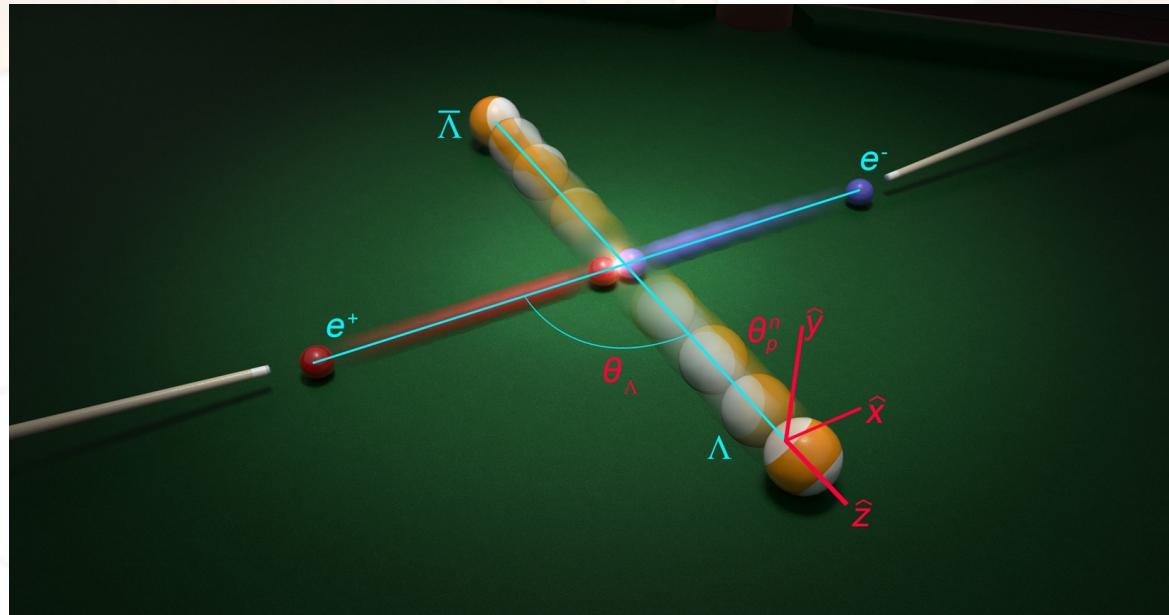




UPPSALA  
UNIVERSITET

# Discrete symmetry tests using hyperon-antihyperon pairs at BESIII

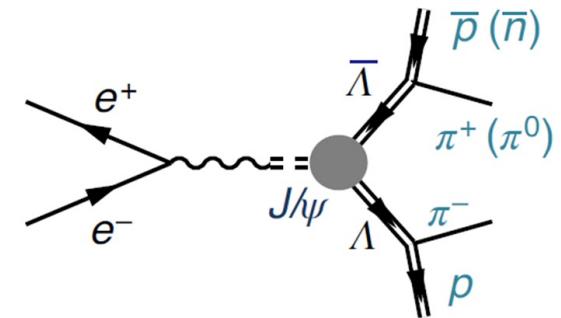
Andrzej Kupsc



and

- G.Fäldt, AK PLB772 (2017) 16
- E.Perotti,G.Fäldt,AK,S.Leupold,J.J.Song PRD99 (2019)056008
- P.Adlarson, AK PRD100 (2019) 114005
- N.Salone,P.Adlarson,V.Batozskaya,AK,S.Leupold, J. Tandean *PRD* 105 (2022) 116022

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



## Polarization and entanglement in baryon-antibaryon pair production in electron-positron annihilation

Nature Phys. 15 (2019) 631

The BESIII Collaboration\*

arXiv:2204.11058

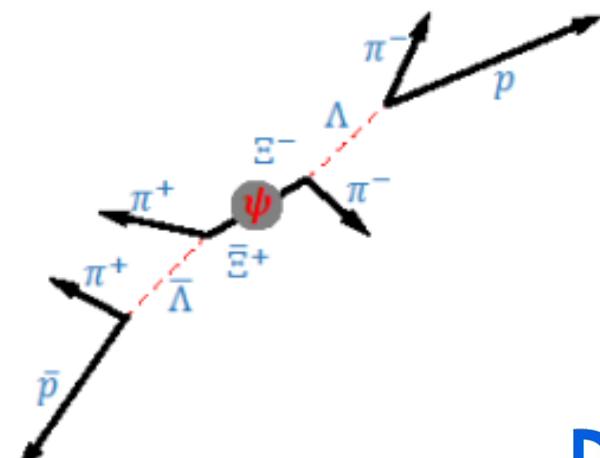
$$e^+ e^- \rightarrow J/\psi \rightarrow \Xi^- \bar{\Xi}^+$$

Article | Open Access | Published: 01 June 2022

## Probing CP symmetry and weak phases with entangled double-strange baryons

[The BESIII Collaboration](#)

[Nature](#) 606, 64–69 (2022) | [Cite this article](#)



BES<sup>2</sup>III

## CP symmetry in s-quark sector

CP violation due to quantum corrections

CPT restricts on CP violation

$K^0 - \bar{K}^0 (d\bar{s} - \bar{d}s)$  mixing  $\epsilon$ : 1964

Direct CP violation in  $K^0 \rightarrow \pi\pi$ :  $\text{Re}(\epsilon'/\epsilon) > 1988$

Measurement of (CP) asymmetries uses quantum interference

$$\text{Asym} = \frac{1}{2} |M_{SM} + \Delta_{BSM}|^2 - \frac{1}{2} |M_{SM} - \Delta_{BSM}|^2 = 2 \text{Re}(M_{SM} \Delta_{BSM}^*)$$

$$\sigma(\text{Asym}) \approx \frac{\mathcal{O}(1)}{\sqrt{N}} = \frac{\sigma_c}{\sqrt{N}} \quad \sigma(\text{Asym}) \sim 10^{-4} \text{ requires } N \sim 10^8$$

minimize  $\sigma_c$

eg 4× reduction implies 16×less data needed

# Direct CP violation in $K^0$ decays

$$(\text{I}) K^0 \rightarrow \pi^+ \pi^-$$

$$(\text{II}) K^0 \rightarrow \pi^0 \pi^0$$

$$|\mathcal{A}_{\text{I}}|^2 + |\mathcal{A}_{\text{II}}|^2 \xrightleftharpoons{CPT} |\bar{\mathcal{A}}_{\text{I}}|^2 + |\bar{\mathcal{A}}_{\text{II}}|^2$$

$$\begin{aligned} K^0 \rightarrow \pi^+ \pi^- & \quad \mathcal{A}_{\text{I}} = A_0 \exp(i\xi_0 + i\delta_0) + A_2 \exp(i\xi_2 + i\delta_2) \\ \bar{K}^0 \rightarrow \pi^+ \pi^- & \quad \bar{\mathcal{A}}_{\text{I}} = A_0 \exp(-i\xi_0 + i\delta_0) + A_2 \exp(-i\xi_2 + i\delta_2) \end{aligned}$$

$$\text{Re}(\epsilon') := \frac{1}{2} \frac{|\mathcal{A}_{\text{I}}|^2 - |\bar{\mathcal{A}}_{\text{I}}|^2}{|\mathcal{A}_{\text{I}}|^2 + |\bar{\mathcal{A}}_{\text{I}}|^2} \approx (\xi_0 - \xi_2) \sin(\delta_0 - \delta_2) \frac{A_2}{A_0}$$

