

CP asymmetries in Strange Baryon Decays^{*}

I.I. Bigi^{2;1)} Xian-Wei Kang(康现伟)^{1,3,4;2)} Hai-Bo Li(李海波)^{4,5;3)}¹ College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875² Department of Physics, University of Notre Dame du Lac, Notre Dame, IN 46556³ Institute of Physics, Academia Sinica, Taipei 115⁴ Institute of High Energy Physics, Beijing 100049⁵ University of Chinese Academy of Science, Beijing 100049

Abstract: While indirect and direct CP violation (CPV) has been established in the decays of strange and beauty mesons, no CPV has yet been found for baryons. There are different paths to finding CP asymmetry in the decays of strange baryons; they are all highly non-trivial. The HyperCP Collaboration has probed CPV in the decays of single Ξ and Λ [1]. We discuss future lessons from e^+e^- collisions at BESIII/BEPCII: probing decays of *pairs* of strange baryons, namely Λ , Σ and Ξ . Realistic goals are to learn about non-perturbative QCD. One can hope to find CPV in the decays of strange baryons; one can also dream of finding the impact of New Dynamics. We point out that an important new era will start with the BESIII/BEPCII data accumulated by the end of 2018. This also supports new ideas to trigger $J/\psi \rightarrow \bar{\Lambda}\Lambda$ at the LHCb collaboration.

Keywords: CP asymmetry, J/ψ decay, hyperon decay, BESIII/BEPCII

PACS: 11.30.Er, 13.25.Gv, 13.30.Eg **DOI:** 10.1088/1674-1137/42/1/013101

1 The landscape

CP violation (CPV) was found in $K_L \rightarrow \pi^+\pi^-$ in 1964 [2] (it was actually ‘predicted’ by L.B. Okun in 1963 [3]), and tiny *direct* CPV was found from the differences of $K_L \rightarrow \pi^+\pi^-$ vs. $K_L \rightarrow \pi^0\pi^0$ in the 1990s by the NA31/NA48 and KTeV experiments. The most recent analyses given by the Particle Data Group (PDG2016) [4] are:

$$\begin{aligned} |\epsilon_K|_{\text{exp.}} &= (2.228 \pm 0.011) \cdot 10^{-3}, \\ \text{Re}(\epsilon'/\epsilon_K)_{\text{exp.}} &= (1.66 \pm 0.23) \cdot 10^{-3}; \end{aligned} \quad (1)$$

i.e., CPV in $\Delta S=1$ has been found around the scale of $5 \cdot 10^{-6}$. The impact of New Dynamics (ND) can possibly hide in the uncertainties in *direct* CPV. The Buras team gives for the Standard Model [5]:

$$\text{Re}(\epsilon'/\epsilon_K)_{\text{“Buras”}} = (0.86 \pm 0.32) \cdot 10^{-3}. \quad (2)$$

Actually, it has been argued by Buras et al. for a long time that the SM cannot produce the value given by the

data.

We have now obtained the first result from a LQCD group [6]:

$$\text{Re}(\epsilon'/\epsilon_K)_{\text{LQCD}} = (0.138 \pm 0.515 \pm 0.443) \cdot 10^{-3}. \quad (3)$$

Obviously we need more lattice data. So far, it is not clear which lesson we can learn here: does it mean that these data are consistent with what the SM gives us, or it is a sign of the impact of ND?

Soon after 1964 it was hoped to probe CPV in the transitions of strange baryons. This is a huge challenge. However, the goal is so important that we should not give up. Present experimental limits are high above the level at which one can even think about the possible impact of ND. In 1998 several situations were proposed, in particular for CP observables in $B^0(t) \rightarrow$ hyperon-antihyperon, where CPV could be found based on predictions at that time [7].

The landscape of fundamental dynamics has changed very much since then. Neutrinos are massless in the SM,

Received 26 September 2017, Published online 29 November 2017

^{*} Supported by National Science Foundation (PHY-1520966), National Natural Science Foundation of China (11335009, 11125525), Joint Large-Scale Scientific Facility Funds of the NSFC and CAS (U1532257), the National Key Basic Research Program of China (2015CB856700), Key Research Program of Frontier Sciences, CAS, (QYZDJ-SSW-SLH003), XWK’s work is also supported by MOST (Taiwan) (104-2112-M-001-022)

1) E-mail: ibigi@nd.edu

2) E-mail: kxw198710@126.com

3) E-mail: lihb@ihep.ac.cn



Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Article funded by SCOAP³ and published under licence by Chinese Physical Society and the Institute of High Energy Physics of the Chinese Academy of Sciences and the Institute of Modern Physics of the Chinese Academy of Sciences and IOP Publishing Ltd

but neutrino oscillations have been discovered. The SM produces true large CP asymmetries in $\Delta B \neq 0$ transitions, and indeed the BABAR/Belle Collaborations have found this with $B^0 \rightarrow J/\psi K_S$ and other systems, but no non-zero values of CP asymmetries have yet been established in the decays of baryons in general, beyond the huge asymmetry in matter vs. anti-matter in our Universe (or our ‘existence’). However, evidence has been seen by the LHCb experiment in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ for regional CPV [8]. Obviously we are talking about direct CPV in $\Delta B = 1$. In two-body final states of beauty mesons the usual scale is ~ 0.1 ; for Λ_b^0 decays it suggests that the regional scale is sizably enhanced. Can this happen also for strange baryons?

