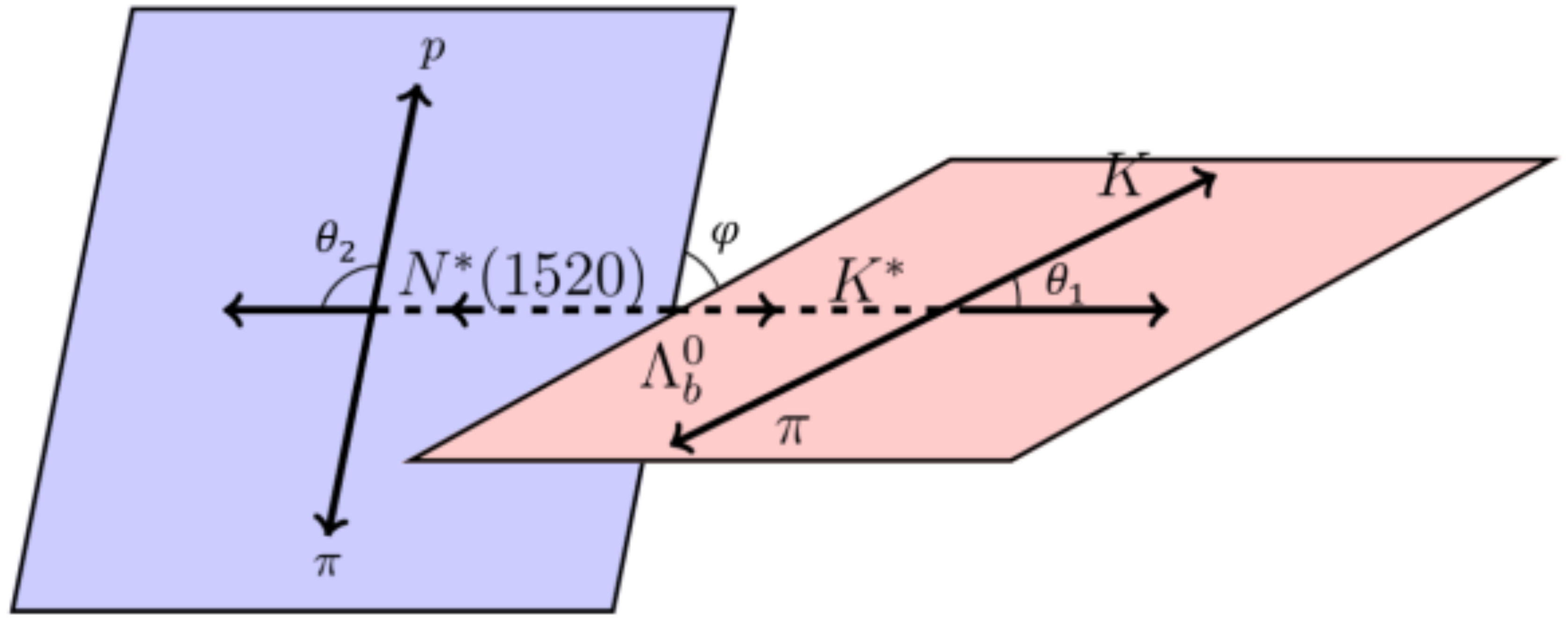
# Angular distributions

- Complementary observables can be constructed in the angular distributions

- Example: $\Lambda_b \to N^*(3/2^+)K^*,\ N^*(3/2^+)\rho$

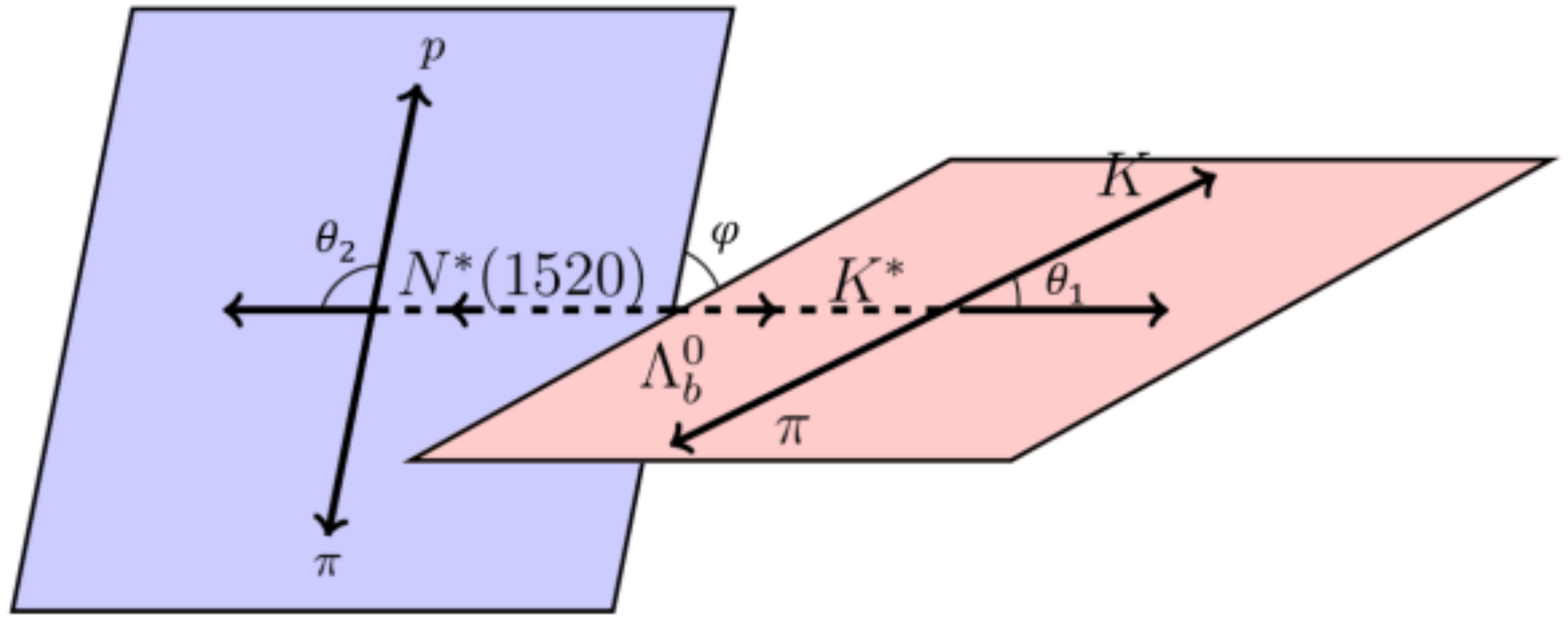



$$
\begin{aligned}
\frac{d\Gamma}{dc_1\,dc_2\,d\varphi} \propto\; & -\frac{s_1^2 s_2^2}{\sqrt{3}}\,\mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin 2\varphi \\
& + \frac{s_1^2 s_2^2}{\sqrt{3}}\,\mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos 2\varphi \\
& - \frac{4 s_1 c_1 s_2 c_2}{\sqrt{6}}\,\mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin\varphi \\
& + \frac{4 s_1 c_1 s_2 c_2}{\sqrt{6}}\,\mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos\varphi
\end{aligned}
$$



# Angular distributions

$$
\begin{aligned}
\frac{d\Gamma}{dc_1\,dc_2\,d\varphi} \propto\; & -\frac{s_1^2 s_2^2}{\sqrt{3}} \mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin 2\varphi \\
& + \frac{s_1^2 s_2^2}{\sqrt{3}} \mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos 2\varphi \\
& - \frac{4 s_1 c_1 s_2 c_2}{\sqrt{6}} \mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin\varphi \\
& + \frac{4 s_1 c_1 s_2 c_2}{\sqrt{6}} \mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos\varphi
\end{aligned}
$$

