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The physics case for the CP-violation tests in hyperon decays at SCTF

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XIV International Conference on Beauty, Charm and Hyperon Hadrons
Kraków, Poland

5th-11th June 2022

NARODOWE CENTRUM NAUKI

CP violation

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However, the current CP violation mechanism theorized within the SM is not enough to explain the detected asymmetry.

Since its signal is subtle, a systematical mapping of various complementary hadronic systems is needed.

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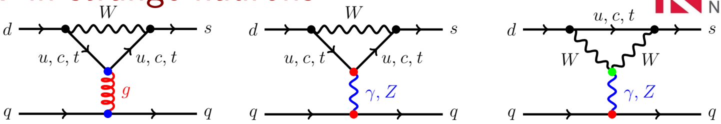
CPV in strange hadrons



(a) (b)

+ BSM

1. Neutral kaons ($\Delta S = 1$) [2]

$$\frac{\mathcal{A}(K_L \to \pi^+\pi^-)}{\mathcal{A}(K_S \to \pi^+\pi^-)} := \epsilon + \epsilon' \quad ; \quad \frac{\mathcal{A}(K_L \to \pi^0\pi^0)}{\mathcal{A}(K_S \to \pi^0\pi^0)} := \epsilon - 2\epsilon' \qquad (1)$$

$$\Re\left(\frac{\epsilon'}{\epsilon}\right) = (16.6 \pm 2.3) \times 10^{-4} \qquad (2)$$

CPV from interference between isospin transitions $|\Delta I| = \frac{1}{2}, \frac{3}{2}$.

[2] PDG rev. based on [PLB544, 97 (2002)], [PRD70, 079904 (2004)], [PRD83, 092001 (2011)]

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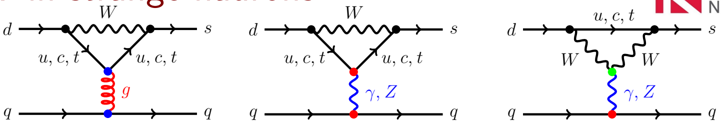

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2. Hyperons, a complementary approach. Study of $\Delta S = 1$ transitions

$$\Lambda \to p\pi^- : \quad \text{single-step;} \quad \Xi^- \to \Lambda(\to p\pi^-)\pi^- : \quad \text{two-step.}$$

[2] PDG rev. based on [PLB544, 97 (2002)], [PRD70, 079904 (2004)], [PRD83, 092001 (2011)]

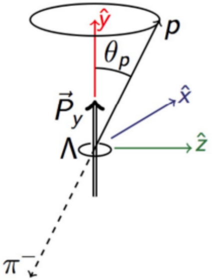
Hyperon decay observables

E.g. Λ decay: using

$$S = |S| \exp(i\xi_S + i\delta_S)$$
$$P = |P| \exp(i\xi_P + i\delta_P) \qquad (3)$$

- $\mathcal{A} = S\sigma_0 + P\boldsymbol{\sigma} \cdot \hat{\mathbf{n}}$
- From $I(\cos\theta_p) \propto 1 + \alpha \mathbf{P}_\Lambda \cdot \hat{\mathbf{n}}$

$$\boldsymbol{\alpha} = \frac{2\Re(S^* P)}{|S|^2 + |P|^2} \qquad (4)$$



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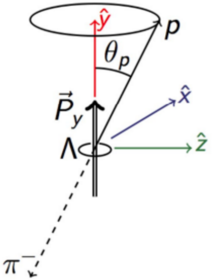
- From $\mathbf{s}_\Lambda \to \mathbf{s}_p$ rotation

$$\beta = \frac{2\Im(S^* P)}{|S|^2 + |P|^2} = \sqrt{1 - \alpha^2} \sin\phi \tag{5}$$

mother and daughter polarizations $\mathbf{P}_\Lambda$, $\mathbf{P}_p$ needed.



