The 13th International Workshop on e^+e^- Collisions From Phi to Psi

Hyperon Physics at BESIII

Yunlong Xiao

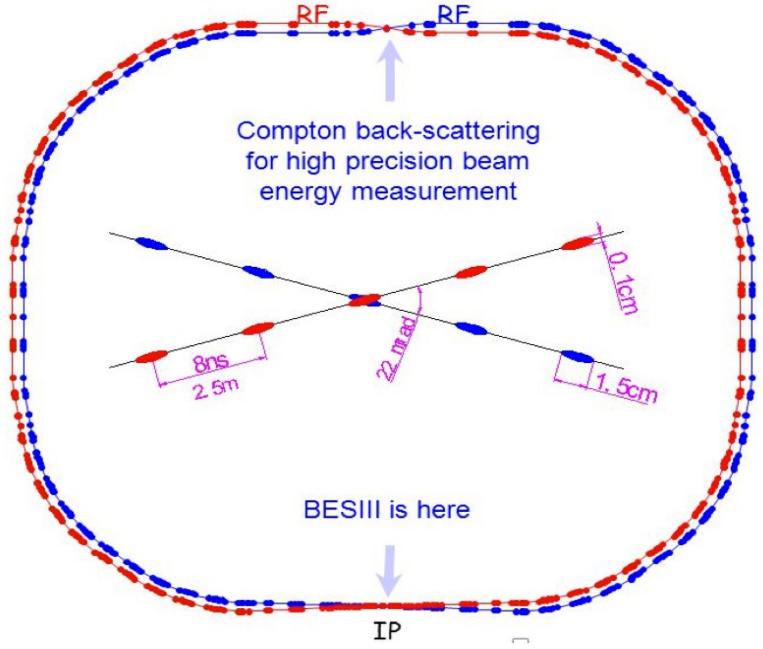
(On behalf of BESIII Collaboration)

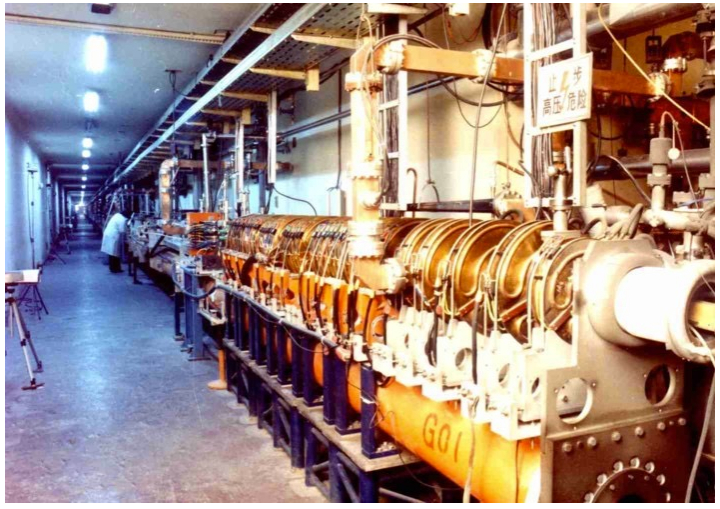
Shanghai, 15th-19th Aug 2022

Outline

- Status of BEPC-II and BESIII
- Introduction
- Hyperon physical results
- Summary & Outlook

