

# Light Hyperon Physics at BESIII

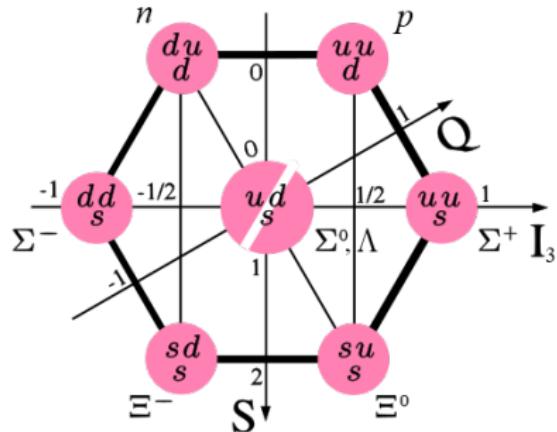
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collaboration

EPS-HEP Conference 2021

2021-07-26



# Hyperons



+  $\Omega^- (sss)$  Spin 3/2

| Hyperon    | Mass [ $\text{GeV}/c^2$ ] | Decay (BF)   |
|------------|---------------------------|--|
| $\Lambda$  | 1.116                     | $p\pi^-$ (63.9%)<br>$n\pi^0$ (35.8%)                                 |
| $\Sigma^-$ | 1.197                     | $n\pi^-$ (99.8%)   |
| $\Sigma^+$ | 1.189                     | $p\pi^0$ (51.6%)<br>$n\pi^+$ (48.3%)                                 |
| $\Xi^0$    | 1.315                     | $\Lambda\pi^0$ (99.5%)   |
| $\Xi^-$    | 1.321                     | $\Lambda\pi^-$ (99.8%)   |
| $\Omega$   | 1.672                     | $\Lambda K^-$ (67.8%)<br>$\Xi^0\pi^-$ (23.6%)<br>$\Xi^-\pi^0$ (8.6%) |

# Direct CP-Violation: Hyperon vs. Kaon Decays

To see CPV, need  $\geq 2$  amplitudes

**Kaons:**

Isospin amplitudes  $\mathcal{A}_{\Delta I=1/2}$  and  $\mathcal{A}_{\Delta I=3/2}$

Test direct CPV via  $\frac{\mathcal{A}(K_L \rightarrow \pi^0 \pi^0)}{\mathcal{A}(K_S \rightarrow \pi^0 \pi^0)} \equiv \epsilon - 2\epsilon'$ ,  $\frac{\mathcal{A}(K_L \rightarrow \pi^+ \pi^-)}{\mathcal{A}(K_S \rightarrow \pi^+ \pi^-)} \equiv \epsilon + \epsilon'$

**Hyperons:**

Two amplitudes  $S, P$  even for

$\Delta I = 1/2$ :

$$\mathcal{A} = S + P\sigma \cdot \hat{n}$$

**Strong phases**

$$S = |S| \exp(i\xi_S) \exp(i\delta_S)$$

$$P = |P| \exp(i\xi_P) \exp(i\delta_P)$$

**Weak CP-odd phases**

Two Measureable Parameters

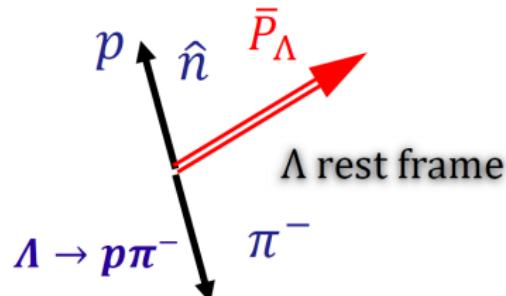
$$\alpha = \frac{2\text{Re}(S^*P)}{|S|^2 + |P|^2}$$

$$\beta = \frac{2\text{Im}(S^*P)}{|S|^2 + |P|^2}$$

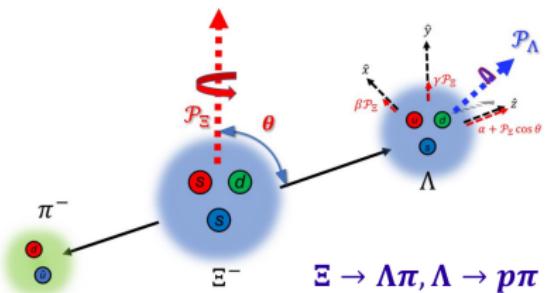
$$= \sqrt{1 - \alpha^2} \sin \phi$$

# Methods in Hyperon Decays

$$\frac{d\Gamma}{d\Omega} = \frac{1}{4\pi} (1 + \alpha_\Lambda \hat{n} \bar{P}_\Lambda)$$