For antibaryon, use

$$\overline{S} = -|S| \exp(-i\xi_S + i\delta_S) \qquad \overline{P} = |P| \exp(-i\xi_P + i\delta_P)$$

CP tests

CP tests [PRD 100, 114005 (2019)]

$$A_{\mathrm{CP}} := \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}} \quad ; \quad B_{\mathrm{CP}} := \frac{\beta + \overline{\beta}}{\alpha - \overline{\alpha}} \quad ; \quad \Phi_{\mathrm{CP}} := \frac{\phi + \overline{\phi}}{2} \qquad (6)$$

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A parametrization independent of decay channel

$$A_{\text{CP}} = -\tan(\delta_P - \delta_S)\,\tan(\xi_P - \xi_S) \tag{7}$$

$$B_{\text{CP}} = \tan(\xi_P - \xi_S) \tag{8}$$

$$\Phi_{\text{CP}} = \frac{\alpha}{\sqrt{1-\alpha^2}} \cos\phi\,\tan(\xi_P - \xi_S) \tag{9}$$

- same phase difference: these tests are related.
- **Single-step decays**: $B_{\text{CP}}(\Phi_{\text{CP}})$ also needs $\mathbf{P}_p$, not included at e^+e^- colliders $\rightarrow$ use only A_{CP} for Λ.
- **Two-step decays**: simultaneous A_{CP}, $B_{\text{CP}}(\Phi_{\text{CP}})$ measurement is possible.

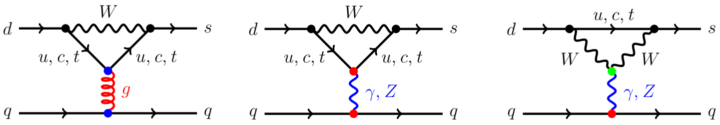
Hadron comparison

kaons

- $\Delta I = 1/2, 3/2$ amplitudes are both consequential
- CP-odd phases from QCD + EW penguins

hyperons

- $\Delta I = 1/2$ is **enough**
- CP-odd phases from **dominant** QCD penguin



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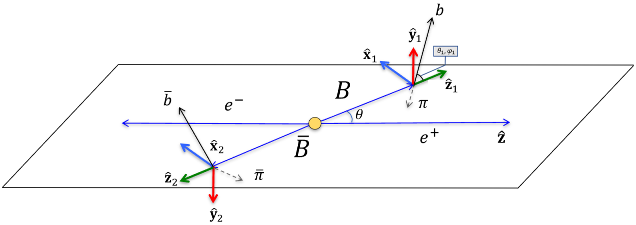
Hyperons can also provide complementary BSM info, e.g.: **chromomagnetic operator** [PRD69, 076008 (2004)]

$$(\xi_P - \xi_S)_{\mathrm{BSM}} = \frac{C'_B}{B_G}\left(\frac{\epsilon'}{\epsilon}\right)_{\mathrm{BSM}} + \frac{C_B}{\kappa}\epsilon_{\mathrm{BSM}} \tag{10}$$

- Model-independent constraint on hyperons from kaons: improving sensitivity in hyperon results can in turn affect kaon predictions.
- **However**, theoretical recalculations of the involved parameters are needed (χPT 1-loop corrections to S-, P-waves at Uppsala University, Sweden).

CPV in $e^+e^- \to J/\psi \to B\bar{B}$



	$\sigma(A_{CP}^{\Lambda})$	$\sigma(A_{CP}^{\Xi})$	$\sigma(B_{CP}^{\Xi})$	N
BESIII	1.0×10^{-2}	1.3×10^{-2}	3.5×10^{-2}	$1.3 \times 10^{9}\ J/\psi$
BESIII	3.6×10^{-3}	4.8×10^{-3}	1.3×10^{-2}	$1.0 \times 10^{10}\ J/\psi$
SCTF	2.0×10^{-4}	2.6×10^{-4}	6.8×10^{-4}	$3.4 \times 10^{12}\ J/\psi$

SM: $A_{CP}^{\Lambda} \sim (1-5) \times 10^{-5}$; $B_{CP}^{\Xi} \simeq \mathcal{O}(10^{-4})$[PRD67, 056001 (2003)]

Uncertainty still larger than SM CPV signals! **Improvements**:

- CM energy spread ΔE compensation
- **e$^-$ beam polarization**.