BEPCII storage rings: a τ-charm factory

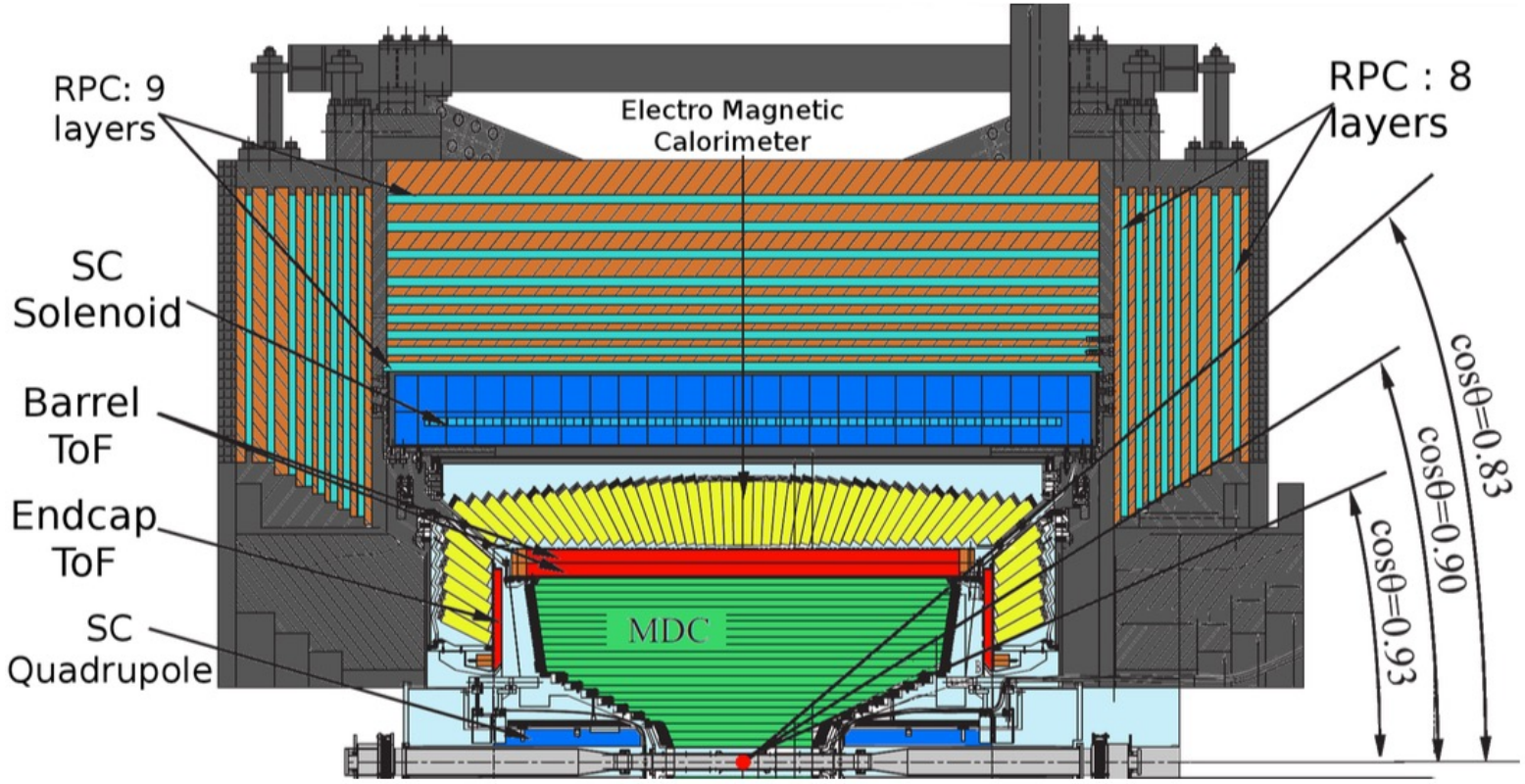




Update of BEPC (started 2004, first collisions July 2008)

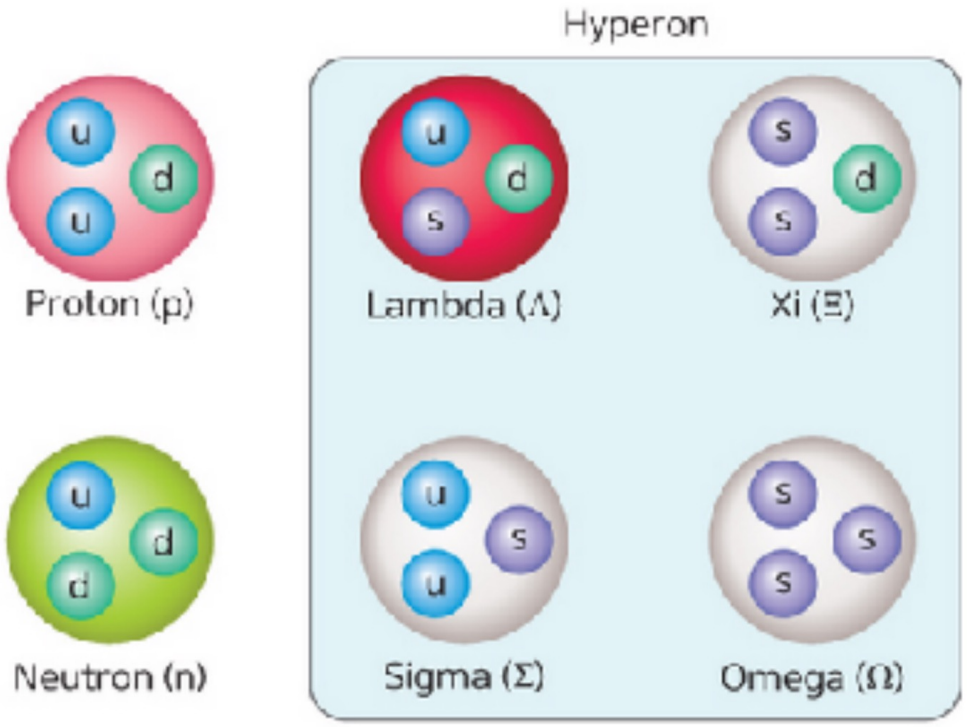
Beam energy	1 - 2.47 GeV
Optimum energy	1.89 GeV
Single beam current	0.91 A
Crossing angle	11mrad
Design luminosity	1×10^{33} cm^{-2} s^{-1}
Achieved	1×10^{33} cm^{-2} s^{-1}