Experimentally,  $\phi$  accessible when polarization of mother and daughter hyperon measured.



$$\beta = \sqrt{1 - \alpha^2} \sin \phi$$

# CP Tests in Hyperon Decays

If CP conserved:  $\bar{\alpha} = -\alpha$ ,  $\bar{\beta} = -\beta$  (Experimentally  $\bar{\phi} = -\phi$ )

CP-tests:  $A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$ ,  $B_{CP} = \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}} = (\xi_P - \xi_S)$

SM prediction <sup>1</sup>:

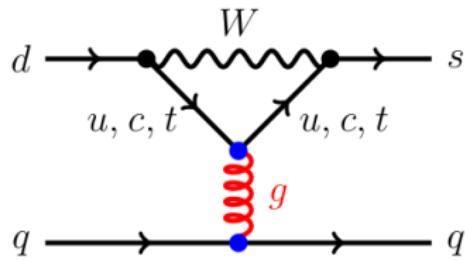
$$-3 \times 10^{-5} \leq A_\Lambda \leq 4 \times 10^{-5}$$

$$-2 \times 10^{-5} \leq A_\Xi \leq 1 \times 10^{-5}$$

| Decay mode                     | $\xi_S - \xi_P$  |
|--------------------------------|------------------|
| $\Lambda \rightarrow p\pi^-$   | $-(0.2 \pm 1.6)$ |
| $\Xi \rightarrow \Lambda\pi^-$ | $(1.4 \pm 1.2)$  |

HyperCP measurement<sup>2</sup>:

$$A_{CP}^\Xi + A_{CP}^\Lambda = 0(5)(4) \times 10^{-4}$$



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

$$0.5 < B_G < 2 \text{ and } 0.2 < |\kappa| < 1$$
<sup>3</sup>

| Decay                          | $C_B$          | $C'_B$        |
|--------------------------------|----------------|---------------|
| $\Lambda \rightarrow p\pi^-$   | $1.1 \pm 2.2$  | $0.4 \pm 0.8$ |
| $\Xi \rightarrow \Lambda\pi^-$ | $-0.5 \pm 1.0$ | $0.4 \pm 0.7$ |

<sup>1</sup>Tandean, Valencia PRD67 (2003) 056001

<sup>2</sup>PRL 93 (2004) 262001

<sup>3</sup>Tandean, PRD69 (2004) 076008

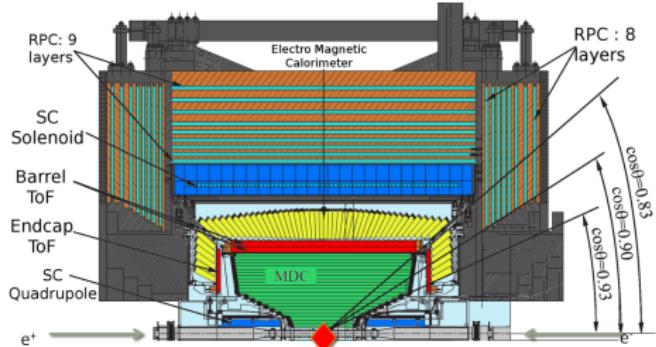
# BESIII at BEPCII

## Beijing Electron-Positron Collider (BEPCCII)

- CMS Energy from 2 to 4.95 GeV/ $c^2$
- Design luminosity  $10^{33}$  cm $^{-2}$ s $^{-1}$

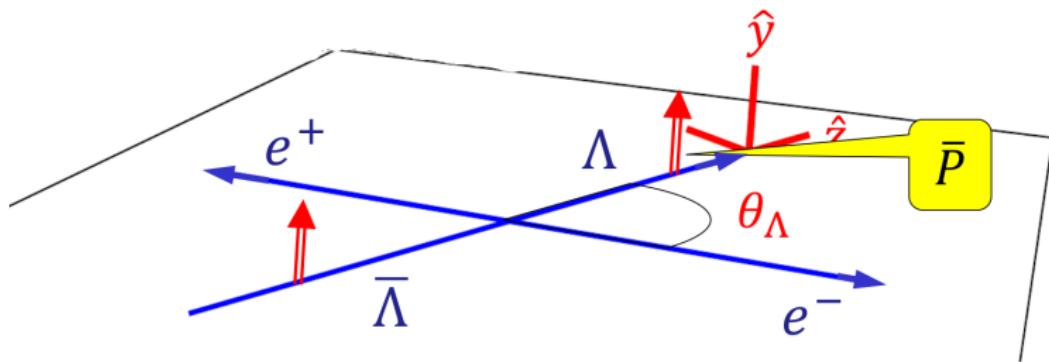
## Beijing Spectrometer (BESIII)