Spin production matrix

Jacob-Wick formalism: $B\overline{B}$ spin correlation matrix for $1/2 + \overline{1/2}$ [PRD99, 056008 (2019)]

$$\rho_{B,\bar{B}} = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}}(\theta)\ \sigma_{\mu}^{B} \otimes \sigma_{\bar{\nu}}^{\bar{B}} \tag{11}$$

$C_{\mu\bar{\nu}}(\theta)$ with longitudinal polarization of electron beam

$$\frac{3}{3+\alpha_\psi}\begin{pmatrix} 1+\alpha_\psi\cos^2\theta & \gamma_\psi P_e\sin\theta & \beta_\psi\sin\theta\cos\theta & (1+\alpha_\psi)P_e\cos\theta \\ \gamma_\psi P_e\sin\theta & \sin^2\theta & 0 & \gamma_\psi\sin\theta\cos\theta \\ -\beta_\psi\sin\theta\cos\theta & 0 & \alpha_\psi\sin^2\theta & -\beta_\psi P_e\sin\theta \\ -(1+\alpha_\psi)P_e\cos\theta & -\gamma_\psi\sin\theta\cos\theta & -\beta_\psi P_e\sin\theta & -\alpha_\psi-\cos^2\theta \end{pmatrix}$$

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spin-correlation terms

$$\langle \mathbf{P}_B^2 \rangle = \int \mathbf{P}_B^2 \left(\frac{1}{\sigma} \frac{d\sigma}{d\Omega_B} \right) d\Omega_B\ . \tag{12}$$

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B polarization

$$\frac{3}{3+\alpha_\psi}\begin{pmatrix} 1+\alpha_\psi \cos^2\theta & \gamma_\psi P_e \sin\theta & \beta_\psi \sin\theta\cos\theta & (1+\alpha_\psi)P_e\cos\theta \\ \gamma_\psi P_e \sin\theta & \sin^2\theta & 0 & \gamma_\psi \sin\theta\cos\theta \\ -\beta_\psi \sin\theta\cos\theta & 0 & \alpha_\psi \sin^2\theta & -\beta_\psi P_e \sin\theta \\ -(1+\alpha_\psi)P_e\cos\theta & -\gamma_\psi \sin\theta\cos\theta & -\beta_\psi P_e \sin\theta & -\alpha_\psi - \cos^2\theta \end{pmatrix}$$

$\overline{B}$ polarization

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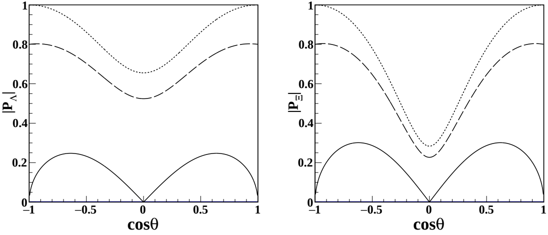
Projections with polarized beam

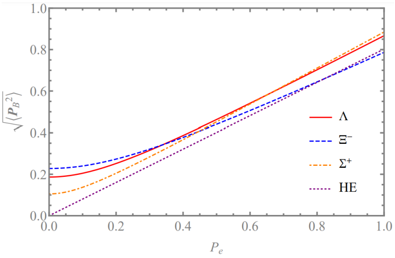
$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$ $\qquad$ $e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$



...... $P_e = 1$

- - $P_e = 0.8$

— $P_e = 0$



$$\langle \mathbf{P}_B^2 \rangle = \mathbb{p}_0 + \mathbb{p}_2 P_e^2 \qquad (13)$$

Approx. maximum likelihood method

Fisher information matrix

$$\mathcal{I}(\omega_k, \omega_l) := N \int \frac{1}{\mathcal{P}} \frac{\partial \mathcal{P}}{\partial \omega_k} \frac{\partial \mathcal{P}}{\partial \omega_l} \mathrm{d}\boldsymbol{\xi} \tag{14}$$

To compute e.g. $\mathcal{I}_0(A_{\mathrm{CP}})$ assume

$$\frac{1}{\mathcal{P}} = \frac{\mathcal{V}}{C_{00}} \frac{1}{1+\mathcal{G}} = \frac{\mathcal{V}}{C_{00}} \sum_{i=0}^{\infty} (-\mathcal{G})^i \text{ with } \int \mathcal{G} \mathrm{d}\boldsymbol{\xi} = 0 \ , \ \mathcal{G} \geq -1 \tag{15}$$

Single-step:

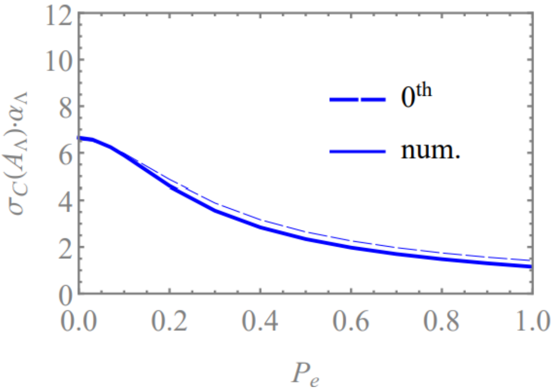
$$\mathcal{I}_0(A_{\mathrm{CP}}) = \frac{2N}{3} \alpha^2 \left\langle \mathbf{P}_B^2 \right\rangle \implies \sigma(A_{\mathrm{CP}}) \approx \sqrt{\frac{3}{2}} \frac{1}{\alpha \sqrt{N \left\langle \mathbf{P}_B^2 \right\rangle}} \ . \tag{16}$$