BESIII detectors



- Main Drift Chamber (MDC)
  - $\sigma(p)/p = 0.5\%$
  - $\sigma_{dE/dX} = 5.0\%$
- Time-of-flight (TOF)
  - $\sigma(t) = 68ps$ (barrel)
  - $\sigma(t) = 65ps$ (endcap)
- Electro Magnetic Calorimeter (EMC)
  - $\sigma(E)/E = 2.5\%$
  - $\sigma_{z,\phi}(E) = 0.5 – 0.7$ cm
- RPC MUON Detector
  - $\sigma(xy) < 2$ cm

Introduction (I)



Hyperons are a laboratory for strong interaction and baryon structure

Decay	$\mathcal{B}$ (10^{-5})	Events at BESIII
$J/\psi \to \Lambda\bar{\Lambda}$	189 ± 9	18.9×10^6
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	150 ± 24	15.0×10^6
$J/\psi \to \Xi\bar{\Xi}$	97 ± 8	9.7×10^6
$\psi(2S) \to \Sigma\bar{\Sigma}$	23.2 ± 1.2	116×10^3
$\psi(2S) \to \Omega\bar{\Omega}$	5.66 ± 0.30	28×10^3

Introduction (II)

- Polarization
  - Study of two-body hyperon weak decays plays an important role in the study of the fundamental symmetries P and CP.
  - The polarization of spin ½ hyperon can be determined in two-body weak decays by $(1 + \alpha_0 \mathbf{P}_{\Sigma^+} \hat{\mathbf{p}}/4\pi)$

Parity violation S state

Parity conservation P state

$$\alpha = \frac{2\,\mathrm{Re}(S^* P)}{|S|^2 + |P|^2}, \quad \beta = \frac{2\,\mathrm{Im}(S^* P)}{|S|^2 + |P|^2}, \quad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

α, β, γ could be determined experimentally.

$$A_{CP} = \frac{\alpha_0 + \bar{\alpha}_0}{\alpha_0 - \bar{\alpha}_0}$$

T. D. Lee and C. N. Yang, Phys. Rev. 108,1645 (1957)

Introduction (II)