The final states are mostly two-body in the decays of strange baryons. There are two classes of transitions, as given in the PDG2016 data:

1) Re-scattering gives a sizable impact, and it is obvious for Λ and Σ^+ :

$$\begin{aligned} \text{BR}(\Lambda \rightarrow p\pi^-) &= 0.639 \pm 0.005 \\ \text{BR}(\Lambda \rightarrow n\pi^0) &= 0.358 \pm 0.005 \\ \text{BR}(\Lambda \rightarrow p\pi^-\gamma) &= (8.4 \pm 1.4) \times 10^{-4} \\ \text{BR}(\Sigma^+ \rightarrow p\pi^0) &= 0.5157 \pm 0.0030 \\ \text{BR}(\Sigma^+ \rightarrow n\pi^+) &= 0.4831 \pm 0.0030 \end{aligned} \quad (4)$$

CPT invariance is ‘usable’, telling us about average asymmetry¹⁾. These widths are basically produced with two hadrons, thus: $\Gamma(\Lambda \rightarrow p\pi^-) + \Gamma(\Lambda \rightarrow n\pi^0) \simeq \Gamma(\bar{\Lambda} \rightarrow \bar{p}\pi^+) + \Gamma(\bar{\Lambda} \rightarrow \bar{n}\pi^0)$; likewise for Σ^+ . Therefore,

$$A_{CP}(\Lambda \rightarrow p\pi^-) \simeq -A_{CP}(\Lambda \rightarrow n\pi^0) \quad (5)$$

$$A_{CP}(\Sigma^+ \rightarrow p\pi^0) \simeq -A_{CP}(\Sigma^+ \rightarrow n\pi^+). \quad (6)$$

The goal is to establish CP asymmetry in $\Lambda \rightarrow p\pi^-$ and in $\Sigma^+ \rightarrow p\pi^0$. To find it also in $\Lambda \rightarrow n\pi^0$ & $\Sigma^+ \rightarrow n\pi^+$ would be nice, but not important. The situations are very different for the decays of Λ_b^0 , where the final states are mostly many-body.

For the decay $\Lambda \rightarrow p\pi^-$ without the spins of the baryons included, there is only one observable, namely a number. The data depend on production asymmetries in $\Lambda \rightarrow p\pi^-$ vs. $\bar{\Lambda} \rightarrow \bar{p}\pi^+$. That is not a problem for e^+e^- annihilations for the BESIII experiment or for pp collisions; however, the situation is quite different for pp collisions from LHCb data.

2) The situation is more complex: the impact of re-scattering is not obvious, when one cannot use polarized

baryons, as one can see in the branching ratios:

$$\begin{aligned} \text{BR}(\Sigma^- \rightarrow n\pi^-) &= (99.848 \pm 0.005) \times 10^{-2} \\ \text{BR}(\Sigma^- \rightarrow n\pi^-\gamma) &= (4.6 \pm 0.6) \times 10^{-4} \\ \text{BR}(\Xi^0 \rightarrow \Lambda\pi^0) &= (99.524 \pm 0.012) \times 10^{-2} \\ \text{BR}(\Xi^0 \rightarrow \Lambda\gamma) &= (1.17 \pm 0.07) \times 10^{-3} \\ \text{BR}(\Xi^- \rightarrow \Lambda\pi^-) &= (99.887 \pm 0.035) \times 10^{-2} \\ \text{BR}(\Xi^- \rightarrow \Sigma^-\gamma) &= (1.27 \pm 0.23) \times 10^{-4} \end{aligned} \quad (7)$$

Successfully probing CPV in strange baryon transitions is a true challenge. Previous predictions have been made based on the SM [10, 11]:

$$A_{CP}(\Lambda \rightarrow p\pi^-) \sim (0.05 - 1.2) \cdot 10^{-4} \quad (8)$$

$$A_{CP}(\Xi^- \rightarrow \Lambda\pi^-) \sim (0.2 - 3.5) \cdot 10^{-4} \quad (9)$$

A later SM prediction was made by combining Λ and Ξ decays [12]: $-0.5 \cdot 10^{-4} \leq A_{\Lambda\Xi} \equiv \frac{\alpha_{\Lambda\alpha_{\Xi}} - \alpha_{\Lambda}\alpha_{\Xi}}{\alpha_{\Lambda\alpha_{\Xi}} + \alpha_{\Lambda}\alpha_{\Xi}} \leq 0.5 \cdot 10^{-4}$.

The HyperCP experiment²⁾ searched for CPV using a 800 GeV proton beam on a Cu target [1]:

$$A_{\Lambda\Xi} = (0.0 \pm 5.1 \pm 4.4) \cdot 10^{-4}. \quad (10)$$

It is still not clear whether the theoretical uncertainties are included correctly.

However, two points might help to reach our goal:

1) The BESIII collaboration can probe *pairs* of strange baryons. We will discuss that in Section 2.

2) Future BESIII analyses, namely $e^+e^- \rightarrow J/\psi$ with the unusual narrow resonance, will be enhanced as a source of strange baryons compared to PDG2016:

$$\begin{aligned} \text{BR}(J/\psi \rightarrow \bar{\Lambda}\Lambda) &= (1.61 \pm 0.15) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow \Lambda\bar{\Lambda}\pi^+\pi^-) &= (4.3 \pm 1.0) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow \Lambda\bar{p}K^+/\bar{\Lambda}pK^-) &= (0.89 \pm 0.16) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow \bar{\Sigma}^+\Sigma^-/\bar{\Sigma}^-\Sigma^+) &= (1.50 \pm 0.24) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow \bar{\Xi}^0\Xi^0) &= (1.20 \pm 0.24) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow \bar{\Xi}^+\Xi^-/\bar{\Xi}^-\Xi^+) &= (0.86 \pm 0.11) \cdot 10^{-3} \end{aligned} \quad (11)$$

These rates are produced by strong forces, and they can be compared with

$$\begin{aligned} \text{BR}(J/\psi \rightarrow \bar{p}p) &= (2.120 \pm 0.029) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow \bar{p}p\pi^+\pi^-) &= (6.0 \pm 0.5) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow p\bar{n}\pi^-) &= (2.12 \pm 0.09) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow \bar{n}n) &= (2.09 \pm 0.16) \cdot 10^{-3} \end{aligned} \quad (12)$$

The final state interactions (FSI) show impact, although our community is so far not able to describe it quantitatively.