Two-step:

$$\mathcal{I}_0(\omega_i, \omega_j) = N \left[\mathbb{a}_{ij} + \mathbb{b}_{ij} \left\langle \mathbb{P}_{\Xi}^2 \right\rangle + \mathbb{c}_{ij} \left\langle \mathbb{S}_{\Xi\Xi}^2 \right\rangle \right] \tag{17}$$

Single-step decays: $\Lambda\bar{\Lambda}$

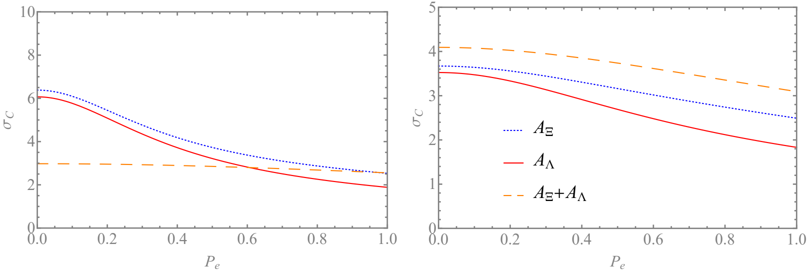
$$\sigma(A_{\mathrm{CP}}) \approx \sqrt{\frac{3}{2}}\frac{1}{\alpha\sqrt{N\left\langle \mathbf{P}_{\Lambda}^{2}\right\rangle}} \tag{18}$$



0-th order approx. already close to full numerical result.

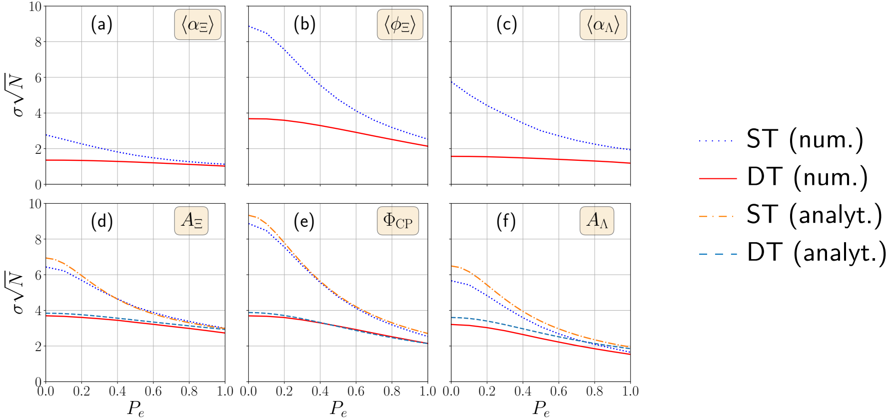
Two-step decays: $\Xi\bar{\Xi}$

Measurable CP asymmetries: A_Ξ, A_Λ, Φ_Ξ. Using the analytical approximation - ST (left), DT (right),



- $\mathrm{Cov}(A^\Lambda_{\mathrm{CP}}, A^{\bar{\Xi}}_{\mathrm{CP}}) \neq 0$: slightly more complicated analytical formulae for $\sigma(A_\Xi)$, $\sigma(A_\Lambda)$;
- Φ_{CP} is uncorrelated to any other variable: the baryon azimuthal angle φ_b is integrated out.

Two-step decays: $\Xi\bar{\Xi}$ (cont.)