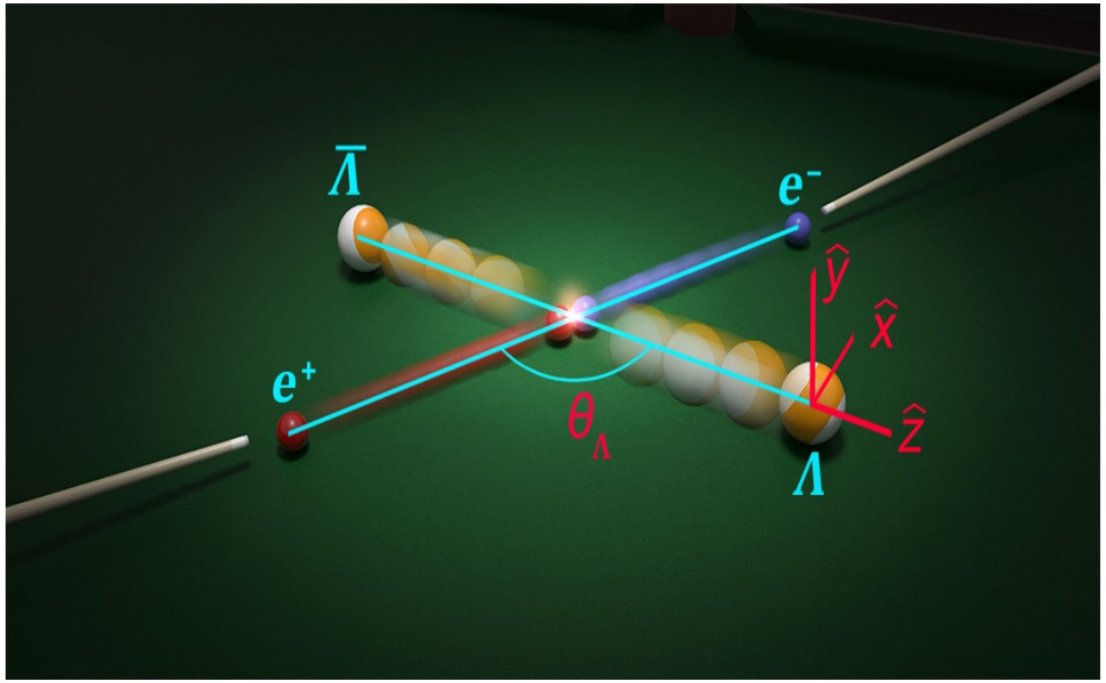
- Polarization
  - Studies of two-body hyperon weak decays plays an important role in the study of the fundamental symmetries P and CP.
  - The polarization of spin ½ hyperon can be determined in two-body weak decays by $(1 + \alpha_0 \mathbf{P}_{\Sigma^+} \hat{\mathbf{p}}/4\pi)$

If the relative phase between hadronic form factor is not zero(Polarized), the decay parameters α_0 and $\overline{\alpha}_0$ could be simultaneous and direct measured, then test CP symmetry.

T. D. Lee and C. N. Yang, Phys. Rev. 108,1645 (1957)

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

Nature Phys. 15 (2019) 631



Unpolarized e^+ e^- beams -> Transverse polarization:

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

Formulas

$$d\sigma \propto \mathcal{W}(\boldsymbol{\xi})d\boldsymbol{\xi} \qquad \boldsymbol{\xi} = (\theta, \theta_p, \phi_p, \theta_{\bar{p}}, \phi_{\bar{p}})$$

Phys. Lett. B 772, 16 (2017)

$$\mathcal{W}(\boldsymbol{\xi}) = \mathcal{T}_0(\boldsymbol{\xi}) + \alpha_\psi \mathcal{T}_5(\boldsymbol{\xi})$$

$$-\alpha_0\bar{\alpha}_0\left(\mathcal{T}_1(\boldsymbol{\xi}) + \sqrt{1-\alpha_\psi{}^2}\cos(\Delta\Phi)\mathcal{T}_2(\boldsymbol{\xi}) + \alpha_\psi\mathcal{T}_6(\boldsymbol{\xi})\right)$$

SPIN CORRELATIONS

$$+\sqrt{1-\alpha_\psi{}^2}\sin(\Delta\Phi)\left(\alpha_0\mathcal{T}_3(\boldsymbol{\xi}) - \bar{\alpha}_0\mathcal{T}_4(\boldsymbol{\xi})\right)$$

