**CP asymmetries in Strange Baryon Decays**

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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 Σ 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/ψ→ΛΛ at the LHCb collaboration.

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

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1 The landscape

CP violation (CPV) was found in K_L → π^+π^- 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 → π^+π^- vs. K_L → π^0π^0 in the 1990s by the NA31/NA48 and KTeV experiments. The most recent analyses given by the Particle Data Group (PDG2016) [4] are:

\[ \xi_K^{\text{exp.}} = (2.228 \pm 0.011) \cdot 10^{-3}, \]

\[ \text{Re}(\epsilon'/\xi_K)^{\text{exp.}} = (1.66 \pm 0.23) \cdot 10^{-3}; \]  

\[ \text{Re}(\epsilon'/\xi_K)^{\text{Buras}} = (0.86 \pm 0.32) \cdot 10^{-3}. \]

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]:

\[ \text{Re}(\epsilon'/\xi_K)^{\text{LQCD}} = (0.138 \pm 0.515 \pm 0.443) \cdot 10^{-3}. \]

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)→ 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,
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 $B^0 \to J/#\psi K_S$ 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 $\Lambda^0_b \to p\pi^-\pi^+\pi^-$ 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 $\Lambda^0_b$ 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 $\Lambda$ and $\Sigma^+$:

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

(4)

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

$$
\begin{align}
A_{\text{CP}}(\Lambda \to p\pi^-) &\simeq -A_{\text{CP}}(\Lambda \to n\pi^0) \\
A_{\text{CP}}(\Sigma^+ \to p\pi^-) &\simeq -A_{\text{CP}}(\Sigma^+ \to n\pi^+).
\end{align}
$$

(5)

(6)

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

For the decay $\Lambda \to p\pi^-$ without the spins of the baryons included, there is only one observable, namely a number. The data depend on production asymmetries in $\Lambda \to p\pi^-$ vs. $\Lambda \to p\pi^+$. That is not a problem for $e^+e^- \text{ annihilation}$ 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 rescattering is not obvious, when one cannot use polarized baryons, as one can see in the branching ratios:

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

(7)

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

$$
\begin{align}
A_{\text{CP}}(\Lambda \to p\pi^-) &\sim (0.05 - 1.2) \times 10^{-4} \\
A_{\text{CP}}(\Xi^- \to \Lambda\pi^-) &\sim (0.2 - 3.5) \times 10^{-4}
\end{align}
$$

(8)

(9)

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

The HyperCP experiment [2] searched for CPV using a 800 GeV proton beam on a Cu target [1]:

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

(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 $e^+e^- \to J/#\psi$ with the unusual narrow resonance, will be enhanced as a source of strange baryons compared to PDG2016:

$$
\begin{align}
\text{BR}(J/#\psi \to \Lambda\Lambda) &= (1.61 \pm 0.15) \times 10^{-3} \\
\text{BR}(J/#\psi \to \Lambda\Lambda\pi^0) &= (4.3 \pm 1.0) \times 10^{-3} \\
\text{BR}(J/#\psi \to \Lambda\Lambda\pi^0\pi^-) &= (0.89 \pm 0.16) \times 10^{-3} \\
\text{BR}(J/#\psi \to \bar{\Sigma}^0\Sigma^-) &= (1.50 \pm 0.24) \times 10^{-3} \\
\text{BR}(J/#\psi \to \bar{\Sigma}^0\Sigma^-) &= (1.20 \pm 0.24) \times 10^{-3}
\end{align}
$$

(11)

(12)

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

$$
\begin{align}
\text{BR}(J/#\psi \to \bar{p}p) &= (2.120 \pm 0.029) \times 10^{-3} \\
\text{BR}(J/#\psi \to \bar{p}p\pi^+\pi^-) &= (6.0 \pm 0.5) \times 10^{-3} \\
\text{BR}(J/#\psi \to \bar{p}p\pi^+\pi^-) &= (2.12 \pm 0.09) \times 10^{-3} \\
\text{BR}(J/#\psi \to \bar{n}n) &= (2.09 \pm 0.16) \times 10^{-3}
\end{align}
$$

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 source 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/ψ → pair of strange baryons

In this section, we mostly discuss the decays of J/ψ into 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

\[
\langle A_{CP}^{(X)} \rangle = \frac{\alpha^{(X)}_Y + \alpha^{(X)}_Y}{\alpha^{(X)}_Y - \alpha^{(X)}_Y}
\]

(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 \(C_\tau = (p^\tau X \times \bar{p}^\tau \bar{X})\) and conjugate transitions \(\bar{C}_\tau = (\bar{p}^\tau X \times p^\tau \bar{X})\), and compare the event numbers \(N\) with positive and negative values

\[
\langle A_\tau \rangle = \frac{N(C_\tau > 0) - N(C_\tau < 0)}{N(C_\tau > 0) + N(C_\tau < 0)}
\]

(16)

\[
\langle \bar{A}_\tau \rangle = \frac{N(\bar{C}_\tau > 0) - N(\bar{C}_\tau < 0)}{N(\bar{C}_\tau > 0) + N(\bar{C}_\tau < 0)}
\]

(17)

Thus

\[
A_\tau = \frac{1}{2} \left[ (A_\tau) + (\bar{A}_\tau) \right] = \langle A_\tau \rangle \neq 0
\]

(18)

are observable CP asymmetries based on CPT invariance. We have taken a different convention for \(A_\tau\) 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 \(J/\psi \to \Lambda \Lambda \to [p^\tau \bar{X}]\) 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 \(D^0(\bar{D}^0) \to K K \pi \pi /4\pi\).