We will discuss in some detail what we can learn about fundamental dynamics including CP asymmetries.

1) The impact of CPT invariance goes well beyond the same mass and width, as discussed in Ref. [9].

2) The authors of this proposal ‘HyperCP: Search for CP Violation in Charged-Hyperon Decays’ quoted Bigi and Sanda from their recent book CP Violation: ‘We are willing to stake our reputation on the prediction that dedicated and comprehensive studies of CP violation will reveal the presence of New Physics.’ At least one of the co-authors of this paper agrees.

It is not trivial at all, and as usual there is a price for the prize.

2 CP asymmetries in $J/\psi \rightarrow$ pair of strange baryons

In this section, we mostly discuss the decays of J/ψ to final states with only two strange baryons. We also include special cases, in Section 2.6.

First, we go back to the history of discrete symmetries, in particular ‘‘parity conservation, charge-conjugation invariance, and time-reversal invariance’’ in the decays of hyperons [13]. PDG2016 gives a T -odd moment $\alpha_\Lambda = 0.642 \pm 0.013$ for the decay of $\Lambda \rightarrow p\pi^-$, while $\alpha_{\bar{\Lambda}} = -0.71 \pm 0.08$ for $\bar{\Lambda} \rightarrow \bar{p}\pi^+$. The most important data for this come from the BES Collaboration: $\alpha_{\bar{\Lambda}} = -0.755 \pm 0.083 \pm 0.063$ [14].

Published 2010 data from the BES Collaboration are based on $5.8 \times 10^7 J/\psi$ events [14], giving 10 % accuracy. To reach the level of $\mathcal{O}(1\%)$ is not trivial. However, we expect that our community will have data to reach 0.1 % level by the end of 2018. We have to be realistic: this prize cannot be reached easily. On the other hand, it would be very pessimistic to suggest we will follow the path of the Higgs boson, namely searching for 40 years.

The BESIII detector has already collected $\simeq 1.3 \times 10^9$ J/ψ events, and it is expected to have close to 10^{10} J/ψ events by the end of 2018 [15]. The situation is more complex for $\text{BR}(J/\psi \rightarrow \Xi\Xi \rightarrow [\bar{\Lambda}\pi][\Lambda\pi])$, which we will discuss in Section 2.5.

Further competition will arrive from the LHCb collaboration by probing $J/\psi \rightarrow \bar{\Lambda}\Lambda$; the challenge comes in triggering for this channel¹⁾.

2.1 General statements about first steps

First we describe the ‘landscape’ and the tools one can use. The super narrow vector resonance J/ψ produces a connection of the spins of a pair of hyperons Y of Λ , Σ , and Ξ and final state X of p , Λ :

$$J/\psi \rightarrow \bar{Y}Y \rightarrow [\bar{X}\pi][X\pi] \quad (13)$$

One can measure T -odd moments:

$$\alpha_Y^{(X)} = \langle \vec{\sigma}_Y \cdot (\vec{\sigma}_X \times \vec{\pi}_X) \rangle, \alpha_{\bar{Y}}^{(\bar{X})} = \langle \vec{\sigma}_{\bar{Y}} \cdot (\vec{\sigma}_{\bar{X}} \times \vec{\pi}_{\bar{X}}) \rangle, \quad (14)$$

where $\vec{\sigma}$ and $\vec{\pi}$ describe the spins and the momenta of the baryons in the rest frames of Y/\bar{Y} . It is not surprising to find sizable or even large non-zero values of T -odd moments; below we will give an example from data with large values. It shows the impact of final state interactions (FSI). Non-zero values of T -odd moments do *not* mean by themselves we have found T violation or CP violation using CPT invariance. However, one can probe

direct CP asymmetries

$$\langle A_{CP}^{(X)} \rangle = \frac{\alpha_Y^{(X)} + \alpha_{\bar{Y}}^{(\bar{X})}}{\alpha_Y^{(X)} - \alpha_{\bar{Y}}^{(\bar{X})}} \quad (15)$$

without polarized Y and \bar{Y} . The crucial point is to use the connection of the spin-1 of the initial state J/ψ with the final state with two spin-1/2. The goal is to find $\langle A_{CP}^{(X)} \rangle \neq 0$ without directly measuring polarization of Y/\bar{Y} and X/\bar{X} baryons and their correlations due to the very narrow resonance J/ψ in their production.

We measure correlations between the pair of final state baryons and pions. In the rest frame of J/ψ one can define $C_T = (\vec{p}_X \times \vec{p}_\pi) \cdot \vec{p}_{\bar{X}}$ and conjugate transitions $\bar{C}_T = (\vec{p}_{\bar{X}} \times \vec{p}_{\bar{\pi}}) \cdot \vec{p}_X$, and compare the event numbers (N) with positive and negative values

$$\langle A_T \rangle = \frac{N(C_T > 0) - N(C_T < 0)}{N(C_T > 0) + N(C_T < 0)} \quad (16)$$

$$\langle \bar{A}_T \rangle = \frac{N(\bar{C}_T > 0) - N(\bar{C}_T < 0)}{N(\bar{C}_T > 0) + N(\bar{C}_T < 0)}. \quad (17)$$

Thus

$$\mathcal{A}_T = \frac{1}{2} [\langle A_T \rangle + \langle \bar{A}_T \rangle] = \langle A_T \rangle \neq 0 \quad (18)$$

are observable CP asymmetries based on CPT invariance. We have taken a different convention for \bar{A}_T compared to Ref. [8].