$$3.7(5) \times 10^{-6} \approx (\xi_0 - \xi_2) \sin 47.7^\circ \frac{1}{22}$$

$$(\xi_0 - \xi_2) \approx 10^{-4} \text{ rad}$$

$$\text{Re}(\epsilon'/\epsilon) = (16.6 \pm 2.3) \cdot 10^{-4}$$

$$|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}$$

# $\epsilon'$ in SM and BSM

$\text{Re}(\epsilon'/\epsilon) = (16.6 \pm 2.3) \cdot 10^{-4}$  Exp. avg PDG

$(21.7 \pm 8.2) \times 10^{-4}$  Lattice QCD

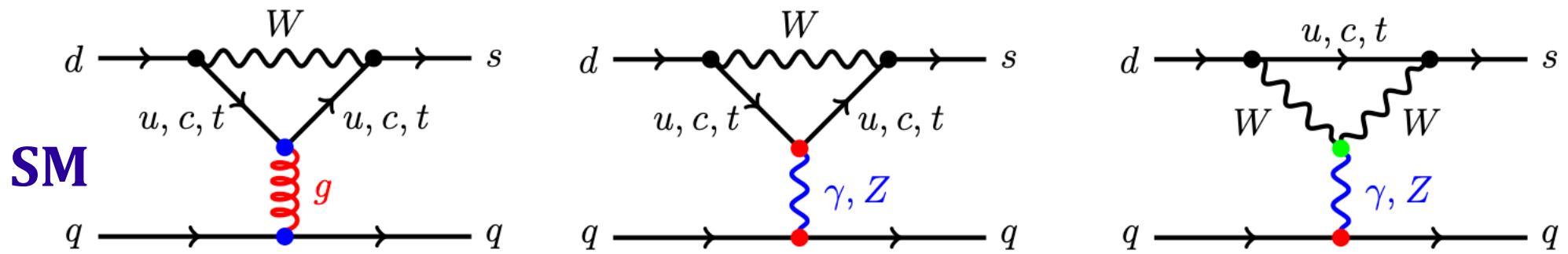
PRD 102 (2020) 054509

$(9.4 \pm 3.5) \times 10^{-4}$

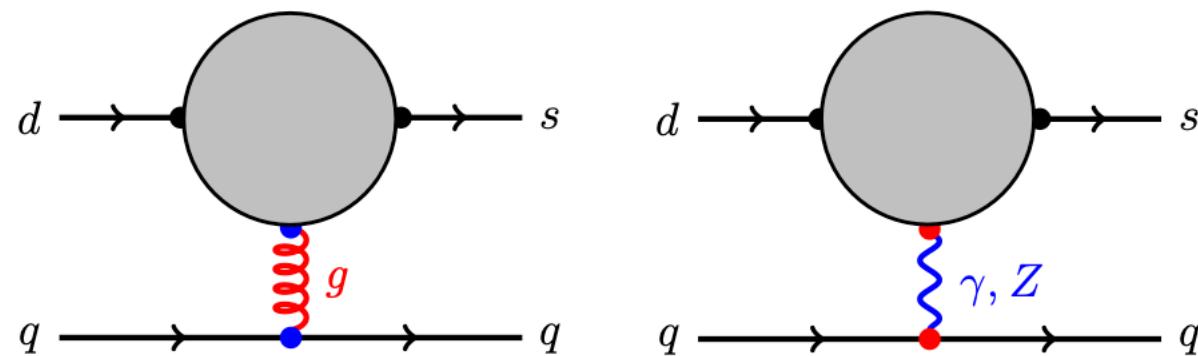
EPJC 80 (2020) 1

$(14 \pm 5) \times 10^{-4}$  EFT

RPP 81 (2018) 076201, JHEP 02 (2020) 032



## BSM



# Hyperon decays

$$\left. \begin{array}{ll} \Lambda(ds\bar{u}) & A(\Lambda \rightarrow p\pi^-) \\ \Xi^-(d\bar{s}s) & A(\Xi^- \rightarrow \Lambda\pi^-) \end{array} \right\} = S\sigma_0 + P \boldsymbol{\sigma} \cdot \hat{\mathbf{n}}$$

Transitions:

P (parity even) final state in p-wave  
 S (parity odd) final state in s-wave

weak CP-odd phases

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

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

Strong phase:  
 interaction of final particles

Measurable: BF and  
 two decay parameters

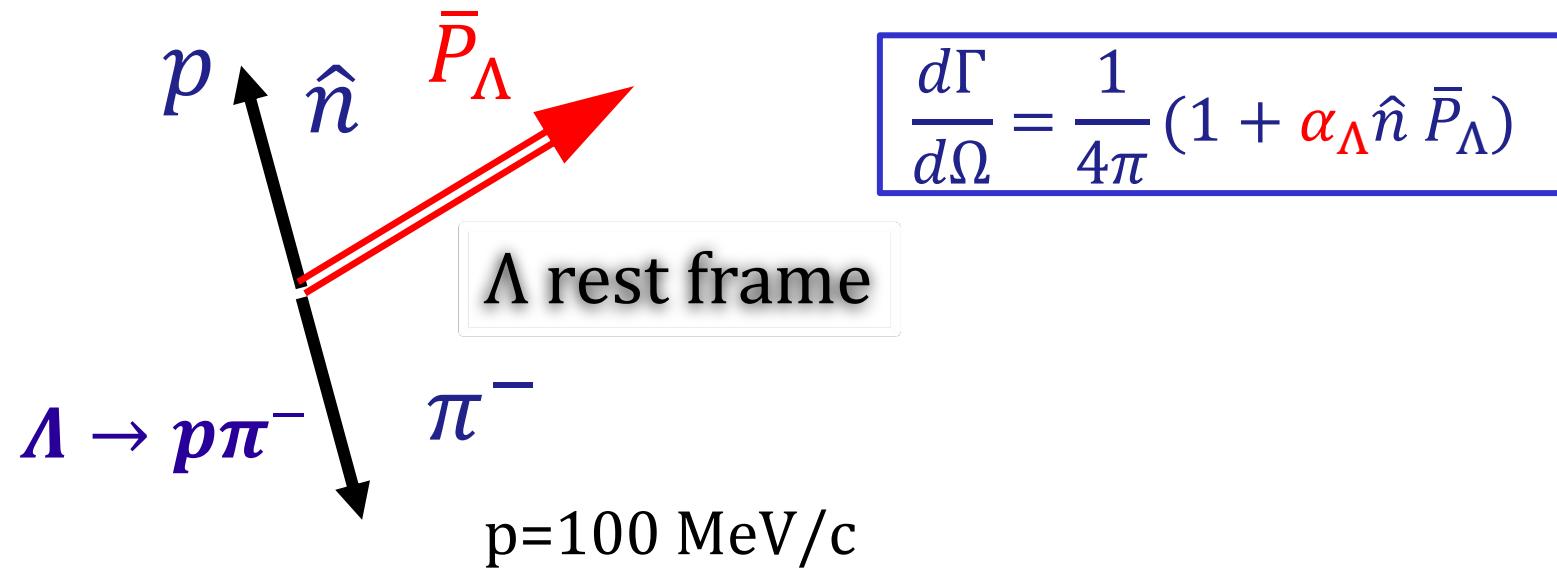
$$\alpha = \frac{2 \operatorname{Re}(S^* P)}{|S|^2 + |P|^2}$$

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

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

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

## Hyperon decay parameter $\alpha$



$$\alpha_\Lambda = 0.750(10)$$

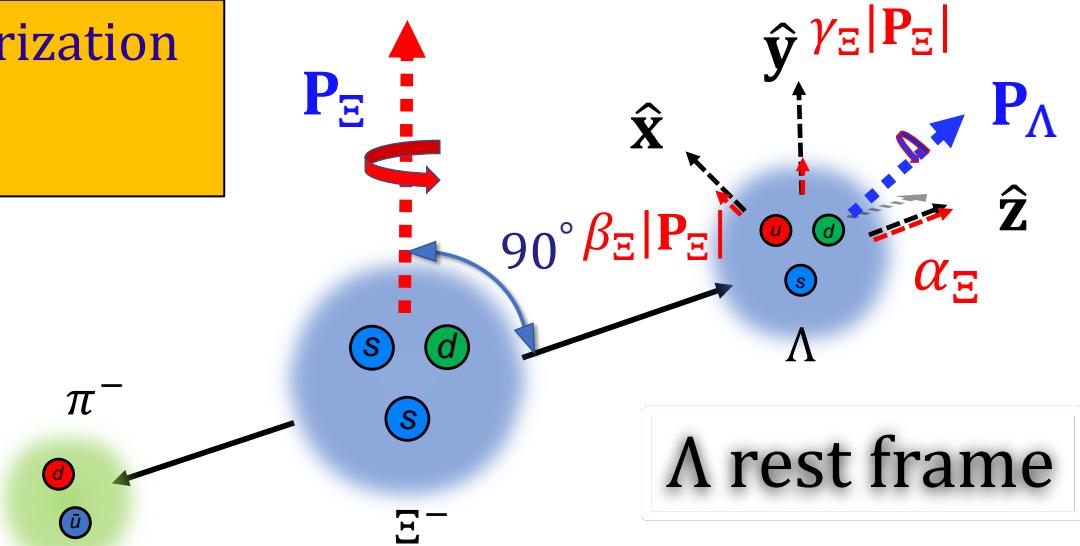
value before 2018:  $\alpha_\Lambda = 0.642(13)$

$$\alpha_\Xi = -0.392(8)$$

# Hyperon decay parameter $\phi$

$$\Xi \rightarrow \Lambda\pi, \Lambda \rightarrow p\pi$$

Accessible if daughter baryon polarization  
is measured eg decay sequence:  
 $\Xi \rightarrow \Lambda\pi, \Lambda \rightarrow p\pi$



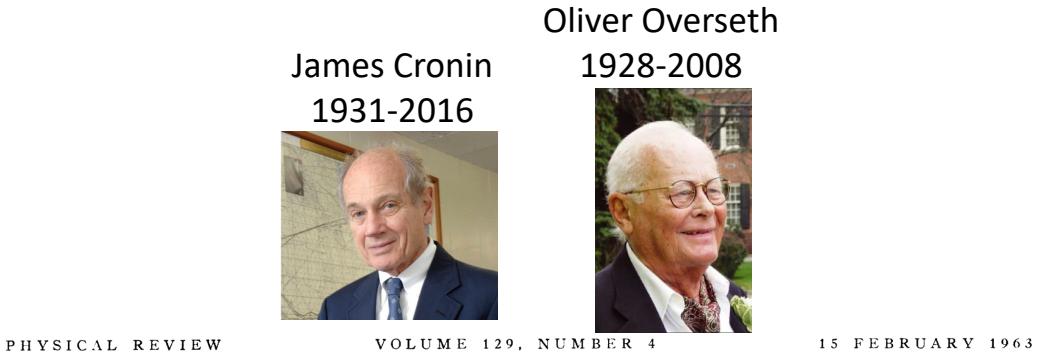
$$P_\Xi = 0 \Rightarrow P_\Lambda = \alpha \hat{z}$$

$$\mathbf{P}_\Lambda^{\parallel} = \alpha_\Xi \hat{z}$$

$$\mathbf{P}_\Lambda^{\perp} = |\mathbf{P}_\Xi| (\beta_\Xi \hat{x} + \gamma_\Xi \hat{y})$$

$$= |\mathbf{P}_\Xi| \sqrt{1 - \alpha_\Xi^2} (\sin \phi_\Xi \hat{x} + \cos \phi_\Xi \hat{y})$$

# $\alpha, \beta, \gamma$ measurements for $\Lambda$



## Measurement of the Decay Parameters of the $\Lambda^0$ Particle\*

JAMES W. CRONIN AND OLIVER E. OVERSETH†  
*Palmer Physical Laboratory, Princeton University, Princeton, New Jersey*  
(Received 26 September 1962)