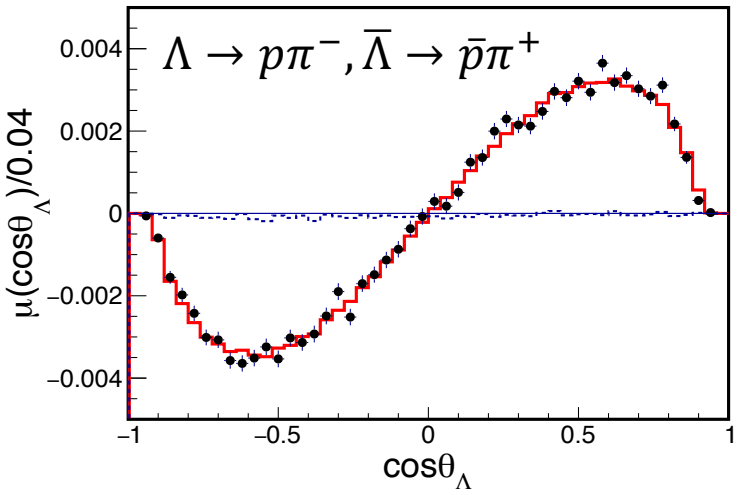
POLARIZATIONS

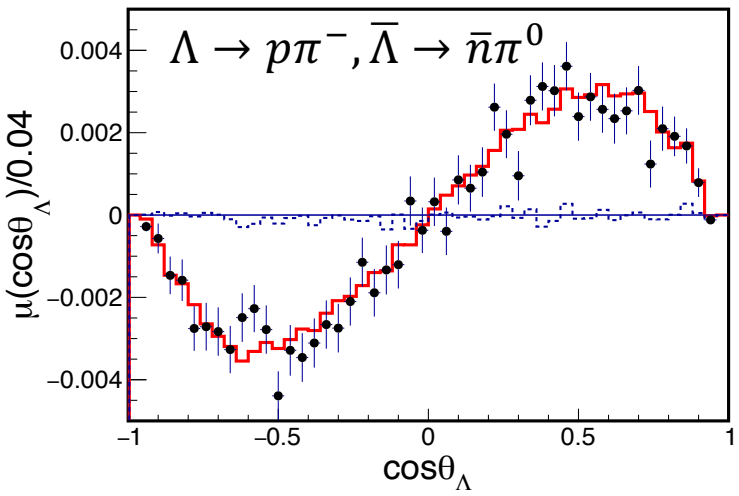
$$\mathcal{T}_0(\boldsymbol{\xi}) = 1$$
$$\mathcal{T}_1(\boldsymbol{\xi}) = \sin^2\theta \sin\theta_p \sin\theta_{\bar{p}} \cos\phi_p \cos\phi_{\bar{p}} + \cos^2\theta \cos\theta_p \cos\theta_{\bar{p}}$$
$$\mathcal{T}_2(\boldsymbol{\xi}) = \sin\theta\cos\theta\,(\sin\theta_p \cos\theta_{\bar{p}} \cos\phi_p + \cos\theta_p \sin\theta_{\bar{p}} \cos\phi_{\bar{p}})$$
$$\mathcal{T}_3(\boldsymbol{\xi}) = \sin\theta\cos\theta\sin\theta_p \sin\phi_p$$
$$\mathcal{T}_4(\boldsymbol{\xi}) = \sin\theta\cos\theta\sin\theta_{\bar{p}} \sin\phi_{\bar{p}}$$
$$\mathcal{T}_5(\boldsymbol{\xi}) = \cos^2\theta$$
$$\mathcal{T}_6(\boldsymbol{\xi}) = \cos\theta_p \cos\theta_{\bar{p}} - \sin^2\theta \sin\theta_p \sin\theta_{\bar{p}} \sin\phi_p \sin\phi_{\bar{p}}.$$

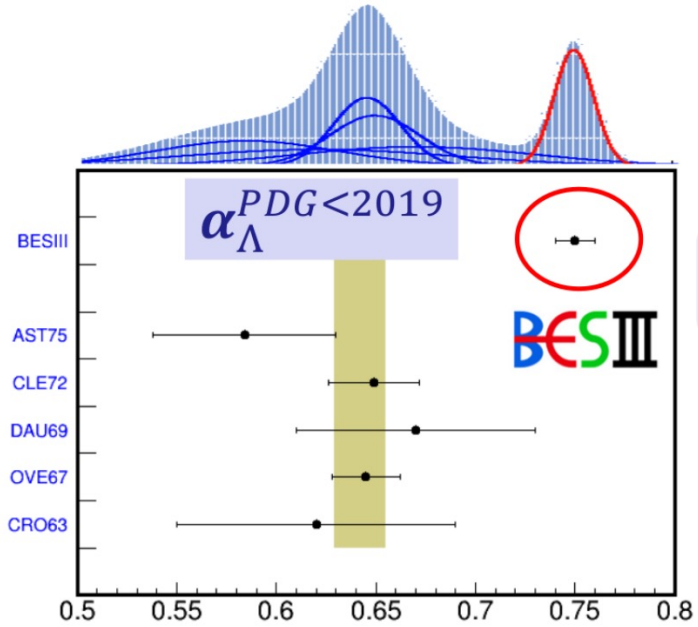
$$A_{CP} = \frac{\alpha_0 + \bar{\alpha}_0}{\alpha_0 - \bar{\alpha}_0}$$