One can compare to its charge-conjugate channel to get rid of a fake CP asymmetry induced by the FSI effect. However, the charge-conjugate of the process $J/\psi \rightarrow \Lambda\bar{\Lambda} \rightarrow [p\pi^-][\bar{p}\pi^+]$ considered here is itself; or it is an untagged sample that cannot be distinguished by experiment. Such a situation is, to some extent, different from a measurement of $D^0(\bar{D}^0) \rightarrow K\bar{K}\pi\pi/4\pi$.

The landscapes are quite different for $\Lambda \rightarrow p\pi^-$ and $\Sigma \rightarrow p\pi$ and even more so for $\Xi \rightarrow \Lambda\pi$, with many paths for transitions: $J/\psi \rightarrow \bar{\Lambda}\Lambda \rightarrow [\bar{p}\pi^+][p\pi^-]$; $J/\psi \rightarrow \bar{\Sigma}^-\Sigma^+ \rightarrow [\bar{p}\pi^0][p\pi^0]$; $J/\psi \rightarrow \bar{\Xi}^0\Xi^0 \rightarrow [\bar{\Lambda}\pi^0][\Lambda\pi^0]$; $J/\psi \rightarrow \bar{\Xi}^+\Xi^- \rightarrow [\bar{\Lambda}\pi^+][\Lambda\pi^-]$ ²⁾.

1) One can calibrate those transitions with $J/\psi \rightarrow \Delta(1232)\bar{\Delta}(1232)$, where CPV cannot appear.

2) That is not the end of the impact of strong resonances of $\Delta(1232)$ with width ~ 117 MeV and $N(1440)$ with width 250–450 MeV. They will affect the lessons we learn from future data about possible CP violations in the transitions of strange baryons.

3) The ‘‘duality’’ between the worlds of quarks and hadrons is very subtle, in particular close to the thresholds of resonances.

Here we estimate the sensitivities for measuring such observables using the collected J/ψ sample. By the end of 2018, 10^{10} J/ψ events will be accumulated by the BESIII experiment [15]. The detection efficiency for pions,

1) G. Punzi, private communication.

2) $M(\Lambda) \simeq 1116$ MeV; $M(\Sigma^+) \simeq 1189$ MeV; $M(\Xi^0) \simeq 1315$ MeV; $M(\Xi^-) \simeq 1322$ MeV.

protons, and kaons with momentum larger than 100 MeV can reach 98%. As for particle identification (PID), pions, kaons and protons can be distinguished with 3σ (three standard deviations) uncertainty below a momentum of 1.0 GeV. Considering the branching fractions of $J/\psi \rightarrow \Lambda\bar{\Lambda} \rightarrow [p\pi^-][\bar{p}\pi^+]$ and $J/\psi \rightarrow \Xi^-\bar{\Xi}^+ \rightarrow [\Lambda\pi^-][\bar{\Lambda}\pi^+]$ [4] etc., we can estimate the expected numbers of events and the further sensitivities, as shown in Table 1. Probing such a large data sample with refined tools will give us rich information about the underlying dynamics.

Table 1. The numbers of reconstructed events after considering decay branching fractions, tracking, and particle identification. The sensitivity is estimated without considering possible background dilutions, which should be small at the BESIII experiment. Estimations are based on the 10^{10} J/ψ data which will be collected by the BESIII collaboration by the end of 2018 (and the branching fractions from PDG2016). Systematic uncertainties are expected to be of the same order as the statistical uncertainties shown in the table.

channel	# of events	sensitivity on \mathcal{A}_T
$J/\psi \rightarrow \Lambda\bar{\Lambda} \rightarrow [p\pi^-][\bar{p}\pi^+]$	2.6×10^6	0.06%
$J/\psi \rightarrow \Sigma^+\bar{\Sigma}^- \rightarrow [p\pi^0][\bar{p}\pi^0]$	2.5×10^6	0.06%
$J/\psi \rightarrow \Xi^-\bar{\Xi}^+ \rightarrow [\Lambda\pi^-][\bar{\Lambda}\pi^+]$	1.1×10^6	0.1%
$J/\psi \rightarrow \Xi^0\bar{\Xi}^0 \rightarrow [\Lambda\pi^0][\bar{\Lambda}\pi^0]$	1.6×10^6	0.08%

2.2 Going beyond first steps

Measuring \mathcal{A}_T is the first step to probe CP asymmetries. There are various options for intermediate steps like:

$$\mathcal{A}_T(d) = \frac{N(C_T > |d|) - N(C_T < -|d|)}{N(C_T > |d|) + N(C_T < -|d|)}. \quad (19)$$

This is a very promising way to go beyond \mathcal{A}_T in Eq. (18). By the end of 2018 we can expect that BESIII can probe CPV in the decays of strange baryons to the level of 10^{-4} sensitivity, as shown in Table 1 (neglecting systematic errors).

The above method can also be applied to $J/\psi \rightarrow \Lambda\bar{\Lambda}\pi\pi$ to probe CPV in Ξ decays. Interestingly, for the case of Ξ baryons, CPV can also be probed by *polarized* Ξ thanks to the decay chain $\Xi^0 \rightarrow \Lambda\pi \rightarrow (p\pi)\pi$, where the CP -violating observable can be related to the helicity amplitudes. A similar proposal was given in Ref. [16] for Λ_c decay. Such a CP -violating signal can be extracted by performing an angular analysis, which is again accessible in the BESIII experiment due to the large J/ψ data sample. However, for Λ decays the interference of the helicity amplitude is absent in the angular observable [14], which handicaps accessing CP the same way as in polarized Ξ decay, i.e., measuring the interference of helicity amplitudes.