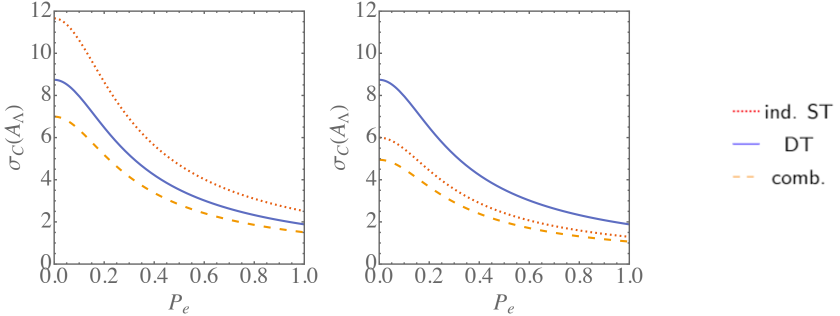


- $\langle\phi_\Xi\rangle$, $\langle\alpha_\Xi\rangle$, $\langle\alpha_\Lambda\rangle$ uncertainties are all correlated;
- A_Ξ, A_Λ, Φ_Ξ: $P_e \neq 0$ improves ST much more than DT; well described by analytical approx.

Experimental considerations

Combining ST and DT events: the best precision can be obtained by overlapping 3 event sets (2xST, DT).

Single-step decay: Λ

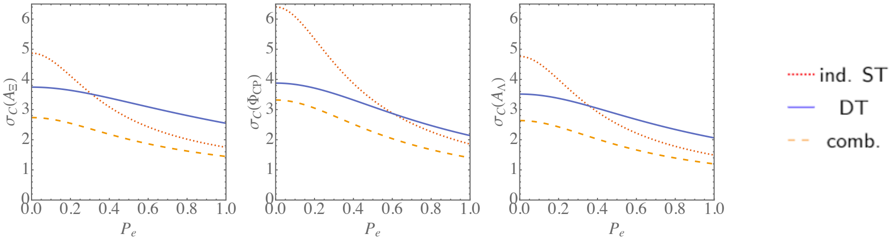


Assumed detection efficiencies: $\epsilon = 1$ (left) and $\epsilon = 0.5$ (right).

ST-DT combined corresponds to a two-times σ_C improvement
(wrt using DT only).

Experimental considerations (cont.)

Two-step decay: Ξ



Assumed detection efficiency: $\epsilon = 0.5$ - for $P_e = 0.8$, realistic ϵ (BESIII ST, DT).

Even more noticeably, **ST improves faster than DT**.

Conclusions and outlook

- Hyperons can provide a complementary source of information about CPV in the strange sector.
- For $e^+e^- \to B\bar{B}$ produced hyperons, a polarized beam affects the final baryon polarization which can **directly** impact statistical uncertainties of CPV observables.
- We have obtained a **model-independent parametrization**: possible extension to charmed baryon CPV studies.
- [arXiv:2203.03035]*Study of CP violation in hyperon decays at Super Charm–Tau Factory with polarized electron beam*, N. Salone, P. Adlarson, V. Batozskaya, A. Kupść, S. Leupold, J. Tandean.

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Thank you for your attention!

Isospin phenomenology

- Weak transitions **do not** conserve isospin:

$$L = \sum_{j=\{2\Delta I, 2I\}} L_j \exp i(\xi_j^L + \delta_{2I}^L) \tag{19}$$

  - $\{2\Delta I, 2I\}$ - I final state isospin, ΔI isospin variation
  - ξ_j^L - weak CP-odd phase
  - δ_{2I}^L - strong and EM final state interaction phase.
- δ_{2I}^L phases for produced $\pi - N$ system [PR625, 1 (2016)]

	$\lvert\mathbf{q}\rvert$ [MeV/c]	$\delta_1^S[^\circ]$	$\delta_3^S[^\circ]$	$\delta_1^P[^\circ]$	$\delta_3^P[^\circ]$
Λ	103	6.52(95)	$-4.60(73)$	$-0.793(79)$	$-0.752(37)$

Case 1: Ξ baryons

From decays

$$\Xi^- \to \Lambda\pi^- \quad , \quad \Xi^0 \to \Lambda\pi^0 \tag{20}$$

neglecting kinematic isospin breaking, at leading order $\Delta I = 1/2$

1. amplitudes squared

$$|\mathcal{A}_{\Xi,-}|^2 + |\mathcal{A}_{\Xi,0}|^2 \quad ; \quad |\mathcal{A}_{\Xi,-}|^2 - 2|\mathcal{A}_{\Xi,0}|^2 \tag{21}$$

$$\frac{1}{2}\frac{\tau_0 - 2\tau_- r_\Xi}{\tau_0 + \tau_- r_\Xi} = s^2 s_3 + (1-s^2)p_3 \overset{\text{exp}}{=} -0.051(11) \tag{22}$$

2. decay parameters [BESIII], [PDG rev.]