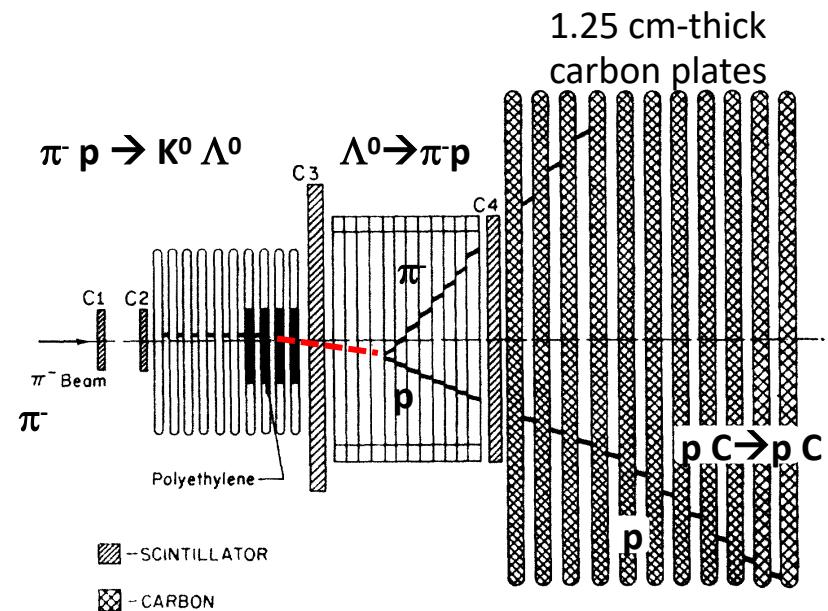
The decay parameters of  $\Lambda^0 \rightarrow \pi^- + p$  have been measured by observing the polarization of the decay protons by scattering in a carbon-plate spark chamber. The experimental procedure is discussed in some detail. A total of 1156 decays with useful proton scatters was obtained. The results are expressed in terms of polarization parameters,  $\alpha$ ,  $\beta$ , and  $\gamma$  given below:

$$\begin{aligned}\alpha &= 2 \operatorname{Re} s^*/(|s|^2 + |p|^2) = +0.62 \pm 0.07, \\ \beta &= 2 \operatorname{Im} s^*/(|s|^2 + |p|^2) = +0.18 \pm 0.24, \\ \gamma &= |s|^2 - |p|^2 / (|s|^2 + |p|^2) = +0.78 \pm 0.06,\end{aligned}$$

where  $s$  and  $p$  are the  $s$ - and  $p$ -wave decay amplitudes in an effective Hamiltonian  $s + p \sigma \cdot \mathbf{p} / |\mathbf{p}|$ , where  $\mathbf{p}$  is the momentum of the decay proton in the center-of-mass system of the  $\Lambda^0$ , and  $\sigma$  is the Pauli spin operator. The helicity of the decay proton is positive. The ratio  $|p|/|s|$  is  $0.36_{-0.06}^{+0.05}$  which supports the conclusion that the  $K\Lambda N$  parity is odd. The result  $\beta = 0.18 \pm 0.24$  is consistent with the value  $\beta = 0.08$  expected on the basis of time-reversal invariance.

$$P_p = \frac{(\alpha + P_\Lambda \cos \theta) \hat{z}' + \beta P_\Lambda \hat{x}' + \gamma P_\Lambda \hat{y}'}{1 + \alpha P_\Lambda \cos \theta}$$

$$\phi_\Lambda = -0.113(61) \text{ rad}$$



no  $H_2$  target, no magnet;  
use kinematics and proton's range in carbon to infer  $E_p$

Slide from Steve Olsen

## Testing CP violation in hyperon decays

$$\Xi^- \rightarrow \Lambda\pi^-$$

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

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

$$\bar{\Xi}^- \rightarrow \bar{\Lambda}\pi^+$$

$$\bar{S} = |\bar{S}| \exp(-i\xi_S + i\delta_S)$$

$$\bar{P} = -|P| \exp(-i\xi_P + i\delta_P)$$

CP-odd phases

$$A_{CP} := \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \text{ and } B_{CP} := \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}} \quad \Phi_{CP} = \frac{\phi + \bar{\phi}}{2}$$

$$\begin{aligned} A_{CP} &= -\frac{\sqrt{1-\alpha^2}}{\alpha} \sin \phi \tan(\xi_P - \xi_S) \\ &= -\tan(\delta_P - \delta_S) \tan(\xi_P - \xi_S) \end{aligned}$$

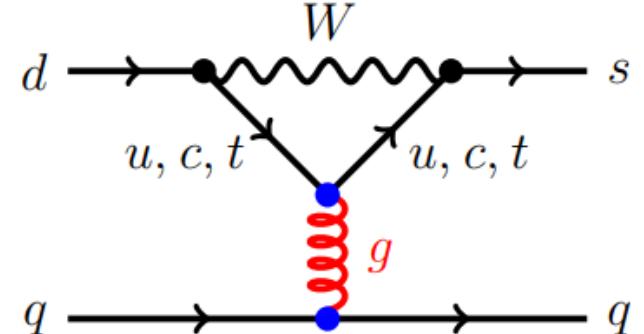
$$B_{CP} = \tan(\xi_P - \xi_S) ,$$

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

# Hyperon CPV in SM and BSM

weak  $P$ - $S$  phase difference

$$\xi_P - \xi_S$$



$(\eta \lambda^5 A^2)$	$\xi_P - \xi_S$ [ $10^{-4}$ rad]	$C_B$	$C'_B$
	SM		BSM
$\Lambda \rightarrow p \pi^-$	$-0.1 \pm 1.5$	$-0.2 \pm 2.2$	$0.9 \pm 1.8$
$\Xi^- \rightarrow \Lambda \pi^-$	$-1.5 \pm 1.2$	$-2.1 \pm 1.7$	$-0.5 \pm 1.0$

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

Kaon bounds for CPV in hyperon decays  
assuming chromomagnetic penguin

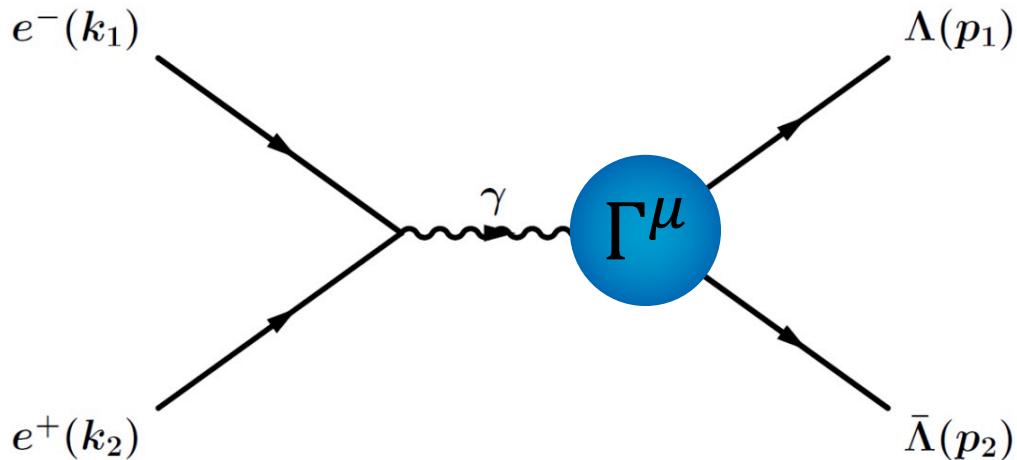
# BEPCII (Beijing)



$\tau$  -charm factory  $2 < \sqrt{s} < 4.95$  GeV:

- Charmonium spectroscopy/decays
- Light hadrons
- Charm
- $\tau$  physics
- R-scan

$$e^+ e^- \rightarrow \gamma^* \rightarrow B\bar{B} \text{ (spin 1/2)}$$



$$s = (p_1 + p_2)^2$$

$$q = p_1 - p_2$$

$$\Gamma^\mu(p_1, p_2) = -ie \left[ \gamma^\mu F_1(s) + i \frac{\sigma^{\mu\nu}}{2M_B} q_\nu F_2(s) \right]$$

$F_1$  (Dirac) and  $F_2$  (Pauli) Form Factors      complex for  $s > 4m_\pi^2$

Sachs Form Factors (FFs)  $\Leftrightarrow$  helicity amplitudes:

$$G_M(s) = F_1(s) + F_2(s), \quad G_E(s) = F_1(s) + \tau F_2(s)$$

$$\alpha_\psi = \frac{\tau|G_M|^2 - |G_E|^2}{\tau|G_M|^2 + |G_E|^2}$$

$$\tau = \frac{s}{4M_B^2}$$

# Hyperon-hyperon pair production at BESIII

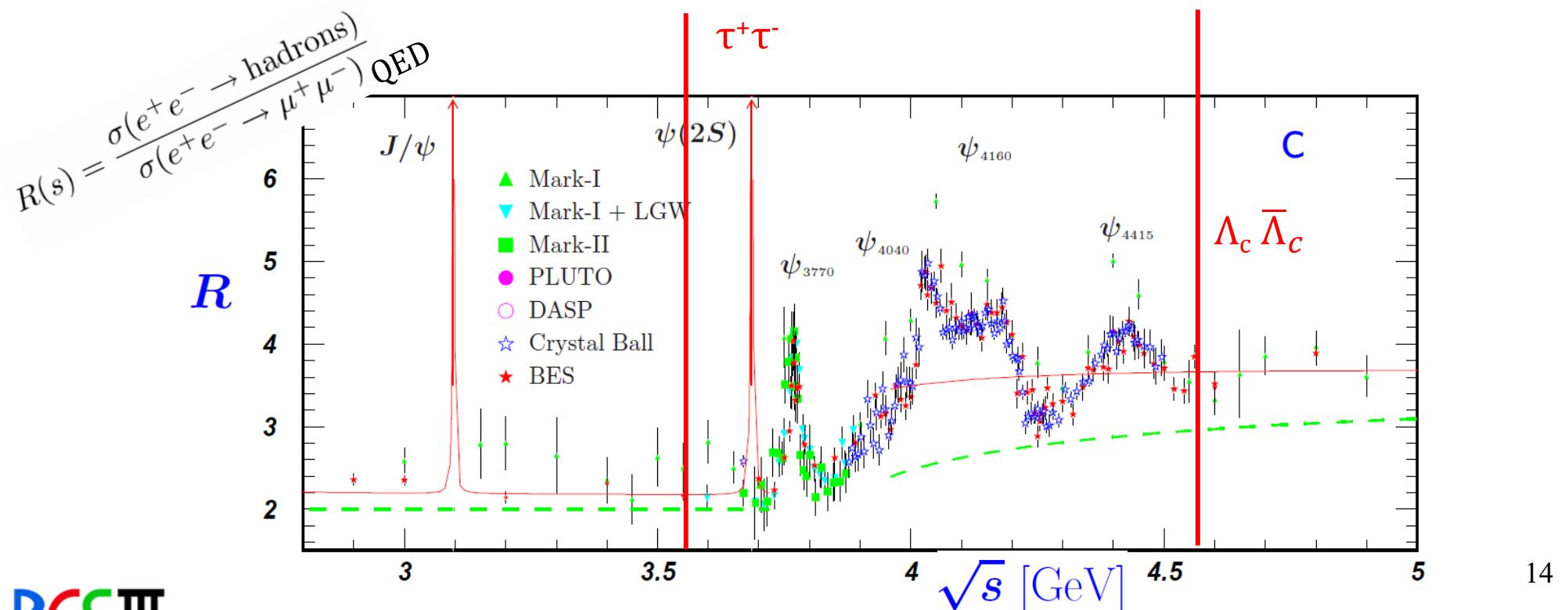
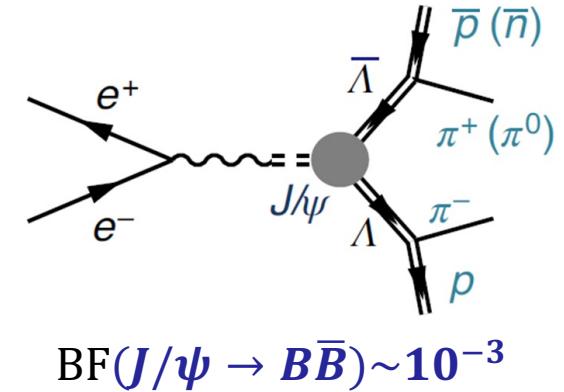
Thresholds:

$\Lambda\bar{\Lambda}$ : 2.231 GeV

$\Xi^-\bar{\Xi}^+$  2.643 GeV

$(\Omega\bar{\Omega})$  3.345 GeV

$10^{10} J/\psi$   
 $3.2 \times 10^9 \psi(2S)$

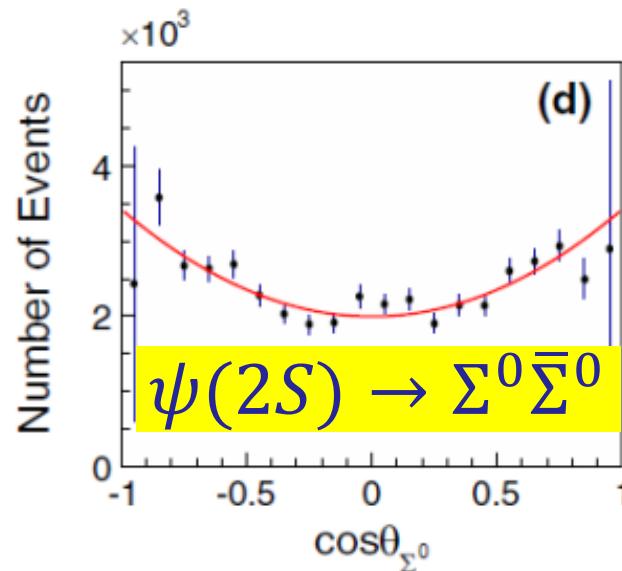
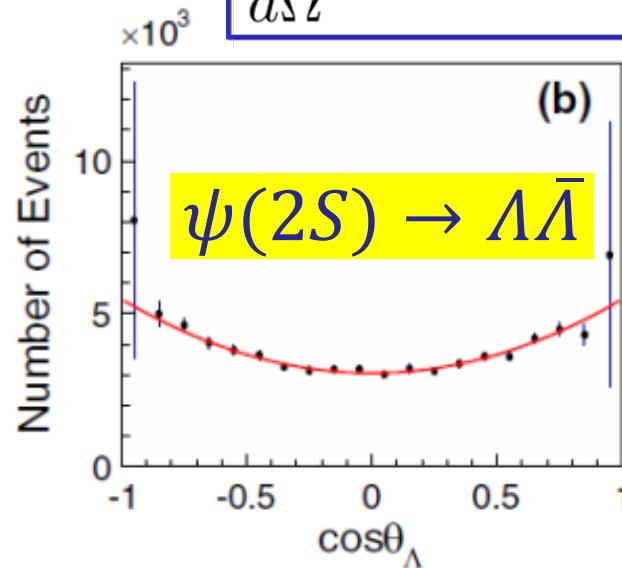
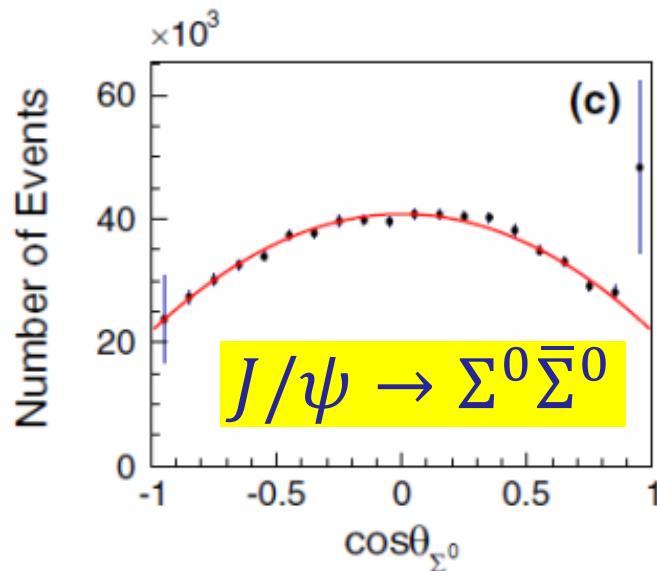
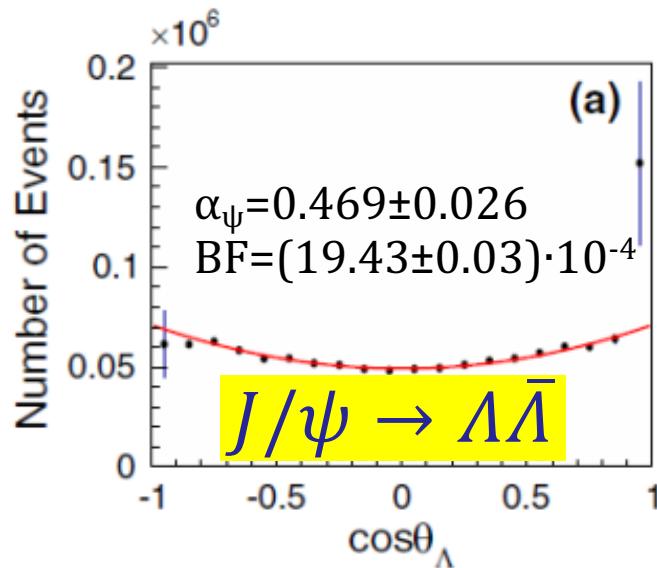


$J/\psi, \psi(2S) \rightarrow B\bar{B}$

Angular distribution:

$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_\psi \cos^2\theta$$

$$-1 < \alpha_\psi < 1$$

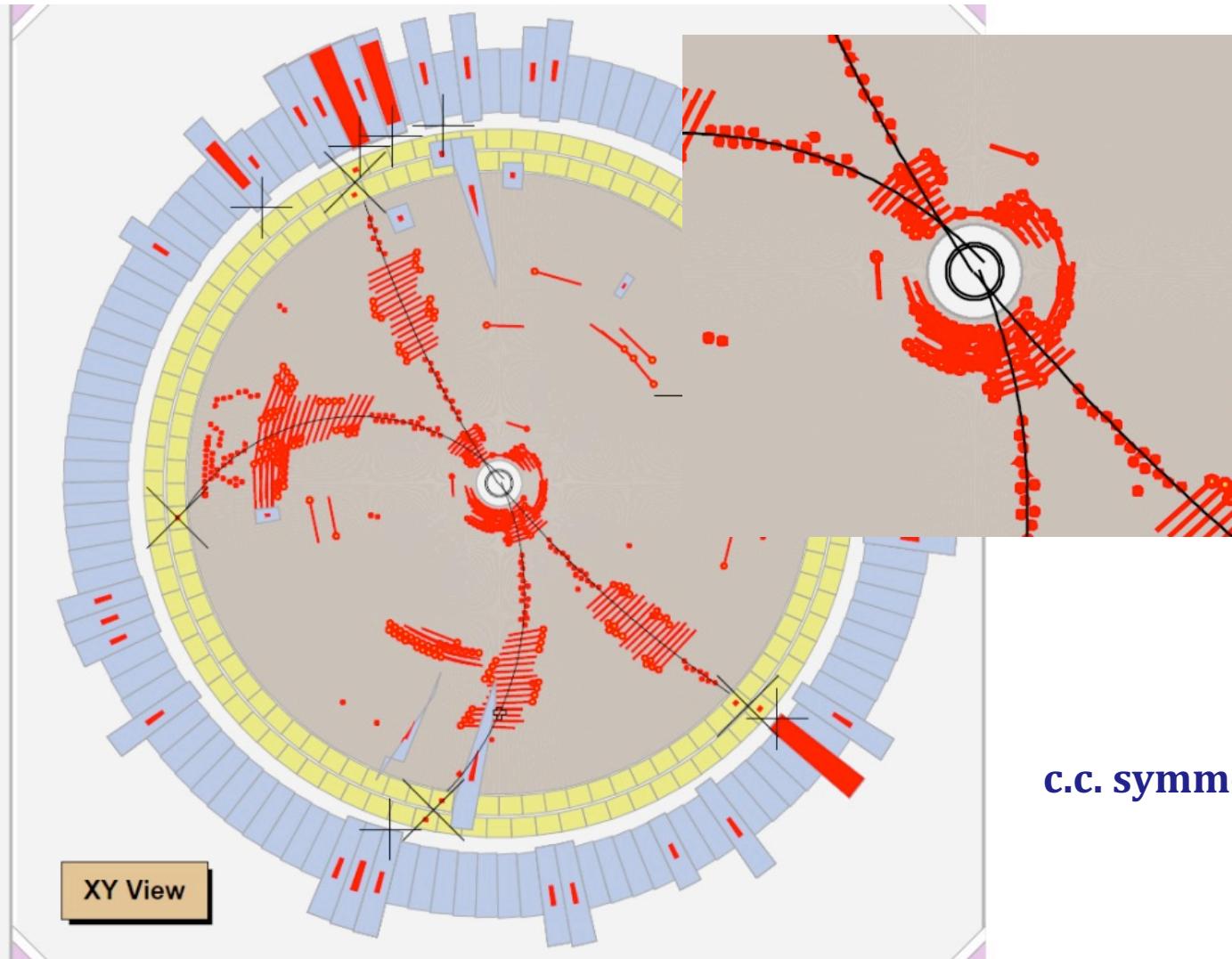


$\alpha_\psi$  measurements  
at ~~BES~~<sup>III</sup>

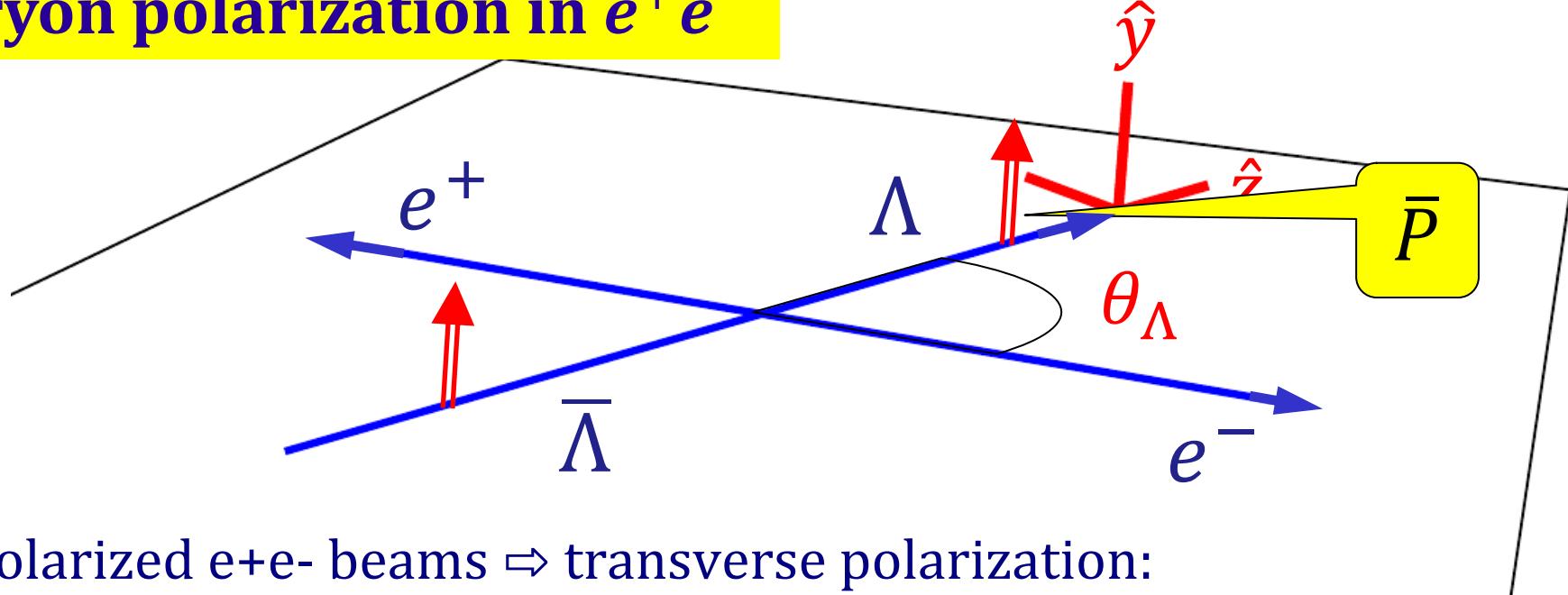
$$\alpha_\psi = \frac{\tau|G_M|^2 - |G_E|^2}{\tau|G_M|^2 + |G_E|^2}$$

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

event in BESIII detector

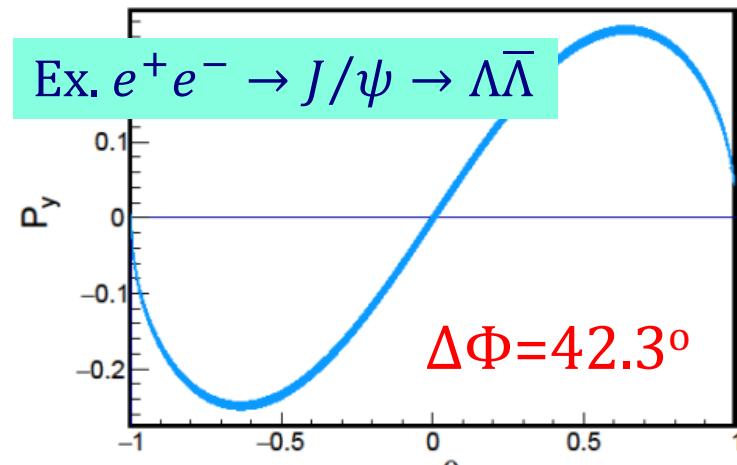


# Baryon polarization in $e^+e^-$



Unpolarized  $e^+e^-$  beams  $\Rightarrow$  transverse polarization:

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



$$\Delta\Phi \neq 0$$

$$\Delta\Phi = \text{Arg}(G_E/G_M)$$

$$\alpha_\psi = 0.469$$

# Baryon-antibaryon spin density matrix

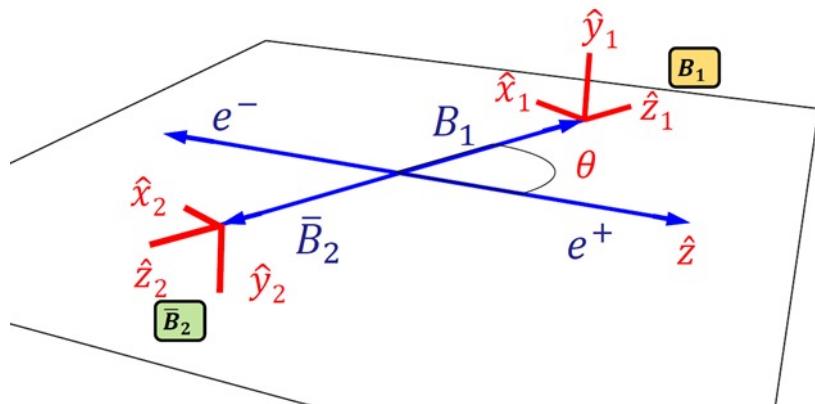
$$e^+ e^- \rightarrow B\bar{B}$$

$$\rho_{1/2,1/2} = \frac{1}{4} \sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}} \sigma_\mu^{B_1} \otimes \sigma_{\bar{\nu}}^{\bar{B}_2}$$

General two spin  $\frac{1}{2}$  particle state:

$$(\sigma_0 = \mathbf{1}_2, \sigma_1 = \sigma_x, \sigma_2 = \sigma_y, \sigma_3 = \sigma_z)$$

$$C_{\mu\bar{\nu}} = (1 + \alpha_\psi \cos^2 \theta)$$



$$\begin{pmatrix} 1 & 0 & P_y & 0 \\ 0 & C_{xx} & 0 & C_{xz} \\ -P_y & 0 & C_{yy} & 0 \\ 0 & -C_{xz} & 0 & C_{zz} \end{pmatrix} \quad \langle \mathbb{P}_B^2 \rangle$$

$$\langle \mathbb{S}_{B\bar{B}}^2 \rangle$$

# Joint angular distribution $e^+e^- \rightarrow (\Lambda \rightarrow p\pi^-)(\bar{\Lambda} \rightarrow \bar{p}\pi^+)$

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

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

Angular distribution:

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

4×4 decay matrix:  $a_{\mu,\nu}$

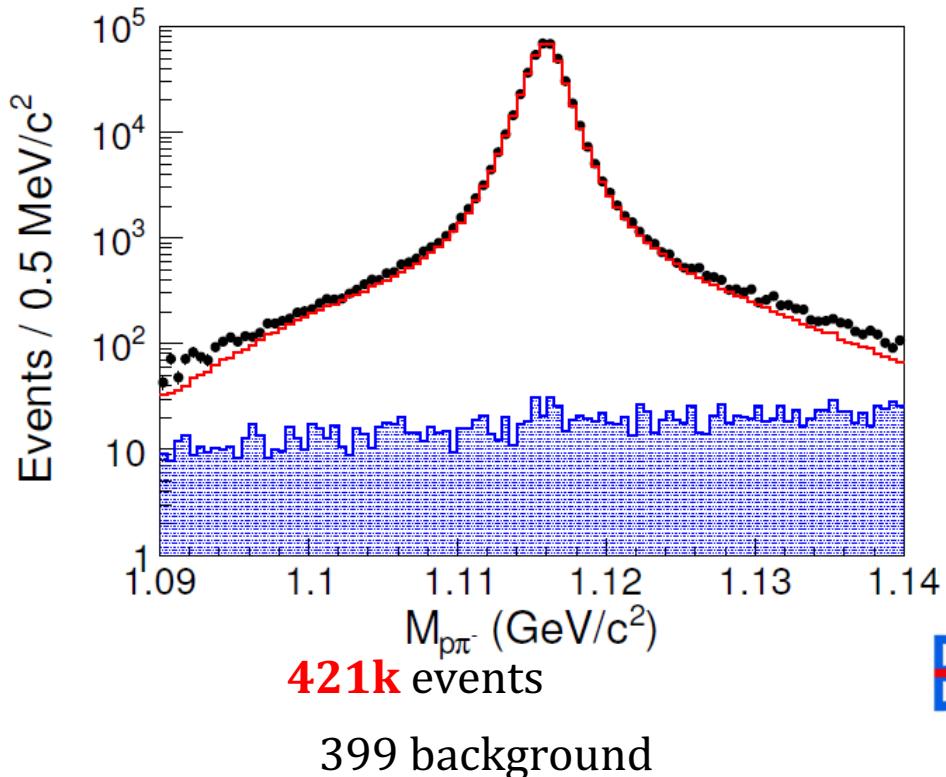
$$d\Gamma \propto W(\xi; \omega) \quad \xi \text{ 5 kinematical variables}$$

Parameters: 2 production + 2 decays

$$\Delta\Phi \neq 0$$

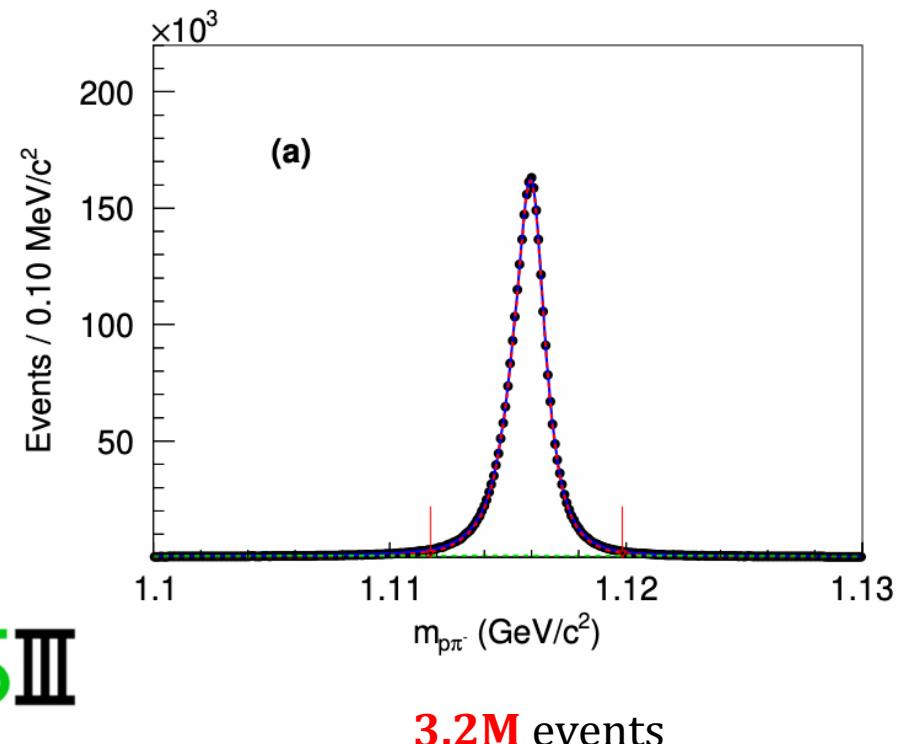
$$\omega = (\alpha_\psi, \Delta\Phi, \alpha_\Lambda, \bar{\alpha}_\Lambda)$$

$$e^+e^- \rightarrow (\Lambda \rightarrow p\pi^-)(\bar{\Lambda} \rightarrow \bar{p}\pi^+)$$



Nature Phys. 15 (2019) 631

(1.31x10<sup>9</sup> J/ψ)



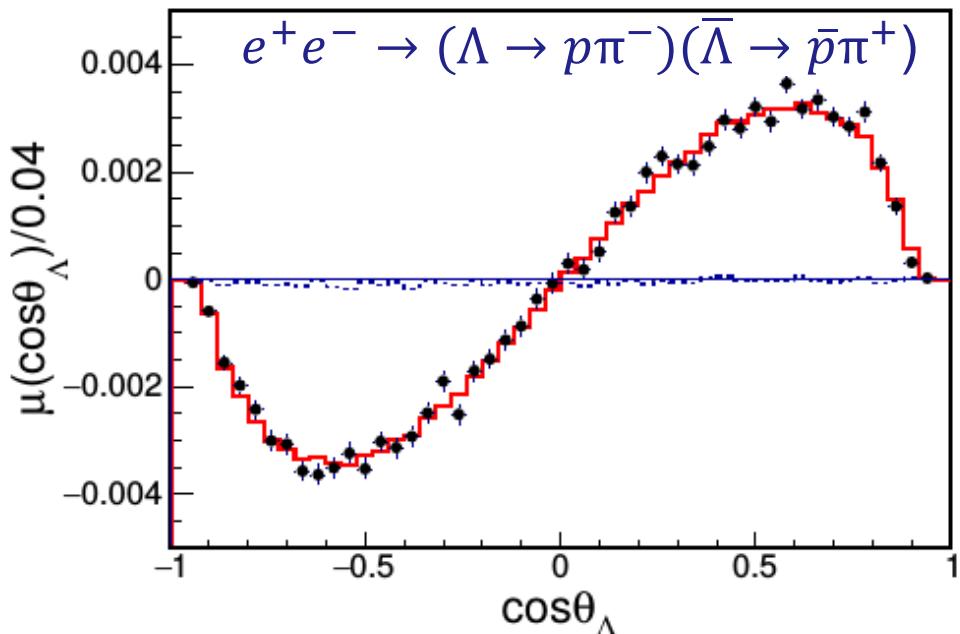
arXiv:2204.11058

(10<sup>10</sup> J/ψ)

Unbinned  
Max Likelihood fit:

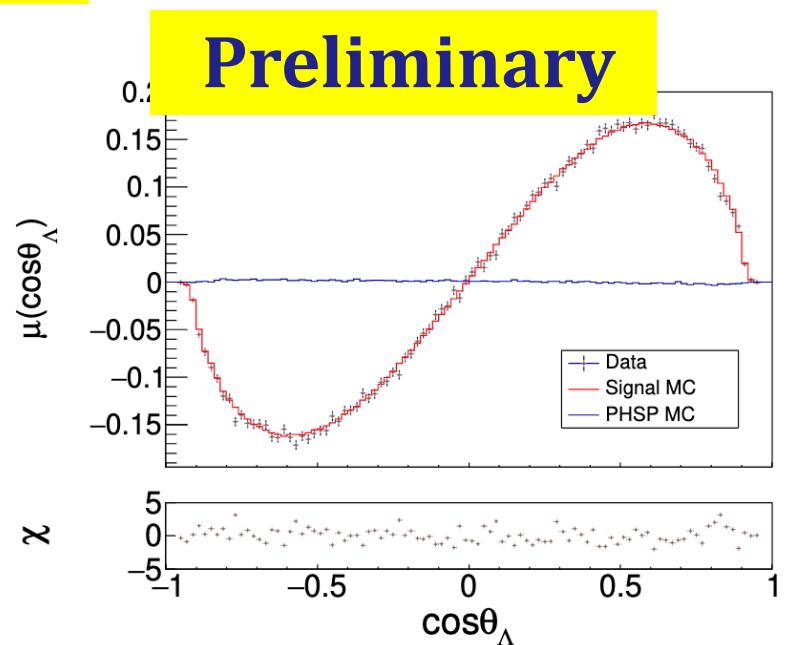
$$\begin{aligned} \mathcal{L}(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2, \dots, \boldsymbol{\xi}_N; \boldsymbol{\omega}) &= \prod_{i=1}^N \mathcal{P}(\boldsymbol{\xi}_i; \boldsymbol{\omega}) \\ &= \prod_{i=1}^N \frac{\mathcal{W}(\boldsymbol{\xi}_i; \boldsymbol{\omega}) \varepsilon(\boldsymbol{\xi}_i)}{\mathcal{N}(\boldsymbol{\omega})}, \end{aligned}$$