2.3 $J/\psi \rightarrow \bar{\Lambda}\Lambda \rightarrow [p\pi^+][\bar{p}\pi^-]$

The DM2 Collaboration measured CP invariance (and quantum mechanics) in $e^+e^- \rightarrow J/\psi \rightarrow \bar{\Lambda}\Lambda \rightarrow [p\pi^+][\bar{p}\pi^-]$ in 1988 without polarized Λ and $\bar{\Lambda}$. Their result was $A_{CP} = 0.01 \pm 0.10$ [17]. This was the first step in an important direction.

Now we describe the situation 30 years later, looking at what BESIII could achieve by 2018. We use the Jacob-Wick helicity formalism [18], as shown in Fig. 3 of Ref. [14]; it was also applied in Refs. [19, 20]:

1) The J/ψ rest frame is along the Λ out-going direction, and the solid angle $\Omega_0(\theta, \phi)$ is between the incoming e^+ and the out-going Λ .

2) For $\Lambda \rightarrow p\pi^-$ the solid angle of the ‘daughter’ particle $\Omega_1(\theta_1, \phi_1)$ is in reference to the Λ rest frame (although in the out-going direction); likewise for $\bar{\Lambda} \rightarrow \bar{p}\pi^+$.

We describe the angular distribution for this process following Ref. [21]:

$$\begin{aligned} \frac{d\Gamma}{d\Omega} \propto (1-\alpha)\sin^2\theta \cdot & \left[1 + \alpha_\Lambda\alpha_{\bar{\Lambda}}(\cos\theta_1\cos\bar{\theta}_1 \right. \\ & \left. + \sin\theta_1\sin\bar{\theta}_1\cos(\phi_1+\bar{\phi}_1)) \right] \\ & - (1+\alpha)(1+\cos^2\theta)(\alpha_\Lambda\alpha_{\bar{\Lambda}}\cos\theta_1\cos\bar{\theta}_1 - 1), \end{aligned} \quad (20)$$

where $d\Omega \equiv d\Omega_0 d\Omega_1 d\bar{\Omega}_1$ and:

- 1) α is the angular distribution parameter for Λ ;
- 2) $\alpha_\Lambda[\alpha_{\bar{\Lambda}}]$ is the $\Lambda[\bar{\Lambda}]$ decay parameter;
- 3) these data depend only on the product of $\alpha_\Lambda\alpha_{\bar{\Lambda}}$, see Eq. (20).

By fitting Eq. (20) to the data, one can determine $\alpha_{J/\psi}$ and $\alpha_\Lambda\alpha_{\bar{\Lambda}}$. One can make a substitution:

$$\alpha_\Lambda\alpha_{\bar{\Lambda}} \equiv \frac{A-1}{A+1}\alpha_\Lambda^2, \quad (21)$$

where A describes a CP asymmetry observable.

As mentioned before, published 2010 data from the BES collaboration show [14] $\alpha_{\bar{\Lambda}}^{(p)} = -0.755 \pm 0.083 \pm 0.063$, based on previously measured $\alpha_{\Lambda}^{(p)} = 0.642 \pm 0.013$. Their non-zero numbers show the impact of re-scattering; it is large, which is not surprising. We also note that Eq. (20) is derived from considering only spin projection $J_z = \pm 1$ for J/ψ , which is a consequence of the QED process $e^+e^- \rightarrow \gamma \rightarrow c\bar{c}(J/\psi)$ [22]. Thus, only the product term $\alpha_\Lambda\alpha_{\bar{\Lambda}}$ can be measured¹⁾.

The present limit on direct CP asymmetry is around a few percent. ND cannot even produce effects close to 1% here. To reach $\mathcal{O}(0.1\%)$ would be a considerable achievement for $\langle A_{CP}^{(p)} \rangle$ based on $\alpha_{\Lambda}^{(p)} \sim \alpha_{\bar{\Lambda}}^{(p)} \sim 0.64$. Measuring semi-local asymmetry would give us new lessons about non-perturbative QCD.

1) In a $p\bar{p}$ machine, the terms α_Λ and $\alpha_{\bar{\Lambda}}$ can be separated [24].

It has been said very recently in Ref. [23] that Ref. [14] missed some contributions for on-shell $J/\psi \rightarrow \bar{\Lambda}\Lambda \rightarrow \bar{p}\pi^+p\pi^-$; so far we are not convinced. Of course, experimental data from BESIII are needed in order to test this.

Even now BESIII has much more data, and by the end of 2018 we will have about 2.6×10^6 events for the $J/\psi \rightarrow \bar{\Lambda}\Lambda \rightarrow [\bar{p}\pi^+][p\pi^-]$ decay chain, after considering the efficiencies for tracking, particle identification and Λ pair reconstruction [15]. The sensitivity might reach 6×10^{-4} by the end of 2018, as listed in Table 1. Now the landscape is different, with some hope to find CP asymmetry here, and also for $J/\psi \rightarrow \bar{\Sigma}\Sigma$, which will be discussed below.

Some general comments are as follows. (a) Except $n-\bar{n}$ (or maybe, even $\Lambda-\bar{\Lambda}$) oscillations [25], one probes only direct CPV with baryons. (b) It is well-known that the impact (local) penguin operators are crucial for $\Delta S=1$ transitions for strange mesons, in particular for the non-zero value for ϵ' . What about decays of strange baryons? The transitions of pairs of strange baryons are not far from the thresholds; thus one has to think about the “duality” between the world of hadrons and that of quarks and gluons. We discuss this further below.