- Near  $4\pi$  coverage
- Helium-gas drift chamber
- CsI(Tl) crystal calorimeter
- MRPC TOF-system
- 1 T super-conducting solenoid
- RPC-based muon chamber
- World's largest datasets at:
  - $J/\psi$ : 10B events  
(here results from 1.3B)
  - $\psi(2S)$ : 3B events  
(here results from 0.4B)



| Decay  | $\mathcal{B} (10^{-5})$ | Events at BESIII   |
|--|-------------------------|--------------------|
| $J/\psi \rightarrow \Lambda \bar{\Lambda}$   | $189 \pm 9$             | $18.9 \times 10^6$ |
| $J/\psi \rightarrow \Sigma^+ \bar{\Sigma}^-$ | $150 \pm 24$            | $15.0 \times 10^6$ |
| $J/\psi \rightarrow \Xi \bar{\Xi}$           | $97 \pm 8$              | $9.7 \times 10^6$  |
| $\psi(2S) \rightarrow \Sigma \bar{\Sigma}$   | $23.2 \pm 1.2$          | $696 \times 10^3$  |
| $\psi(2S) \rightarrow \Omega \bar{\Omega}$   | $5.66 \pm 0.30$         | $170 \times 10^3$  |

# $B\bar{B}$ Production in $e^+e^-$ -Annihilation



Unpolarized  $e^+e^-$  beams  $\rightarrow$  Transverse polarization:

$$P_y(\cos \theta_\Lambda) = \frac{\sqrt{1-\alpha_\psi^2} \cos \theta_\Lambda \sin \theta_\Lambda}{1+\alpha_\psi \cos^2 \theta_\Lambda} \sin(\Delta\Phi)$$

Angular distribution:  $\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_\psi \cos^2 \theta_\Lambda$ ,  $-1 \leq \alpha_\psi \leq 1$

# $B\bar{B}$ Production in $e^+e^-$ -Annihilation: Modular Description

Two spin 1/2 particle state:

$$\rho_{1/2, \overline{1}/\overline{2}} = \frac{1}{4} \sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}} \sigma_\mu^\Lambda \otimes \sigma_{\bar{\nu}}^{\bar{\Lambda}}$$

$$C_{\mu\bar{\nu}} = \begin{pmatrix} 1 + \alpha_\psi \cos^2 \theta & 0 & \beta_\psi \sin \theta \cos \theta & 0 \\ 0 & \sin^2 \theta & 0 & \gamma_\psi \sin \theta \cos \theta \\ -\beta_\psi \sin \theta \cos \theta & 0 & \alpha_\psi \sin^2 \theta & 0 \\ 0 & -\gamma_\psi \sin \theta \cos \theta & 0 & -\alpha_\psi - \cos^2 \theta \end{pmatrix}$$

Spin correlations

$$\beta_\psi = \sqrt{1 - \alpha_\psi^2} \sin(\Delta\Phi) \quad \gamma_\psi = \sqrt{1 - \alpha_\psi^2} \cos(\Delta\Phi)$$

Include decay via decay matrices:

$$\sigma_\mu^\Lambda \rightarrow \sum_{\mu'=0}^3 a_{\mu,\mu'}^\Lambda \sigma_{\mu'}^p$$

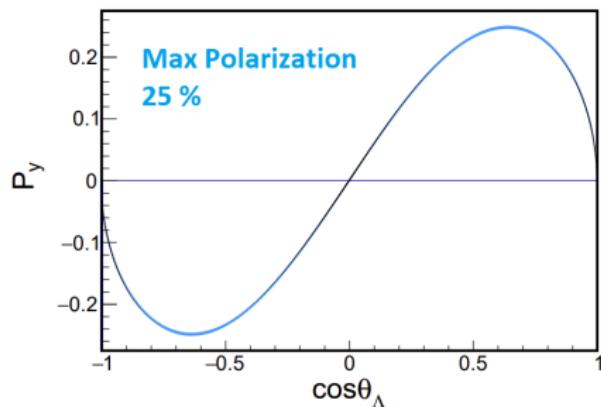
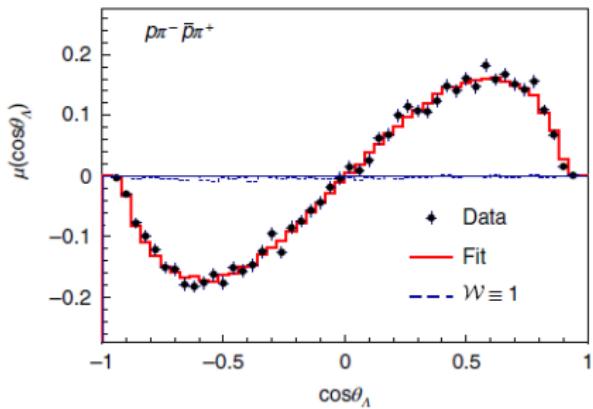
Full angular distribution:

$$W = Tr \rho_{p,\bar{p}} = \sum_{\mu,\bar{\nu}=0}^3 C_{\mu\bar{\nu}} a_{\mu,0}^\Lambda a_{\bar{\nu},0}^{\bar{\Lambda}}$$

$$e^+e^- \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\pi^- + c.c.$$

(Based on  $1.31 \times 10^9$   $J/\psi$  events)

Exclusive analysis. 421k events (399 background)



| Parameters             | This work                    | Previous results         |
|------------------------|------------------------------|--------------------------|
| $\alpha_\psi$          | $0.461 \pm 0.006 \pm 0.007$  | $0.469 \pm 0.027$ BESIII |
| $\Delta\Phi$ (rad)     | $0.740 \pm 0.010 \pm 0.008$  | —                        |
| $\alpha_\Lambda$       | $0.750 \pm 0.009 \pm 0.004$  | $0.642 \pm 0.013$ PDG    |
| $\bar{\alpha}_\Lambda$ | $-0.758 \pm 0.010 \pm 0.007$ | $-0.71 \pm 0.08$ PDG     |



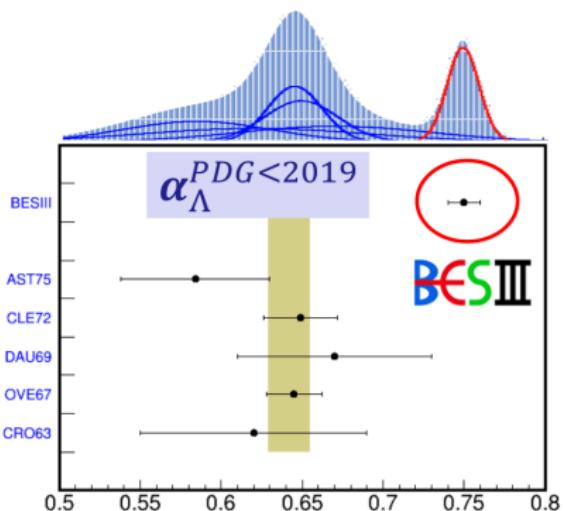
$$e^+e^- \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\pi^- + c.c.$$

$$A_{CP} = \frac{\alpha_\Lambda + \alpha_{\bar{\Lambda}}}{\alpha_\Lambda - \alpha_{\bar{\Lambda}}} = -0.006 \pm 0.012 \pm 0.007$$

PS185:  $A_\Lambda = 0.013 \pm 0.021$   
 PRC54(96)1877

$$\langle \alpha \rangle = \frac{\alpha + \bar{\alpha}}{2} = 0.754 \pm 0.003 \pm 0.002$$

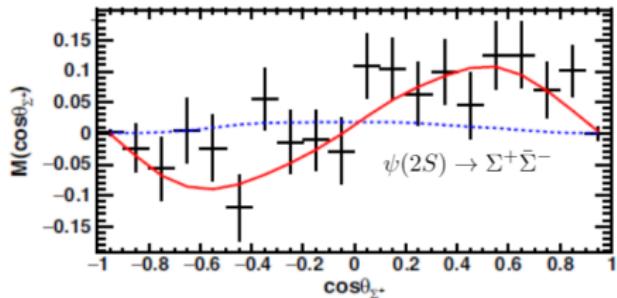
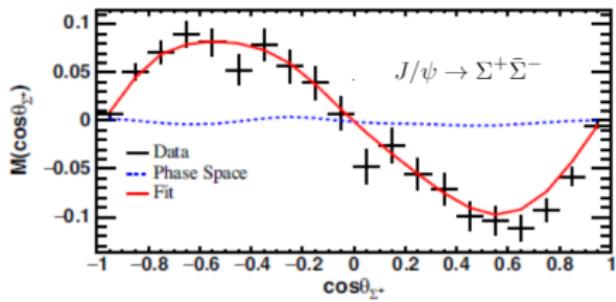
CLAS:  $\alpha_\Lambda = 0.721 \pm 0.006 \pm 0.005$   
 PRL 123 (2019) 182301



$$e^+e^- \rightarrow J/\psi, \psi(2S) \rightarrow \Sigma^+\bar{\Sigma}^-, \Sigma^+ \rightarrow p\pi^0 + c.c.$$

Based on  $1.31 \times 10^9$   $J/\psi$  events, and  $0.5 \times 10^9$   $\psi(2S)$  events.