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

1) One can calibrate those transitions with \(J/\psi \to \Delta/(1232)\Delta/(1232)\), where CPV cannot appear.

2) That is not the end of the impact of strong resonances of \(\Delta/(1232)\) with width \(\sim 117\) 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, \(10^{10} J/\psi\) events will be accumulated by the BESIII experiment [15]. The detection efficiency for pions, 1) G. Punzi, private communication.

2) \(M(\Lambda) \approx 1116\) MeV; \(M(\Sigma^+) \approx 1189\) MeV; \(M(\Xi^0) \approx 1315\) MeV; \(M(\Xi^-) \approx 1322\) 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 $3\sigma$ (three standard deviations) uncertainty below a momentum of 1.0 GeV. Considering the branching fractions of $J/\psi \to \Lambda \Lambda \to [p\pi^-][p\pi^+]$ and $J/\psi \to \Xi^0 \Xi^0 \to [\Lambda\pi^+]\Lambda\pi^+$ [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 $10^{10}$ $J/\psi$ 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 $A_T$ |
|---------|-------------|----------------------|
| $J/\psi \to \Lambda \Lambda \to [p\pi^-][p\pi^+]$ | $2.6 \times 10^9$ | 0.06% |
| $J/\psi \to \Sigma^+ \Sigma^- \to [p\pi^0][p\pi^0]$ | $2.5 \times 10^6$ | 0.06% |
| $J/\psi \to \Xi^0 \Xi^0 \to [\Lambda\pi^+]\Lambda\pi^+$ | $1.1 \times 10^6$ | 0.1% |
| $J/\psi \to \Xi^0 \Xi^0 \to [\Lambda\pi^+]\Lambda\pi^+$ | $1.6 \times 10^6$ | 0.08% |

2.2 Going beyond first steps

Measuring $A_T$ is the first step to probe $CP$ asymmetries. There are various options for intermediate steps like:

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

This is a very promising way to go beyond $A_T$ 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 $J/\psi \to \Lambda\Lambda'\pi\pi$ to probe $CP$ in $\Xi$ decays. Interestingly, for the case of $\Xi$ baryons, $CPV$ can also be probed by polarized $\Xi$ thanks to the decay chain $\Xi^0 \to \Lambda\pi^0 \pi^0$, where the $CP$-violating observable can be related to the helicity amplitudes. A similar proposal was given in Ref. [16] for $\Lambda$ decays. 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 $J/\psi$ data sample. However, for $\Lambda$ decays the interference of the helicity amplitude is absent in the angular observable [14], which handicaps accessing $CP$ the same way as in polarized $\Xi$ decay, i.e., measuring the interference of helicity amplitudes.

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

The DM2 Collaboration measured $CP$ invariance and quantum mechanics in $e^+e^- \to J/\psi \to \Lambda\Lambda \to [p\pi^+]|[p\pi^-]$ in 1988 without polarized $\Lambda$ 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 $J/\psi$ rest frame is along the $\Lambda$ out-going direction, and the solid angle $\Omega_0(\theta, \phi)$ is between the incoming $e^+$ and the out-going $\Lambda$.

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

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

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

where $d\Omega \equiv d\Omega_0 d\Omega_1 d\Omega_1$ and:

1) $\alpha$ is the angular distribution parameter for $\Lambda$;

2) $\alpha_\Lambda$ 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] $\alpha_\Lambda^{(p)} = -0.755 \pm 0.083 \pm 0.063$, 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 $J_s = \pm 1$ for $J/\psi$, which is a consequence of the QED process $e^+e^- \to \gamma \to c\bar{c}(J/\psi)$ [22]. Thus, only the product term $\alpha_\Lambda \alpha_{\bar{\Lambda}}$ can be measured.

The present limit on direct $CP$ asymmetry is around a few percent. ND cannot even produce effects close to 1% here. To reach $O(0.1\%)$ would be a considerable achievement for $\langle A^{(p)}_T \rangle$ 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+p machine, the terms $\alpha_\Lambda$ 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/ψ → ΛΛ → ppπ⁺π⁻; 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 2.6×10⁶ events for the J/ψ → ΛΛ → [pπ⁺][pπ⁻] 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/ψ → ΣΣ, which will be discussed below.