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

Nature Phys. 15 (2019) 631







$$<\alpha>=\frac{\alpha-\bar{\alpha}}{2}=0.754\pm0.003\pm0.002$$

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

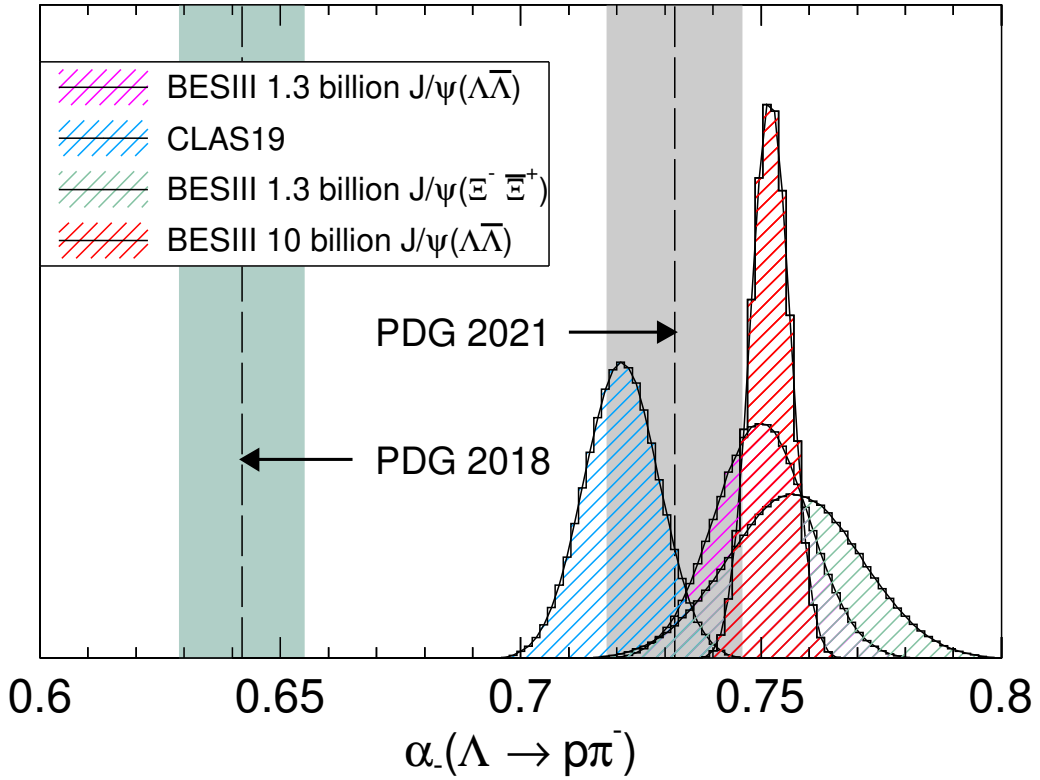
Parameters	This work	Previous results
α_ψ	$\mathbf{0.461 \pm 0.006 \pm 0.007}$	0.469 ± 0.027 BESIII
$\Delta\Phi$ (rad)	$\mathbf{0.740 \pm 0.010 \pm 0.008}$	–
α_Λ	$\mathbf{0.750 \pm 0.009 \pm 0.004}$	0.642 ± 0.013 PDG
$\bar{\alpha}_\Lambda$	$\mathbf{-0.758 \pm 0.010 \pm 0.007}$	-0.71 ± 0.08 PDG

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

arXiv:2204.11058

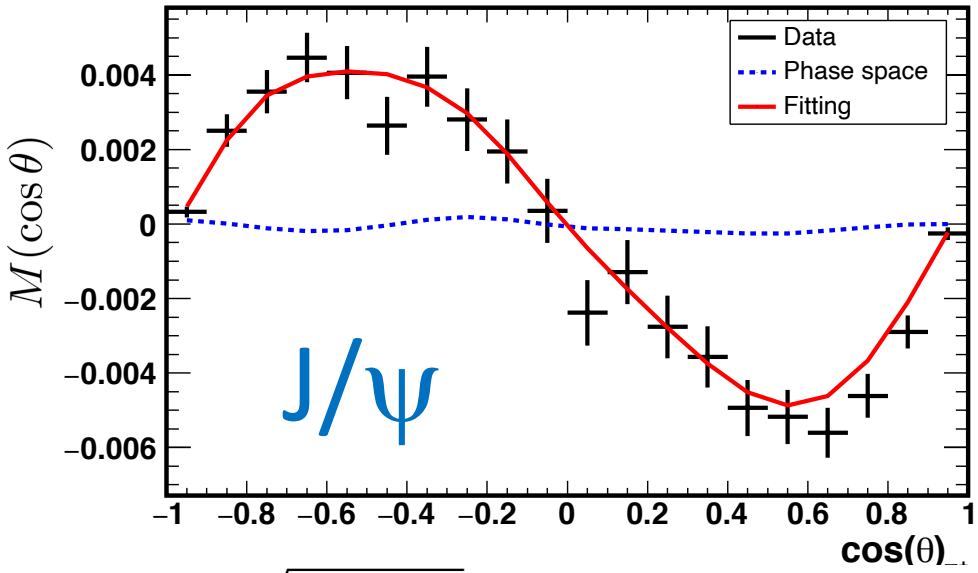
- 10 Billion J/psi events are used to update the results.
- The decay parameters are consistent with previous measurements.
- Acp value is improved with both statistical and systematical uncertainties.