Plots acceptance uncorrected



87k events (5% bkg)

$$\alpha_{J/\psi} = -0.507 \pm 0.006 \pm 0.002$$

$$\Delta\Phi(J/\psi) = (-15.4 \pm 0.7 \pm 0.3)^\circ$$

$$\langle \alpha \rangle = (\alpha - \bar{\alpha})/2 = -0.994 \pm 0.004 \pm 0.002$$

$$A_{CP} = -0.004 \pm 0.037 \pm 0.010$$

5k events (1% bkg)

$$\alpha_\psi = 0.676 \pm 0.030 \pm 0.006$$

$$\Delta\Phi(\psi) = (21.5 \pm 0.4 \pm 0.5)^\circ$$



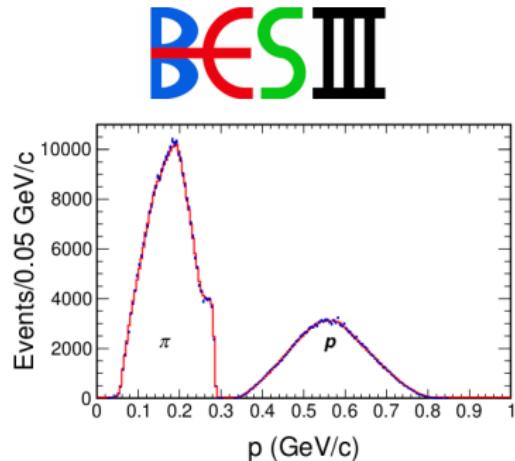
$$e^+e^- \rightarrow J/\psi \rightarrow \Xi^-\bar{\Xi}^+ \rightarrow \Lambda\pi^-\bar{\Lambda}\pi^+ \rightarrow p\pi^-\pi^-\bar{p}\pi^+\pi^+$$

$$W = \sum_{\mu,\bar{\nu}=0}^3 C_{\mu\bar{\nu}} \sum_{\mu',\bar{\nu}'=0}^3 a_{\mu,\mu'}^{\Xi} a_{\bar{\nu},\bar{\nu}'}^{\bar{\Xi}} a_{\mu',0}^{\Lambda} a_{\bar{\nu}',0}^{\bar{\Lambda}}$$

$d\Gamma \propto W(\xi, \omega)$ ,  $\xi$ : 9 kin. variables

**8 parameters:**

$$\omega = (\alpha_{\Psi}^{\text{Production}}, \Delta\Phi, \alpha_{\Xi}, \phi_{\Xi}, \alpha_{\Lambda}, \bar{\alpha}_{\Xi}, \bar{\phi}_{\Xi}, \bar{\alpha}_{\Lambda})_{\text{Decay}}$$



- Exclusive analysis. 73k events (190 bkg)
- Parameters estimated using unbinned MLL fit

$$e^+ e^- \rightarrow J/\psi \rightarrow \Xi^- \bar{\Xi}^+ \rightarrow \Lambda \pi^- \bar{\Lambda} \pi^+ \rightarrow p \pi^- \pi^- \bar{p} \pi^+ \pi^+$$