Some general comments are as follows. (a) Except n–̅n (or maybe, even Λ–̅Λ) oscillations [25], one probes only direct CPV with baryons. (b) It is well-known that the impact (local) penguin operators are crucial for ΔS=1 transitions for strange mesons, in particular for the non-zero value for c'. 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/ψ → N(1440)N(1440) with Γ(1440)~(250–450) MeV carrying isospin I = 1/2, and J/ψ → Δ(1232)Δ(1232) with ΓΔ(1232)~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 2.6×10⁶ signal events, and assuming the CPV is on the level of 10⁻⁴, one has ΔN = N⁺ₚ – N⁻ₚ = 260. The background can induce ΔN_bg = \sqrt{2.6×10⁶} ≈ 51. This illustrates that a nonzero Aₚ will really indicate the observation of CP asymmetry. However, if the CPV Aₚ is below the level of 10⁻⁵, the impact of the background is important.

2.4 J/ψ → Σ⁻Σ⁺ → [pπ⁺][pπ⁻]

Above, we discussed J/ψ → Δ(1232)Δ(1232) as background for J/ψ → ΛΛ. 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,Iₐ) = (1,+1), while Λ has isospin zero.

2) Looking at straightforward diagrams we get J/ψ → Σ⁻Σ⁺ → [pπ⁺][pπ⁻] vs. J/ψ → Δ(1232)Δ(1232) → pπττ as a background.

3) However, we have to go beyond that, as you can see by comparing M(Σ⁺) ≈ 1189 MeV vs. M(Δ(1232)) ≈ 1232 MeV with width Δ(1232) ≈ 117 MeV. Off-shell intermediate amplitudes sizably affect total amplitudes and also measurable CP asymmetries in [pπ⁺][pπ⁻] final states.

In other words, there should be a sizable overlap between the waves of Σ/Σ and Δ(1232)/Δ(1232) due to F(Δ(1232)), which cannot be ignored.

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

J/ψ ⇒ Σ⁻Σ⁺ → [pπ⁺][pπ⁻],

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

J/ψ ⇒ Δ(1232)Δ(1232) ⇒ Σ⁻Σ⁺ → [pπ⁺][pπ⁻].

As said before, the impact of re-scattering is complex, as one can see from comparing BR(Σ⁺ → pπ⁰) ≈ 0.52 & BR(Σ⁺ → nπ⁺) ≈ 0.48 vs. BR(Λ → pπ⁻) ≈ 0.64 & BR(Λ → nπ⁰) ≈ 0.36.

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

J/ψ ⇒ Σ⁻Σ⁺ ⇒ Δ(1232)Δ(1232) ⇒ [pπ⁺][pπ⁻].

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 Δ(1232)Δ(1232) might impact the CP asymmetries more in J/ψ → Σ⁻Σ⁺ → [pπ⁺][pπ⁻] than in J/ψ → ΛΛ → [pπ⁺][pπ⁻], since off-shell Δ(1232)Δ(1232) are closer to the on-shell Σ⁻Σ⁺; the second vertex technique will help greatly to distinguish them from the background from Δ(1232)Δ(1232).

Using the 10¹⁰ J/ψ events, we expect 2.5×10⁶ signal events, with sensitivity at 0.06%, as shown in Table 1.

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1) BESIII collaboration, “Measurement of decay asymmetry parameters of Λ”, in preparation.
2.5 \( J/\psi \rightarrow \Xi \Xi \rightarrow [\Lambda \pi][\Lambda \pi] \)

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

One can also compare the transitions \( J/\psi \rightarrow \Lambda \bar{X} \) vs. \( J/\psi \rightarrow \Lambda X \), in particular \( J/\psi \rightarrow \Lambda pK^+ \) vs. \( J/\psi \rightarrow \Lambda pK^- \). The 2016 data tell us \( BR(J/\psi \rightarrow \Lambda pK^+ / \Lambda pK^-) = (0.89 \pm 0.16) \times 10^{-3} \). By the end of 2018 the expected number of events is about 9 x 10^6, which has sensitivity for CP asymmetry of 2.4 x 10^{-4} by comparing the partial widths between \( J/\psi \rightarrow \Lambda \bar{X} \) and \( J/\psi \rightarrow \Lambda X \) 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 findings.

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 \( \mu \sim 1.0 \text{ GeV} \) 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 \( J/\psi \rightarrow \Lambda \Lambda \) and \( J/\psi \rightarrow \Sigma^- \Sigma^+ \); 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 \( \Lambda, \Sigma^+ \) and \( \Xi \) 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 \( 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \), 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 \( e^+e^- \rightarrow \Lambda^-\Lambda^+ \) can also give us novel lessons about non-perturbative QCD and also allow us to compare \( e^+e^- \rightarrow \Lambda^-\Lambda^+ \rightarrow \Lambda+X \) vs. \( e^+e^- \rightarrow \Lambda^-\Lambda^+ \rightarrow \Lambda+X \).

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.

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