# Results of multidimensional fit



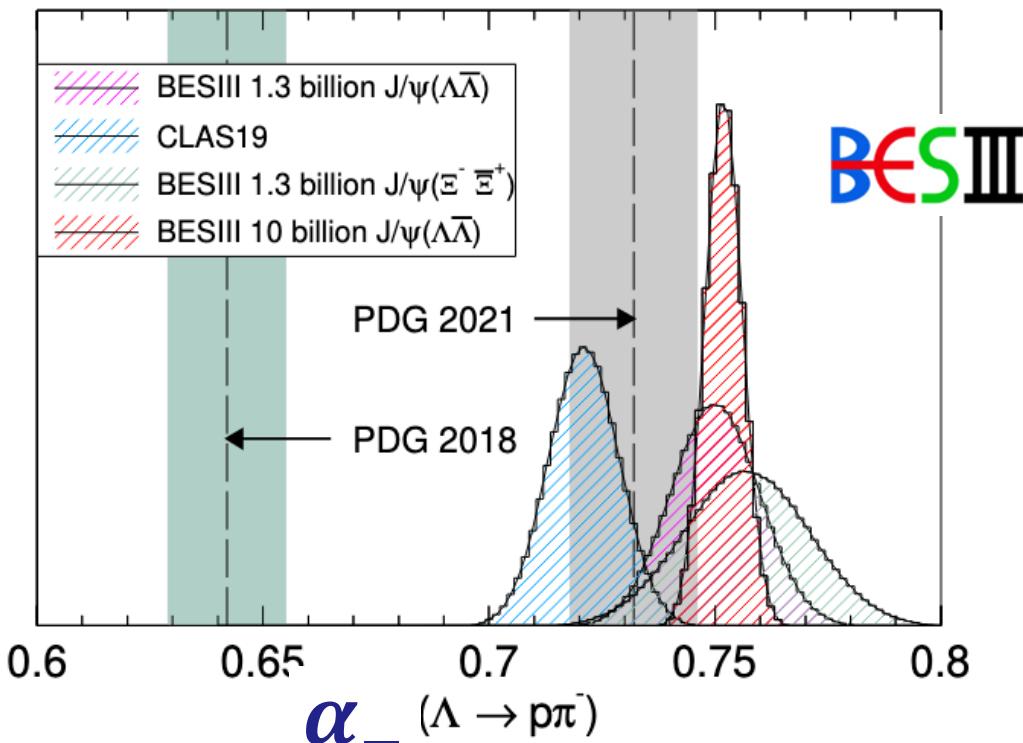
**Moment  $\mu$ :**  $\mu(\cos \theta_\Lambda) = \frac{1}{N} \sum_{i=1}^{N(\theta_\Lambda)} (n_{1,y}^{(i)} - n_{2,y}^{(i)})$

Preliminary



BESIII

Par.	This work	Nature Phys. 15 (2019) 631	arXiv:2204.11058
$\alpha_{J/\psi}$	$0.4748 \pm 0.0022 \pm 0.0024$	$0.461 \pm 0.006 \pm 0.007$	
$\Delta\Phi$	$0.7521 \pm 0.0042 \pm 0.0080$	$0.740 \pm 0.010 \pm 0.009$	
$\alpha_-$	$0.7519 \pm 0.0036 \pm 0.0019$	$0.750 \pm 0.009 \pm 0.004$	
$\alpha_+$	$-0.7559 \pm 0.0036 \pm 0.0029$	$-0.758 \pm 0.010 \pm 0.007$	
$A_{CP}$	$-0.0025 \pm 0.0046 \pm 0.0011$	$0.006 \pm 0.012 \pm 0.007$	
$\alpha_{avg}$	$0.7542 \pm 0.0010 \pm 0.0020$	-	



$$\langle \alpha_\Lambda \rangle = \frac{\alpha_- - \alpha_+}{2}$$

$$0.7542 \pm 0.0010 \pm 0.002$$

BESIII  
10<sup>10</sup> J/ψ

arXiv:2204.11058

CP test:

$$A_\Lambda = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$$

$$A_\Lambda = -0.0025(46)$$

$$A_\Lambda = -\tan(\delta_P^\Lambda - \delta_S^\Lambda) (\xi_P^\Lambda - \xi_S^\Lambda)$$

Known strong  $p\pi^-$   $s$  and  $p-$  wave phases:  $= 0.12 (\xi_P^\Lambda - \xi_S^\Lambda)$

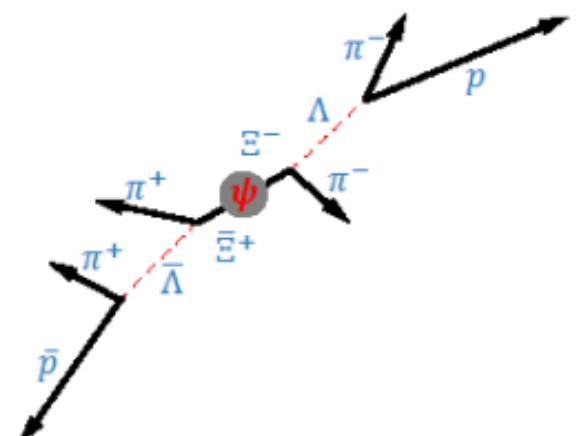
$$e^+ e^- \rightarrow J/\psi \rightarrow \Xi^- \bar{\Xi}^+ \rightarrow \Lambda \pi^- \bar{\Lambda} \pi^+ \rightarrow p \pi^- \pi^- \bar{p} \pi^+ \pi^+$$

$d\Gamma \propto W(\xi; \omega)$        $\xi$  9 kinematical variables

Parameters: 2 production + 6 for decay chains

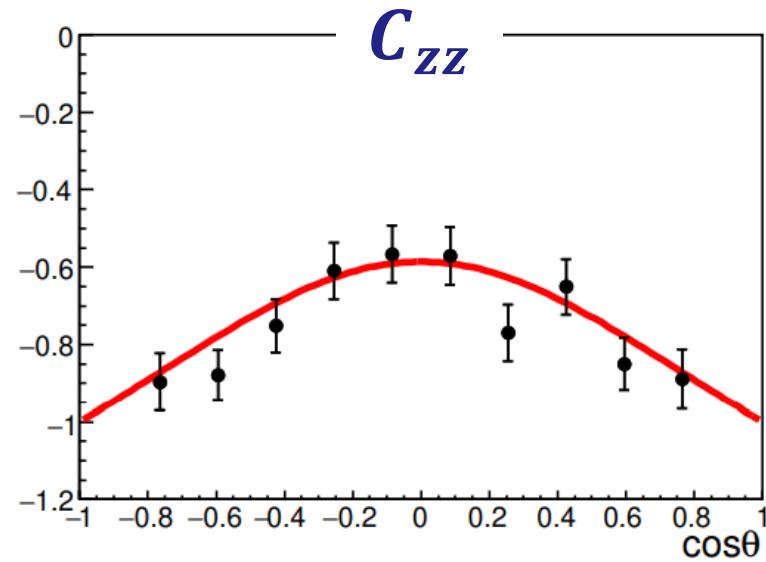
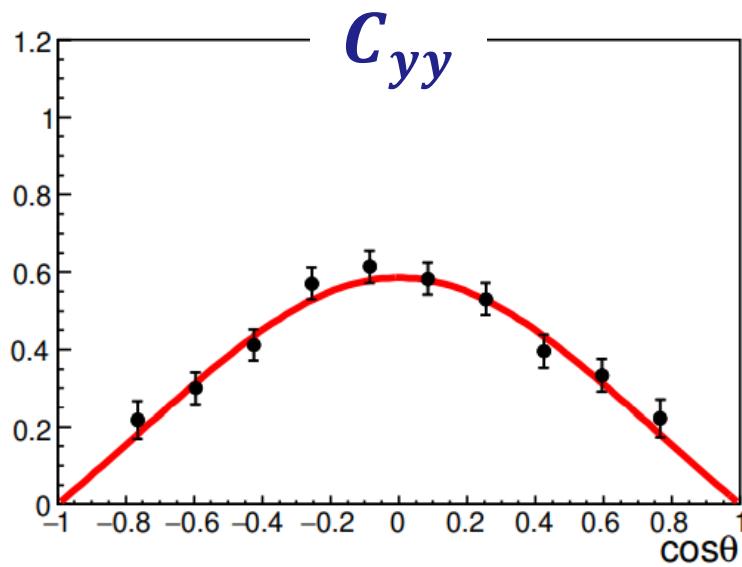
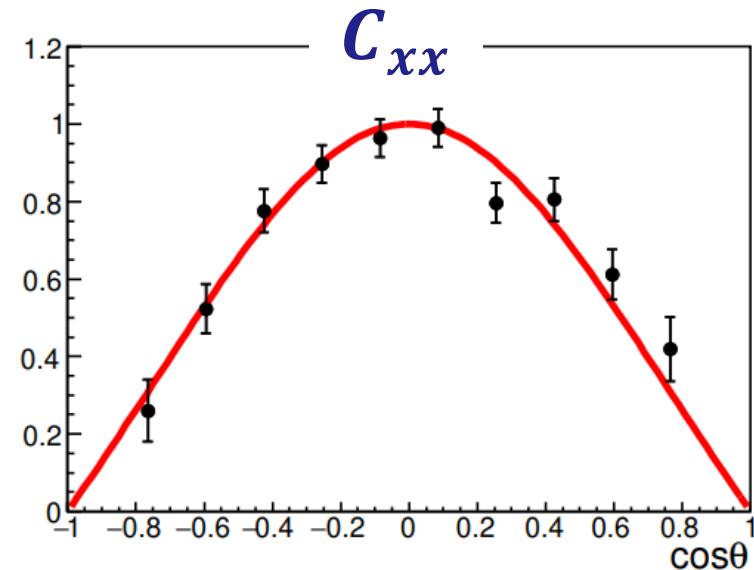
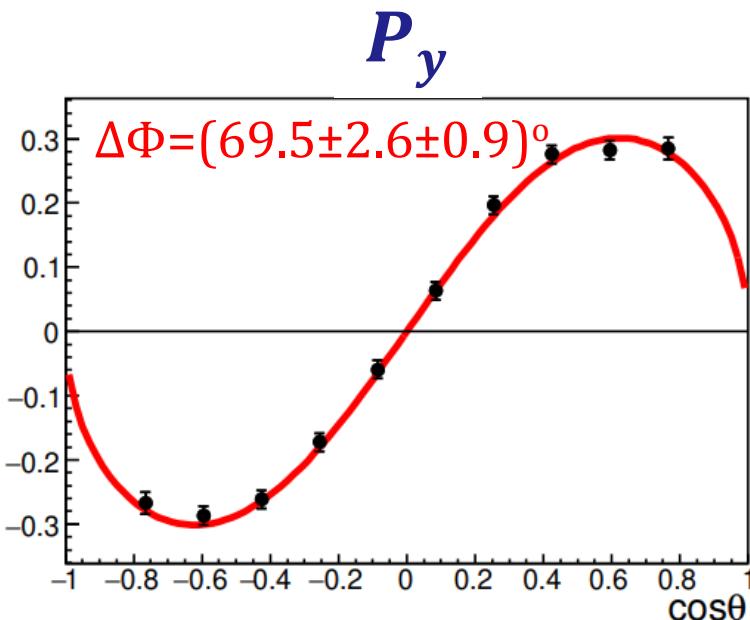
$$\omega = (\alpha_\psi, \Delta\Phi, \alpha_\Xi, \phi_\Xi, \alpha_\Lambda, \bar{\alpha}_\Xi, \bar{\phi}_\Xi, \bar{\alpha}_\Lambda)$$