To probe CP asymmetries with accuracy, BESIII can calibrate with transitions where CP asymmetries cannot happen. We have two examples with broad resonances, where the situations are complex: $J/\psi \rightarrow \bar{N}(1440)N(1440)$ with $\Gamma_{N(1440)} \sim (250-450)$ MeV carrying isospin $I=1/2$, and $J/\psi \rightarrow \bar{\Delta}(1232)\Delta(1232)$ with $\Gamma_{\Delta(1232)} \sim 117$ MeV carrying isospin $I=3/2$. The BESIII experiment has measured the background very well and continues to do so. The total background is very small, which provides good opportunity for a clean probe of the CPV signal.

From knowledge of the previous BES measurement [14] (the main background channels are also listed in this reference) and the ongoing measurement¹⁾, we can conservatively estimate that the number of combinatorial background events is roughly 10^{-3} of the signal events, a very small fraction, such that CPV can be cleanly probed. This is one of the strengths of the BESIII collaboration. We can show this more transparently with an example. By the end of 2018 we can expect 2.6×10^6 signal events, and assuming the CPV is on the level of 10^{-4} , one has $\Delta N = N_+ - N_- = 260$. The background can induce $\Delta N_{\text{bkg}} = \sqrt{2.6 \times 10^3} \approx 51$. This illustrates that a nonzero A_T will really indicate the observation of CP asymmetry. However, if the CPV A_T is below the level of 10^{-5} , the impact of the background is important.

2.4 $J/\psi \rightarrow \bar{\Sigma}^-\Sigma^+ \rightarrow [\bar{p}\pi^0][p\pi^0]$

Above, we discussed $J/\psi \rightarrow \bar{\Delta}(1232)\Delta(1232)$ as back-

ground for $J/\psi \rightarrow \bar{\Lambda}\Lambda$. We also said that it is very important to analyze pairs of baryons. However, the situation here is even more complex, as we have discussed just above:

1) Σ^+ carries isospin $(I, I_3) = (1, +1)$, while Λ has isospin zero.

2) Looking at straightforward diagrams we get $J/\psi \rightarrow \bar{\Sigma}^-\Sigma^+ \rightarrow [\bar{p}\pi^0][p\pi^0]$ vs. $J/\psi \rightarrow \bar{\Delta}(1232)\Delta(1232) \rightarrow \bar{p}\pi p\pi$ as a background.

3) However, we have to go beyond that, as you can see by comparing $M(\Sigma^+) \simeq 1189$ MeV vs. $M(\Delta(1232)) \simeq 1232$ MeV with width $\Delta(1232) \simeq 117$ MeV. Off-shell intermediate amplitudes sizably affect total amplitudes and also measurable CP asymmetries in $[\bar{p}\pi^0][p\pi^0]$ final states.

In other words, there should be a sizable overlap between the waves of $\bar{\Sigma}/\Sigma$ and $\bar{\Delta}(1232)/\Delta(1232)$ due to $\Gamma(\Delta(1232))$, which cannot be ignored.

4) Therefore, we use two different diagrams for transitions: “ \Rightarrow ” describes the amplitudes due to QCD(\times QED) that conserve P and C symmetries; “ \rightarrow ” includes $SU(2)_L$ with weak dynamics, including sources of P, C and CP asymmetries. The direct path is

$$J/\psi \Rightarrow \bar{\Sigma}^-\Sigma^+ \rightarrow [\bar{p}\pi^0][p\pi^0], \quad (22)$$

while a somewhat indirect path can happen due to off-shell intermediate amplitudes:

$$J/\psi \Rightarrow \bar{\Delta}(1232)\Delta(1232) \Rightarrow \bar{\Sigma}^-\Sigma^+ \rightarrow [\bar{p}\pi^0][p\pi^0]. \quad (23)$$

As said before, the impact of re-scattering is complex, as one can see from comparing $\text{BR}(\Sigma^+ \rightarrow p\pi^0) \simeq 0.52$ & $\text{BR}(\Sigma^+ \rightarrow n\pi^+) \simeq 0.48$ vs. $\text{BR}(\Lambda \rightarrow p\pi^-) \simeq 0.64$ & $\text{BR}(\Lambda \rightarrow n\pi^0) \simeq 0.36$.

5) There is another possible amplitude that is even more complex, in particular with

$$J/\psi \Rightarrow \bar{\Sigma}^-\Sigma^+ \rightarrow \bar{\Delta}(1232)\Delta(1232) \Rightarrow [\bar{p}\pi^0][p\pi^0]. \quad (24)$$

We hypothesize off-line exchanges of kaons or new dynamics.

The data produced by the end of 2018 will be analyzed by the BESIII collaboration with the best available tools. It is possible that off-line resonances like $\bar{\Delta}(1232)\Delta(1232)$ might impact the CP asymmetries more in $J/\psi \rightarrow \bar{\Sigma}^-\Sigma^+ \rightarrow [\bar{p}\pi^0][p\pi^0]$ than in $J/\psi \rightarrow \bar{\Lambda}\Lambda \rightarrow [\bar{p}\pi^+][p\pi^-]$, since off-shell $\bar{\Delta}(1232)\Delta(1232)$ are closer to the on-shell $\bar{\Sigma}^-\Sigma^+$; the second vertex technique will help greatly to distinguish them from the background from $\bar{\Delta}(1232)\Delta(1232)$.

Using the $10^{10} J/\psi$ events, we expect 2.5×10^6 signal events, with sensitivity at 0.06%, as shown in Table 1.

1) BESIII collaboration, “Measurement of decay asymmetry parameters of Λ ”, in preparation.