| Parameter                    | Preliminary                                 | Previous result                         |
|------------------------------|---|---|
| $\alpha_\psi$                | $0.586 \pm 0.012 \pm 0.010$                 | $0.58 \pm 0.04 \pm 0.08$ *              |
| $\Delta\Phi$                 | $1.213 \pm 0.046 \pm 0.016$ rad             | —                                       |
| $\alpha_{\Xi}$               | $-0.376 \pm 0.007 \pm 0.003$                | $-0.401 \pm 0.010$ **                   |
| $\phi_{\Xi}$                 | $0.011 \pm 0.019 \pm 0.009$ rad             | $-0.037 \pm 0.014$ rad **               |
| $\bar{\alpha}_{\Xi}$         | $0.371 \pm 0.007 \pm 0.002$                 | —                                       |
| $\bar{\phi}_{\Xi}$           | $-0.021 \pm 0.019 \pm 0.007$ rad            | —                                       |
| $\alpha$                     | $0.757 \pm 0.011 \pm 0.008$                 | $0.750 \pm 0.009 \pm 0.004$ ***         |
| $\bar{\alpha}$               | $-0.763 \pm 0.011 \pm 0.007$                | $-0.758 \pm 0.010 \pm 0.007$ ***        |
| $\delta_P - \delta_S$        | $(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad | $(10.2 \pm 3.9) \times 10^{-2}$ rad**** |
| $\xi_P - \xi_S$              | $(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad  | —                                       |
| $A_{\text{CP}}^{\Xi}$        | $(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$     | —                                       |
| $A_{\text{CP}}^{\Lambda}$    | $(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$    | $(-6 \pm 12 \pm 7) \times 10^{-3}$ ***  |
| $\langle \phi_{\Xi} \rangle$ | $0.016 \pm 0.014 \pm 0.007$ rad             |   |

## 8 Fit Parameters

### 3 CP tests



\* PRD 93, 072003 (2016)

\*\* PDG 2020

\*\*\* Nat. Ph. 15, 631 (2019)

\*\*\*\* PRL 93, 011802 (2004)

$$e^+e^- \rightarrow J/\psi \rightarrow \Xi^-\bar{\Xi}^+ \rightarrow \Lambda\pi^-\bar{\Lambda}\pi^+ \rightarrow p\pi^-\pi^-\bar{p}\pi^+\pi^+$$

| Parameter                    | Preliminary                                 | Previous result                     |      |
|------------------------------|---|-------------------------------------|------|
| $\alpha_\psi$                | $0.586 \pm 0.012 \pm 0.010$                 | $0.58 \pm 0.04 \pm 0.08$            | *    |
| $\Delta\Phi$                 | $1.213 \pm 0.046 \pm 0.016$ rad             | —                                   |      |
| $\alpha_{\Xi}$               | $-0.376 \pm 0.007 \pm 0.003$                | $-0.401 \pm 0.010$                  | **   |
| $\phi_{\Xi}$                 | $0.011 \pm 0.019 \pm 0.009$ rad             | $-0.037 \pm 0.014$ rad              | **   |
| $\bar{\alpha}_{\Xi}$         | $0.371 \pm 0.007 \pm 0.002$                 | —                                   |      |
| $\bar{\phi}_{\Xi}$           | $-0.021 \pm 0.019 \pm 0.007$ rad            | —                                   |      |
| $\alpha$                     | $0.757 \pm 0.011 \pm 0.008$                 | $0.750 \pm 0.009 \pm 0.004$         | ***  |
| $\bar{\alpha}$               | $-0.763 \pm 0.011 \pm 0.007$                | $-0.758 \pm 0.010 \pm 0.007$        | ***  |
| $\delta_P - \delta_S$        | $(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad | $(10.2 \pm 3.9) \times 10^{-2}$ rad | **** |
| $\xi_P - \xi_S$              | $(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad  | —                                   |      |
| $A_{CP}^-$                   | $(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$     | —                                   |      |
| $A_{CP}^{\Lambda}$           | $(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$    | $(-6 \pm 12 \pm 7) \times 10^{-3}$  | ***  |
| $\langle \phi_{\Xi} \rangle$ | $0.016 \pm 0.014 \pm 0.007$ rad             |                                     |      |

First  
measurement of  
weak phase  
difference

\* PRD 93, 072003 (2016)

\*\* PDG 2020

\*\*\* Nat. Ph. 15, 631 (2019)

\*\*\*\* PRL 93, 011802 (2004)



$$e^+e^- \rightarrow J/\psi \rightarrow \Xi^-\bar{\Xi}^+ \rightarrow \Lambda\pi^-\bar{\Lambda}\pi^+ \rightarrow p\pi^-\pi^-\bar{p}\pi^+\pi^+$$