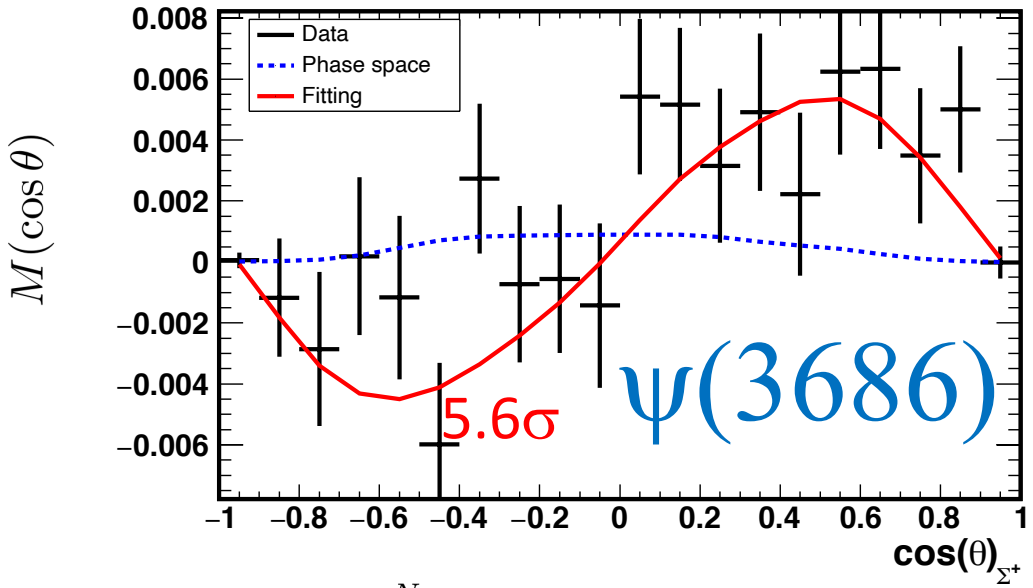
Par.	This work	Previous results [8]
$\alpha_{J/\psi}$	$0.4748 \pm 0.0022 \pm 0.0024$	$0.461 \pm 0.006 \pm 0.007$
$\Delta\Phi$	$0.7521 \pm 0.0042 \pm 0.0080$	$0.740 \pm 0.010 \pm 0.009$
α_-	$0.7519 \pm 0.0036 \pm 0.0019$	$0.750 \pm 0.009 \pm 0.004$
α_+	$-0.7559 \pm 0.0036 \pm 0.0029$	$-0.758 \pm 0.010 \pm 0.007$
A_{CP}	$-0.0025 \pm 0.0046 \pm 0.0011$	$0.006 \pm 0.012 \pm 0.007$
$\alpha_{\rm avg}$	$0.7542 \pm 0.0010 \pm 0.0020$	-



J/ψ and ψ(3686) ->$\Sigma^+\bar{\Sigma}^-$

Phys. Rev. Lett. 125, 052004 (2020)





$$\frac{dM}{d\cos\theta} \sim \sqrt{1-\alpha_\psi^2}\,\alpha_0 \sin\Delta\Phi\cos\theta\sin\theta$$