2.5 $J/\psi \rightarrow \bar{\Xi}\Xi \rightarrow [\bar{\Lambda}\pi][\Lambda\pi]$

It is also interesting to probe CP violation by using the decays $J/\psi \rightarrow \bar{\Xi}^+\Xi^-$ and $\bar{\Xi}^0\Xi^0$. One can reconstruct both Ξ s in the $\Xi \rightarrow \Lambda\pi$ mode. For the neutral channel $\Xi \rightarrow \Lambda\pi^0$, the π^0 in $\bar{\Xi}^0$ decay can be easily separated from that in Ξ^0 decay without ambiguity, since both Ξ s are back to back and strongly boosted in the rest frame of the J/ψ . That is, the $\Xi^0 \rightarrow \Lambda\pi^0$ is reconstructed in the opposite decay hemisphere against the decay hemisphere for the $\bar{\Xi} \rightarrow \bar{\Lambda}\pi^0$. This situation will be similar to that in Section 2.4 for $J/\psi \rightarrow \bar{\Sigma}^-\Sigma^+ \rightarrow [\bar{p}\pi^0][p\pi^0]$. By the end of 2018 we will have data for $J/\psi \rightarrow \bar{\Xi}^+\Xi^- \rightarrow \bar{\Lambda}\pi^+\Lambda\pi^-$ and $\bar{\Xi}^0\Xi^0 \rightarrow \bar{\Lambda}\pi^0\Lambda\pi^0$ with 1.1×10^6 and 1.6×10^6 events, respectively [15]. Thus, the reaches for the triple-product asymmetry are about 10×10^{-4} and 8×10^{-4} for the charged and neutral Ξ , respectively.

Once non-zero values for CP asymmetries are found, one can attempt another challenge: do they come from the transition of $\Xi \rightarrow \Lambda\pi$ or $\Lambda \rightarrow p\pi^-$, or the interferences between them?

2.6 $J/\psi \rightarrow \Lambda\bar{X}$ vs. $J/\psi \rightarrow \bar{\Lambda}X$

One can also compare the transitions $J/\psi \rightarrow \Lambda\bar{X}$ vs. $J/\psi \rightarrow \bar{\Lambda}X$, in particular $J/\psi \rightarrow \Lambda\bar{p}K^+$ vs. $J/\psi \rightarrow \bar{\Lambda}pK^-$. The 2016 data tell us $\text{BR}(J/\psi \rightarrow \Lambda\bar{p}K^+/\bar{\Lambda}pK^-) = (0.89 \pm 0.16) \cdot 10^{-3}$. By the end of 2018 the expected number of events is about 9×10^6 , which has sensitivity for CP asymmetry of 2.4×10^{-4} by comparing the partial widths between $J/\psi \rightarrow \Lambda\bar{X}$ and $J/\psi \rightarrow \bar{\Lambda}X$ decays. The systematic uncertainties are expected to be larger than in the previous cases discussed above, but not by an order of ten.

2.7 Summary from the experimental side

We are studying non-perturbative QCD in a novel situation; it is not trivial to know how much to apply it and where. Just below we give comments about available theoretical tools. The hope is to find signs of CP asymmetries in the decays of strange baryons; therefore the goal is not to go for accuracy. We ‘paint’ the landscape to find CP asymmetries. Once our community has found a non-zero value somewhere, one can discuss the correlations with other situations.

3 Comments about tools for CP asymmetries

The realistic goal is to get new lessons about non-perturbative QCD. One can hope to find CP asymmetries in the decays of strange baryons; one can also dream to find the impact of ND [9]. When one goes after accuracy, one needs truly consistent parametrization of the CKM matrix [26]. However, that is not the goal now; therefore one can use the well-known Wolfenstein

parametrization.

We have *local* operators for $\Delta S=1$ amplitudes. One describes the scattering of left-handed quarks $s_L+u_L \rightarrow d_L+u_L$ with refined tree amplitudes and *local* penguin operators. Challenges come from true strong dynamics in different ways. In particular $\mu \sim 1.0$ GeV describe the “fuzzy” boundaries between perturbative and non-perturbative QCD. On the other side the landscape is also complex, since the baryons carry spin-1/2; therefore there are more observables. In other words, the amplitudes can be described with S - or P -waves.

There is another challenge, namely to connect quark and hadronic amplitudes. This issue of “duality” is well known, and it is not just another assumption based on true quantum field theory. However, it does not work well when one has to deal with thresholds that are important in the on-shell transitions $J/\psi \rightarrow \bar{\Lambda}\Lambda$ and $J/\psi \rightarrow \bar{\Sigma}^-\Sigma^+$; in these cases we have broad resonances like $\Delta(1232)$ and $N(1440)$.

4 Future outlook

As mentioned above, a realistic goal is to measure non-leptonic decays of Λ , Σ^+ and Ξ with more data to learn new lessons about non-perturbative QCD. We can ‘hope’ to find CP asymmetries in BESIII data by the end of 2018 and ‘dream’ of finding the impact of ND. When it is not enough to work on data and their analyses, ‘hoping’ or even ‘dreaming’ to learn from that, then – in our view – one is in the wrong business.

Of course, we need much more data, but also powerful analyses to reach even the realistic goal. Here we have listed the directions where more data should improve our understanding of fundamental dynamics (see Table 1). In a future super tau-charm factory [27–29], there will be an unprecedentedly high peak luminosity of $10^{35} \text{ cm}^{-2}\cdot\text{s}^{-1}$, with $10^{12} J/\psi$ events, a data sample 100 times as large as the ongoing BEPCII/BESIII, which will result in a decreasing of the (statistical) uncertainty by 10 times.

We do not give predictions here for CP asymmetries. Our goal here is to point out the paths where our community can learn more in the future. We need more thinking in general, and analysis of correlations in different transitions.

Analyzing $e^+e^- \rightarrow \bar{\Lambda}_c^-\Lambda_c^+$ can also give us novel lessons about non-perturbative QCD and even allow us to compare $e^+e^- \rightarrow \bar{\Lambda}_c^-\Lambda_c^+ \rightarrow \Lambda+\bar{X}$ vs. $e^+e^- \rightarrow \bar{\Lambda}_c^-\Lambda_c^+ \rightarrow \bar{\Lambda}+X$.