$$\alpha := \frac{2\alpha_- + \alpha_0}{3} \approx 2s\sqrt{1-s^2} \overset{\text{exp}}{=} -0.368(4) \tag{23}$$

$$\frac{\alpha_- - \alpha_0}{\alpha} = -\frac{3}{2}(2s^2-1)(s_3-p_3) \overset{\text{exp}}{=} 0.092(25) \tag{24}$$

Case 2: Λ baryons

In the same fashion, from channels

$$\Lambda \to p\pi^- \quad , \quad \Lambda \to n\pi^0 \tag{25}$$

1. amplitudes squared

$$|\mathcal{A}_{\Lambda,-}|^2 + |\mathcal{A}_{\Lambda,0}|^2 \quad ; \quad |\mathcal{A}_{\Lambda,-}|^2 - 2|\mathcal{A}_{\Lambda,0}|^2 \tag{26}$$

$$-\frac{1}{\sqrt{8}}\frac{\mathcal{B}_- - 2\mathcal{B}_0 r_\Lambda}{\mathcal{B}_- + \mathcal{B}_0 r_\Lambda} = s_3 s^2 \cos(\delta_1^S - \delta_3^S) + p_3(1-s^2)\cos(\delta_1^P - \delta_1^P) \overset{\text{exp}}{=} 0.019(4) \tag{27}$$

2. decay parameters [BESIII], [NP15, 631 (2019)]

$$\alpha := \frac{2\alpha_- + \alpha_0}{3} = s\sqrt{1-s^2}\cos(\delta_1^S - \delta_3^P) \overset{\text{exp}}{=} 0.734(06) \tag{28}$$

$$\frac{\alpha_- - \alpha_0}{\alpha} = \frac{3}{\sqrt{2}}\frac{\Delta\alpha_{3/2}}{\cos(\delta_1^P - \delta_1^S)} \overset{\text{exp}}{=} 0.086(24) \tag{29}$$

Results

- s, s_3, p_3 represent different amplitudes fractions:
  - $\Xi : I = 1, \quad \Delta I = \frac{1}{2}, \frac{3}{2} \quad \Longrightarrow \quad s := S_{1,2}, \quad \ell_3 := \frac{L_{3,2}}{L_{1,2}}$
  - $\Lambda : I = \frac{1}{2}, \frac{3}{2}, \quad \Delta I = \frac{1}{2}, \frac{3}{2} \quad \Longrightarrow \quad s := S_{1,1}, \quad \ell_3 := \frac{L_{3,3}}{L_{1,1}}$

Amplitude values [arXiv:2203.03035]:

	s	s_3	p_3
Ξ	$-2.05(1)$	$0.11(2)$	$-0.002(8)$
Λ	$-1.718(8)$	$-0.050(9)$	$0.036(9)$

Note:

- $P_{1,1}$, $P_{1,2}$ are constrained by normalization $S^2_{2\Delta I,2I} + P^2_{2\Delta I,2I} = 1$;
- no on-shell intermediate state: all amplitudes are real.

CP tests

CP tests [PRD 100, 114005 (2019)]

$$A_{\text{CP}} := \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}} \quad ; \quad B_{\text{CP}} := \frac{\beta + \overline{\beta}}{\alpha - \overline{\alpha}} \quad ; \quad \Phi_{\text{CP}} := \frac{\phi + \overline{\phi}}{2} \tag{30}$$

At $\Delta I = 1/2$ + LO corrections

$$B^{\Xi}_{\text{CP}} := \frac{2B^{\Xi,-}_{\text{CP}} + B^{\Xi,0}_{\text{CP}}}{3} = \tan(\xi^P_{1,2} - \xi^S_{1,2}) \tag{31}$$

$$A^{\Xi}_{\text{CP}} := \frac{2A^{\Xi,-}_{\text{CP}} + A^{\Xi,0}_{\text{CP}}}{3} = -\tan(\xi^P_{1,2} - \xi^S_{1,2})\tan(\delta^P_2 - \delta^S_2) \tag{32}$$

$$B^{\Lambda}_{\text{CP}} := \frac{2B^{\Lambda,-}_{\text{CP}} + B^{\Lambda,0}_{\text{CP}}}{3} = \tan(\xi^P_{1,1} - \xi^S_{1,1}) \tag{33}$$

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The dominant **CPV** effect **in hyperons** can be studied using **only** $\boldsymbol{\Delta I = 1/2}$ **amplitudes**.