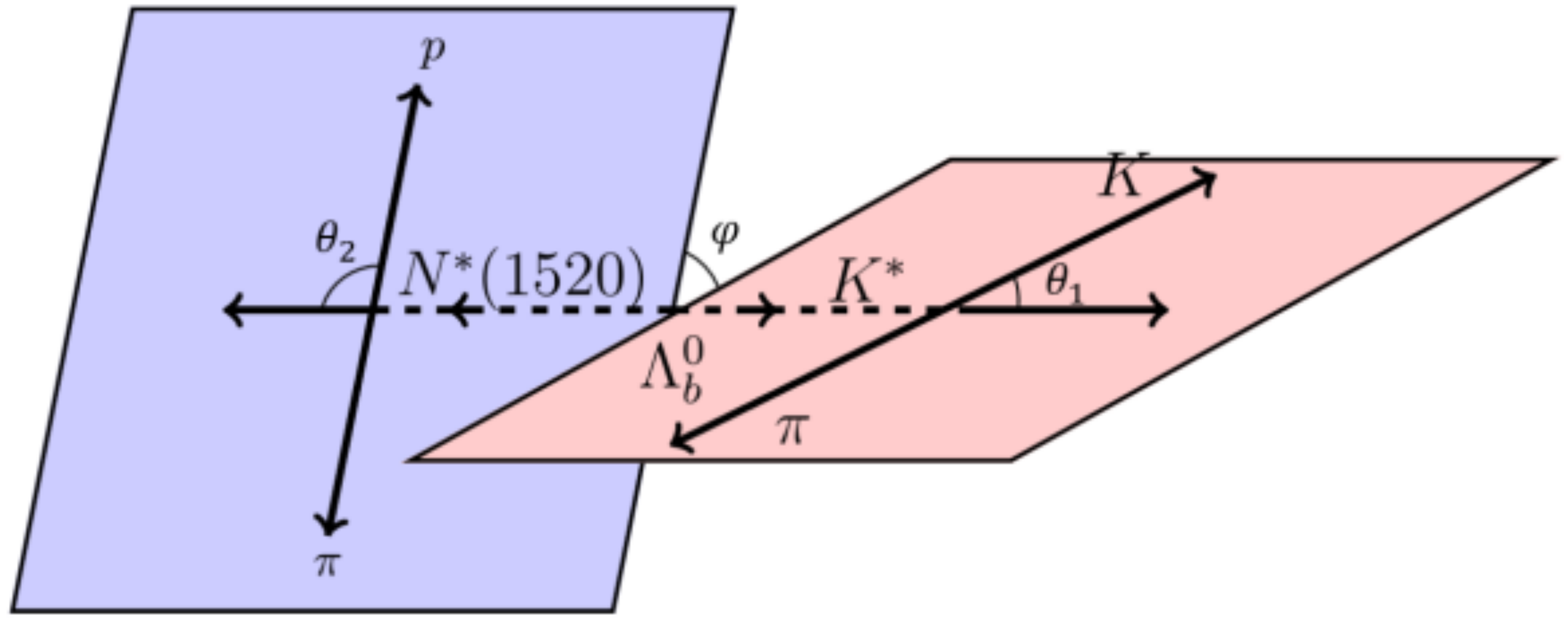



$$\sin\varphi = (\vec{n}_a \times \vec{n}_b)\cdot\hat{p}_b = \vec{n}_a\cdot(\vec{n}_b\times\hat{p}_b) \propto (\vec{p}_1\times\vec{p}_2)\cdot\vec{p}_4$$

$$\sin 2\varphi = 2\sin\varphi\cos\varphi \propto [(\vec{p}_1\times\vec{p}_2)\cdot(\vec{p}_3\times\vec{p}_4)][(\vec{p}_1\times\vec{p}_2)\cdot\vec{p}_4].$$

# Angular distributions

$$
\begin{aligned}
\frac{d\Gamma}{dc_1\,dc_2\,d\varphi} \propto & -\frac{s_1^2 s_2^2}{\sqrt{3}}\mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin 2\varphi \\
& + \frac{s_1^2 s_2^2}{\sqrt{3}}\mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos 2\varphi \\
& - \frac{4s_1c_1s_2c_2}{\sqrt{6}}\mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin\varphi \\
& + \frac{4s_1c_1s_2c_2}{\sqrt{6}}\mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos\varphi
\end{aligned}
$$




$$\sin\varphi = (\vec{n}_a \times \vec{n}_b)\cdot\hat{p}_b = \vec{n}_a\cdot(\vec{n}_b \times \hat{p}_b) \propto (\vec{p}_1 \times \vec{p}_2)\cdot\vec{p}_4$$

$$\sin 2\varphi = 2\sin\varphi\cos\varphi \propto [(\vec{p}_1 \times \vec{p}_2)\cdot(\vec{p}_3 \times \vec{p}_4)][(\vec{p}_1 \times \vec{p}_2)\cdot\vec{p}_4].$$

- Triple-product of momentum, $(\vec{p}_1 \times \vec{p}_2)\cdot\vec{p}_3$, is not good
- Angular distributions of resonant contributions are necessary. It is more clear in theory.

# Summary and outlook

- Baryon physics is an opportunity of heavy flavor physics at the current stage.