We add a comment that one first sees this as a technical challenge: applying “dispersion relations” has a long history in nuclear physics, hadrodynamics, high-energy physics (HEP), and also other branches of physics. Dispersion relations are based on central statements of quantum field theory, while their results depend on low en-

ergy data, with some ‘judgment’ (see e.g., Ref. [30]). If the 2018 data we have discussed above are produced as planned, there is a good chance of convincing members of our community to work on that. There are two tasks in applying dispersion relations: (i) as an input for them, one needs more data from $N\pi$ collisions at low energies; and (ii) non-trivial thinking is needed about where and how to apply them for good reasons.

Finally, in the future our community could have a novel competition between BESIII, LHCb and theorists – actually, different parts of the same team.

XWK thanks Hai-Yang Cheng for the careful reading, encouragement and interesting discussion, and Xinxin Ma for useful discussion.

References

- 1 C. Materniak (HyperCP Collaboration), Nucl. Phys. B (Proc. Suppl.), **187**: 208 (2009); T. Holmstrom et al, Phys. Rev. Lett., **93**: 262001 (2004)
- 2 J. H. Christenson et al, Phys. Rev. Lett., **13**: 138 (1964)
- 3 L. B. Okun, *Weak Interactions of Elementary Particles*, Pergamon, 1965; the Russian original had appeared in 1963, i.e. clearly before the discovery of CP violation
- 4 C. Patrignani et al (Particle Data Group Collaboration), Chin. Phys. C, **40**(10): 100001 (2016)
- 5 A. J. Buras, M. Gorbahn, S. Jäger, and M. Jamin, JHEP, **1511**: 202 (2015); arXiv:1507.06345 [hep-ph]
- 6 N. Garron, PoS CD, **15**: 034 (2016); arXiv:1512.02440 [hep-lat]
- 7 J. Charles, A. Le Yaouanc, L. Oliver, O. Pene, and J. C. Raynal, Phys. Rev. D, **58**: 114021 (1998); [hep-ph/9806347]
- 8 R. Aaij et al (LHCb Collaboration), Nature Phys., (2017); arXiv:1609.05216 [hep-ex]
- 9 I. I. Bigi, A. I. Sanda, ‘*CP Violation*, Second Edition, *Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology* (Cambridge University Press) 2009, Sect.4.10 “The role of final state interactions” & Sect.4.11 “Resume and outlook”, pages 62-70.
- 10 J. F. Donoghue, X.-G. He, and S. Pakvasa, Phys. Rev. D, **34**: 833 (1986)
- 11 I. I. Bigi, A. I. Sanda, *CP Violation*, Second Edition, p.140
- 12 J. Tandean, G. Valencia, Phys. Rev. D, **67**: 056001 (2003)
- 13 T. D. Lee, C.N. Yang, Phys. Rev., **108**: 1645 (1957)
- 14 M. Ablikim et al (BES Collaboration), Phys. Rev. D, **81**: 012003 (2010); arXiv:0911.2972 [hep-ex]
- 15 H. B. Li, Front. Phys., **12**: 121301 (2017); [arXiv:1612.01775 [hep-ex]]
- 16 X. W. Kang, H. B. Li, G. R. Lu, and A. Datta, Int. J. Mod. Phys. A, **26**: 2523 (2011); arXiv:1003.5494 [hep-ph]
- 17 M. H. Tixier et al (DM2 Collaboration), Phys. Lett. B, **212**: 523 (1988)
- 18 M. Jacob and G. C. Wick, Annals Phys., **7**: 404 (1959); Annals Phys., **281**: 774 (2000)
- 19 X. W. Kang and H. B. Li, Phys. Lett. B, **684**: 137 (2010)
- 20 X. W. Kang, H. B. Li, Gong-Ru Lu, and B. S. Zou, Chin. Phys. C, **34**: 1061 (2010)
- 21 H. Chen and R. G. Ping, Phys. Rev. D, **76**: 036005 (2007)
- 22 J. D. Richman, *An Experimenter’s Guide to the Helicity Formalism*, CALT-68-1148, available in INSPIRE, Sec. B6.5; R. Kutschke, “An Angular Distribution Cookbook”, available online, Sec. 13
- 23 G. Fäldt and A. Kupsc, *Hadronic structure functions in the $e^+e^- \rightarrow \bar{\Lambda}\Lambda$ reaction*, arXiv:1702.07288 [hep-ph]
- 24 J. F. Donoghue, B. R. Holstein, and G. Valencia, Phys. Lett. B, **178**: 319 (1986)
- 25 X. W. Kang, H. B. Li, and G. R. Lu, Phys. Rev. D, **81**: 051901 (2010); arXiv:0906.0230 [hep-ph]
- 26 Y. H. Ahn, H. Y. Cheng, and S. Oh, Phys. Lett. B, **703**: 571 (2011); arXiv:1106.0935 [hep-ph]
- 27 A. E. Bondar et al (Charm-Tau Factory Collaboration), Phys. Atom. Nucl., **76**: 1072 (2013); Yad. Fiz., **76**(9): 1132 (2013)
- 28 Z. Zhou, Q. Luo, L. Wang, W. Xu, and B. Zhang, *Preliminary Concept and Key Technologies of HIEPA Accelerator*, talk at the 7th International Particle Accelerator Conference (IPAC 2016) 08-13 May, 2016, Busan, Korea
- 29 A. J. Bevan, Front. Phys. (Beijing), **11**(1): 111401 (2016); arXiv:1508.00222 [hep-ex]
- 30 X. W. Kang, B. Kubis, C. Hanhart, and U. G. Meißner, Phys. Rev. D, **89**: 053015 (2014)