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



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

BESIII

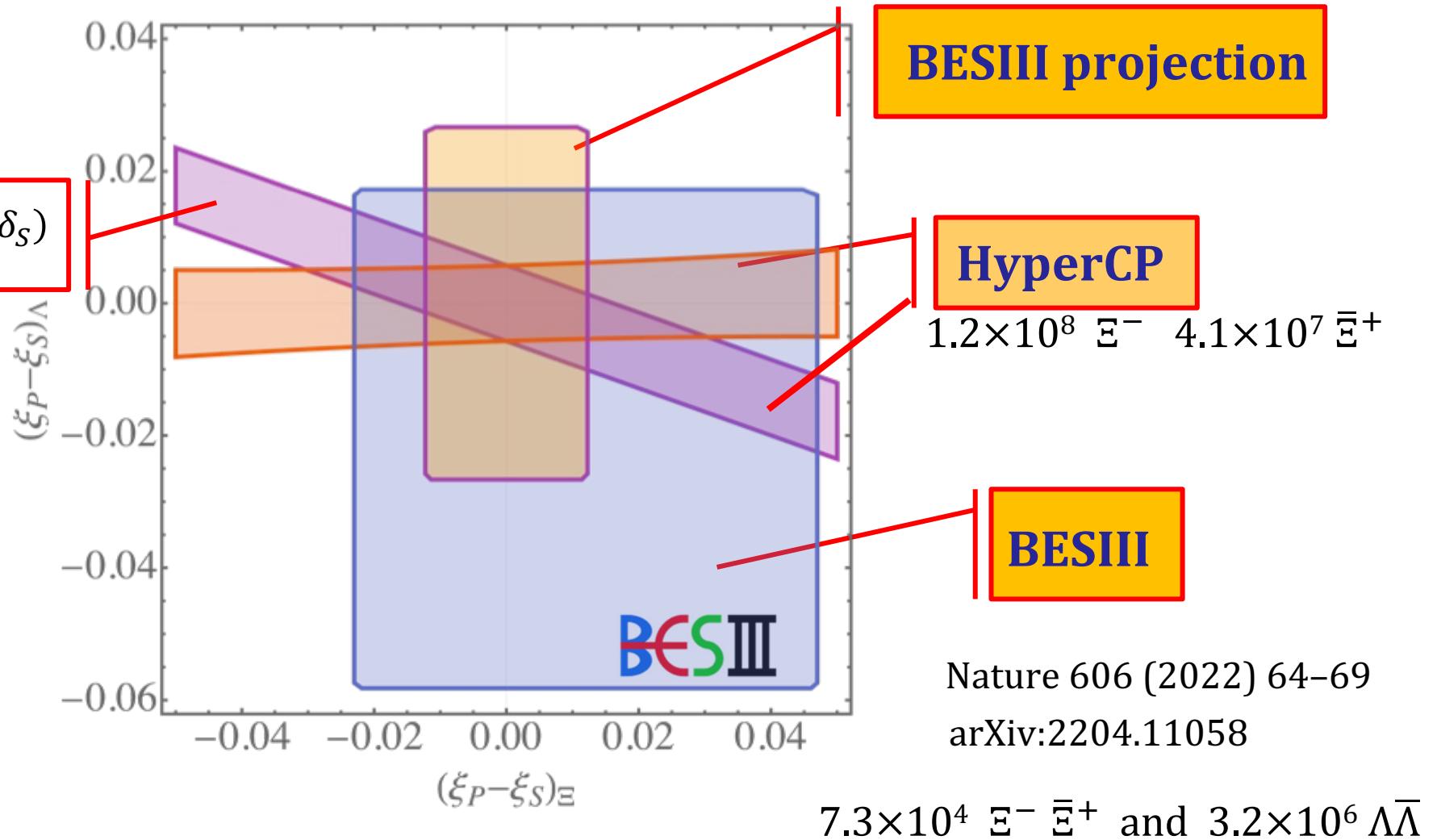


$\alpha_\psi$	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$	39
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad	–	
$\alpha_\Xi$	$-0.376 \pm 0.007 \pm 0.003$	$-0.401 \pm 0.010$	
$\phi_\Xi$	$0.011 \pm 0.019 \pm 0.009$ rad	$-0.037 \pm 0.014$ rad	
$\bar{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	–	
$\bar{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007$ rad	–	
$\alpha_\Lambda$	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$	4
$\bar{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$	4
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad	–	
$\delta_P - \delta_S$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad	$(10.2 \pm 3.9) \times 10^{-2}$ rad <sup>3</sup>	
$A_{\text{CP}}^{\Xi}$	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–	
$\Delta\phi_{\text{CP}}^{\Xi}$	$(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ rad	–	
$A_{\text{CP}}^\Lambda$	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$	.
$\langle \phi_\Xi \rangle$	$0.016 \pm 0.014 \pm 0.007$ rad		

8 fit  
parameters

3 CP  
tests

# Hyperon weak phases



# Conclusions

- J/ $\psi$  and  $\psi'$  decays into hyperon-antihyperon are unique spin entangled system for CP tests and for determination of (anti-)hyperon decay parameters
- Polarization observed for  $J/\psi, (\psi') \rightarrow \Lambda\bar{\Lambda}, \Sigma^+\bar{\Sigma}^-, \Xi^-\bar{\Xi}^+, \Omega^-\bar{\Omega}^+ \dots$

$J/\psi \rightarrow \Lambda\bar{\Lambda}$

$$(\xi_P^\Lambda - \xi_S^\Lambda) = (-2.0 \pm 3.8) \times 10^{-2}$$

BESIII  $10^{10} J/\psi$

$J/\psi \rightarrow \Xi\bar{\Xi}$

Equivalence of polarization and spin correlation terms:

$$\mathbf{1}, \langle \mathbb{P}_{\Xi}^2 \rangle, \langle \mathbb{S}_{B\bar{B}}^2 \rangle$$

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Three independent CP tests

measurement of  $\phi_{\Xi}$ :  $\langle \phi_{\Xi} \rangle = \frac{\phi_{\Xi} - \overline{\phi_{\Xi}}}{2} \Rightarrow \Lambda\pi \quad (\delta_P - \delta_S)$

$$(\xi_P^{\Xi} - \xi_S^{\Xi}) = (1.2 \pm 3.5) \times 10^{-2}$$

BESIII  $1.3 \times 10^9 J/\psi$

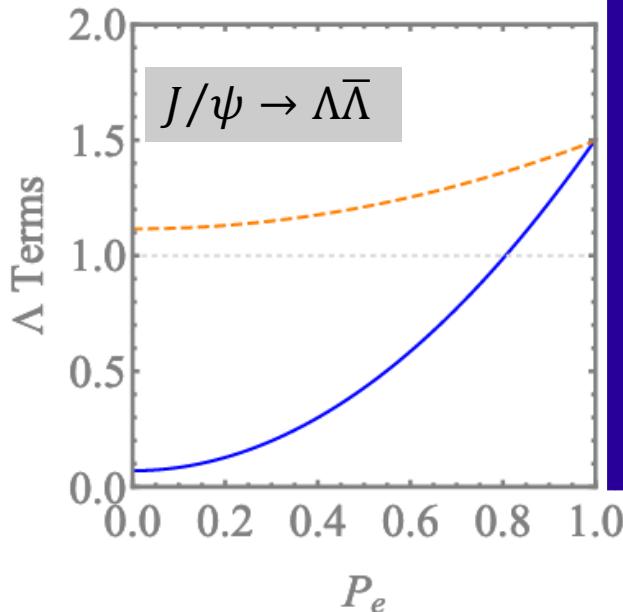
**Future studies:** super-charm-tau factories with a polarized electron beam > $10^{12} J/\psi$   
BelleII, LHCb, PANDA ...



# Polarization and spin correlation terms in $A_{CP}$ , $\Phi_{CP}$ measurements

covariance matrix =  $I^{-1}$

$$I(A_\Lambda) = N \frac{1}{3} \alpha_\Lambda^2 \langle \mathbb{P}_\Lambda^2 \rangle$$



$$I(\Phi_\Xi) = N \frac{2}{27} (1 - \alpha_\Xi^2) \alpha_\Lambda^2 [3.08 \langle \mathbb{P}_\Xi^2 \rangle + 1.30 \langle \mathbb{S}_{\Xi\Xi}^2 \rangle]$$

$$I(A_\Xi) = N \frac{2}{3} \alpha_\Xi^2 \alpha_\Lambda^2 (1 + 1.05 \langle \mathbb{P}_\Xi^2 \rangle + 0.38 \langle \mathbb{S}_{\Xi\Xi}^2 \rangle)$$

$$I(A_\Lambda) = N \frac{2}{3} \alpha_\Xi^2 \alpha_\Lambda^2 (1 + 3.28 \langle \mathbb{P}_\Xi^2 \rangle + 0.30 \langle \mathbb{S}_{\Xi\Xi}^2 \rangle)$$

$$I(A_\Xi, A_\Lambda) = N \frac{2}{3} \alpha_\Xi^2 \alpha_\Lambda^2 (1 - \frac{1}{3} \langle \mathbb{P}_\Xi^2 \rangle - \frac{1}{3} \langle \mathbb{S}_{\Xi\Xi}^2 \rangle)$$