| Parameter                | Preliminary                                 | Previous result                     |      |
|--------------------------|---|-------------------------------------|------|
| $\alpha_\psi$            | $0.586 \pm 0.012 \pm 0.010$                 | $0.58 \pm 0.04 \pm 0.08$            | *    |
| $\Delta\Phi$             | $1.213 \pm 0.046 \pm 0.016$ rad             | —                                   |      |
| $\alpha_\Xi$             | $-0.376 \pm 0.007 \pm 0.003$                | $-0.401 \pm 0.010$                  | **   |
| $\phi_\Xi$               | $0.011 \pm 0.019 \pm 0.009$ rad             | $-0.037 \pm 0.014$ rad              | **   |
| $\overline{\alpha}_\Xi$  | $0.371 \pm 0.007 \pm 0.002$                 | —                                   |      |
| $\overline{\phi}_\Xi$    | $-0.021 \pm 0.019 \pm 0.007$ rad            | —                                   |      |
| $\alpha$                 | $0.757 \pm 0.011 \pm 0.008$                 | $0.750 \pm 0.009 \pm 0.004$         | ***  |
| $\overline{\alpha}$      | $-0.763 \pm 0.011 \pm 0.007$                | $-0.758 \pm 0.010 \pm 0.007$        | ***  |
| $\delta_P - \delta_S$    | $(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad | $(10.2 \pm 3.9) \times 10^{-2}$ rad | **** |
| $\xi_P - \xi_S$          | $(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad  | —                                   |      |
| $A_{CP}^\Xi$             | $(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$     | —                                   |      |
| $A_{CP}^\Lambda$         | $(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$    | $(-6 \pm 12 \pm 7) \times 10^{-3}$  | ***  |
| $\langle\phi_\Xi\rangle$ | $0.016 \pm 0.014 \pm 0.007$ rad             |                                     |      |

Independent measurement of

$\alpha_A$



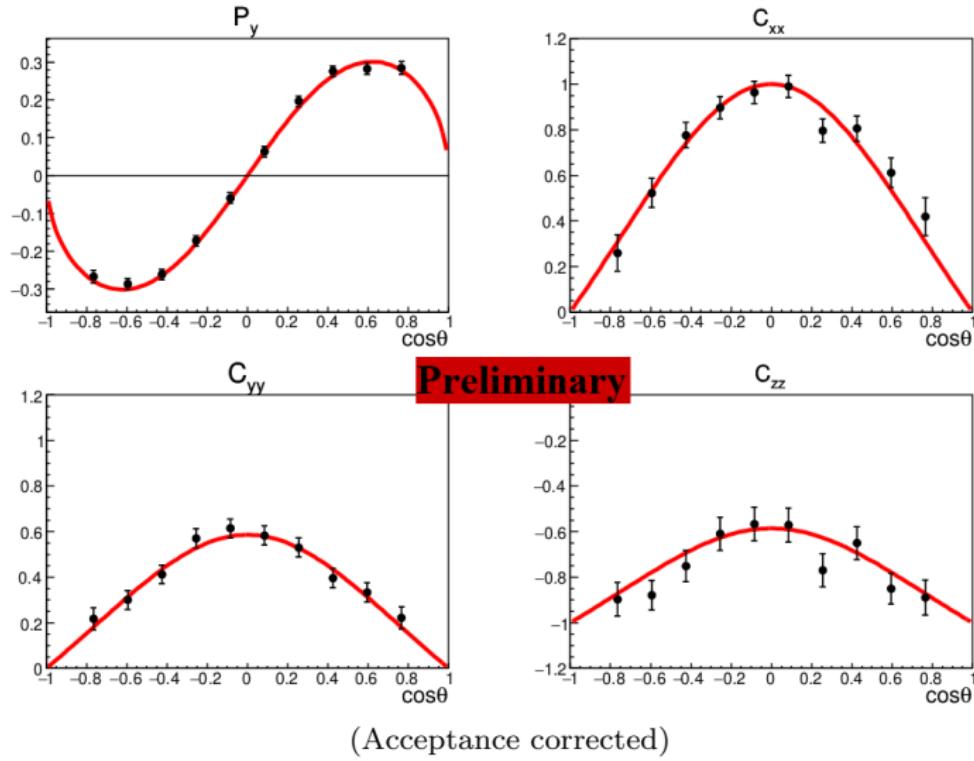
\* PRD 93, 072003 (2016)

\*\* PDG 2020

\*\*\* Nat. Ph. 15, 631 (2019)

\*\*\*\* PRL 93, 011802 (2004)

# Polarization and $C_{ii}$ for $e^+e^- \rightarrow J/\psi, \rightarrow \Xi\bar{\Xi}$

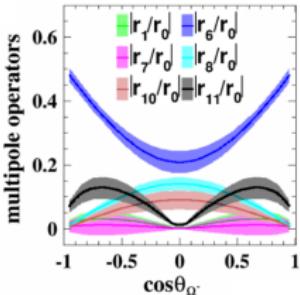
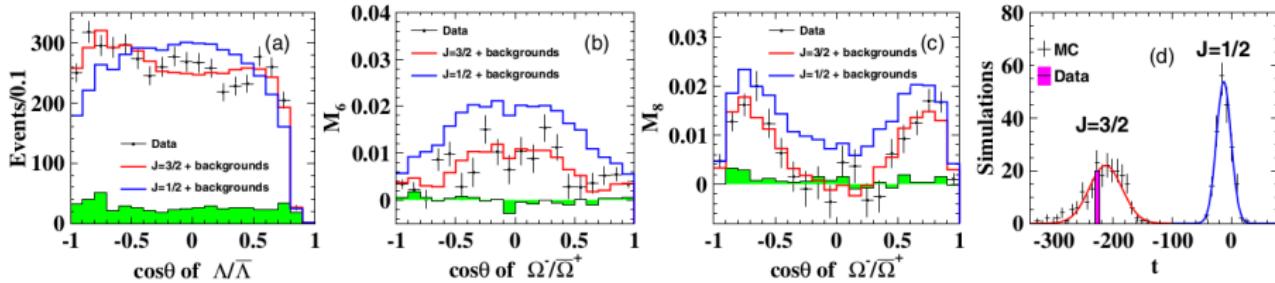


$$e^+e^- \rightarrow \psi(3686) \rightarrow \Omega\bar{\Omega}, \Omega \rightarrow \Lambda\pi^-, \Lambda \rightarrow p\pi^- + c.c.$$

$$W = \sum_{\mu=0}^{15} C_{\mu,0} \sum_{\mu=0}^3 b_{\mu,\mu}^\Omega a_{\mu,0}^\Lambda$$

decay  ${}^1/2 \rightarrow {}^1/2 + 0$   
 decay  ${}^3/2 \rightarrow {}^1/2 + 0$   
 $(\Omega^- \rightarrow \Lambda\pi^-)$

- Single-tag analysis of  $4.48 \times 10^8 \psi(2S)$  events  
 $\rightarrow 2507 \Omega^-$  (298 bkg) and  $2238 \bar{\Omega}^+$  (189 bkg)
- Spin 3/2 confirmed model-independently for the first time.
- Multipolar polarization measured



**BES III**

# Conclusion

## Summary

- Polarization/spin correlations measured in  
 $J/\psi(\psi(2S)) \rightarrow \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}, \Omega\bar{\Omega}$
- Hyperon and anti-hyperon decay parameters determined
- CP-tests in decays of  $\Lambda, \Sigma^+, \Xi^-$
- Model independent determination of  $\Omega^-$  spin

## Outlook

- At BESIII
  - 10B  $J/\psi$
  - 3B  $\psi(2S)$
- Future super charm-tau factory?
  - $2 \times 10^{12} J/\psi$

# Backup: Explicit Formalism for $e^+e^- \rightarrow Y\bar{Y}$ , $Y \rightarrow BM + c.c.$

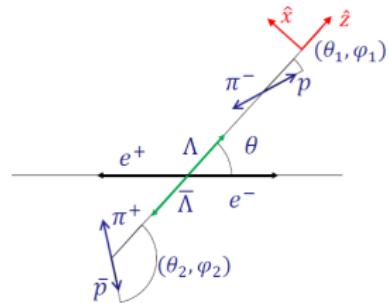
Production parameters:  $\alpha_\psi$ ,  $\Delta\Phi$

Decay parameters:

$$\alpha_\Lambda (\Lambda \rightarrow p\pi^-)$$

$$\bar{\alpha}_\Lambda (\bar{\Lambda} \rightarrow \bar{p}\pi^+)$$

5D phase space  $\xi = (\theta, \theta_1, \phi_1, \theta_2, \phi_2)$



$$d\Gamma \propto \mathcal{W}(\xi) = \mathcal{F}_0(\xi) +_\psi \mathcal{F}_5(\xi) \quad \text{Spin Correlations}$$

$$+ \alpha_\Lambda \bar{\alpha}_\Lambda \left( \mathcal{F}_1(\xi) + \sqrt{1 - \alpha_\psi^2} \cos(\Delta\Phi) \mathcal{F}_2(\xi) + \alpha_\psi \mathcal{F}_6(\xi) \right)$$

$$+ \sqrt{1 - \alpha_\psi^2} \sin(\Delta\Phi) (\alpha_\Lambda \mathcal{F}_3(\xi) + \bar{\alpha}_\Lambda \mathcal{F}_4(\xi)) \quad \text{Polarization}$$

Non-zero  $\Delta\Phi \implies$  independent measurement of  $\alpha_\Lambda$ ,  $\bar{\alpha}_\Lambda$