Parameter	Measured value
$\alpha_{J/\psi}$	$-0.508 \pm 0.006 \pm 0.004$
$\Delta\Phi_{J/\psi}$	$-0.270 \pm 0.012 \pm 0.009$
$\alpha_{\psi'}$	$0.682 \pm 0.03 \pm 0.011$
$\Delta\Phi_{\psi'}$	$0.379 \pm 0.07 \pm 0.014$
α_0	$-0.998 \pm 0.037 \pm 0.009$
$\bar{\alpha}_0$	$0.990 \pm 0.037 \pm 0.011$

$$M(\cos\theta) = (m/N)\sum_i^{N_k}(\sin\theta_p^i\cos\phi_p^i - \sin\theta_{\bar{p}}^i\cos\phi_{\bar{p}}^i)$$

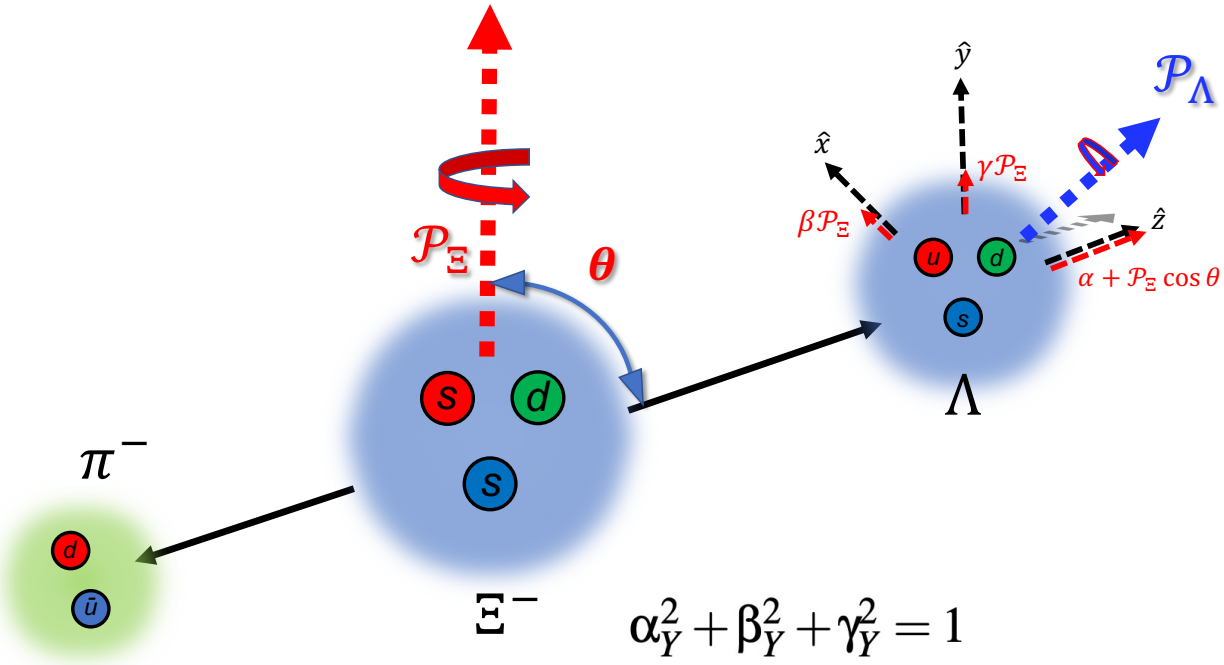
The points with error bars are the data, and the solid-line histogram is the global fit result. The dotted histogram is phase space model.

CP asymmetry $-0.004 \pm 0.037 \pm 0.010$

average decay asymmetry $-0.994 \pm 0.004 \pm 0.002$

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

Nature 606, pages64–69 (2022)



$$\alpha_Y^2 + \beta_Y^2 + \gamma_Y^2 = 1$$

$$\beta_Y = \sqrt{1-\alpha_Y^2}\sin\phi_Y, \quad \gamma_Y = \sqrt{1-\alpha_Y^2}\cos\phi_Y$$

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

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

8 parameters:

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

There are 73k events (190 background), the 8 parameters are estimated with unbinned MLL fit!

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

Nature 606, pages64–69 (2022)

Parameter	This work	Previous result	Reference
α_ψ	0.586±0.012±0.010	0.58±0.04±0.08	Ref. [49]
$\Delta\Phi$	1.213±0.046±0.016 rad	–	
α_Ξ	−0.376±0.007±0.003	−0.401±0.010	Ref. [26]
ϕ_Ξ	0.011±0.019±0.009 rad	−0.037±0.014 rad	Ref. [26]
$\bar{\alpha}_\Xi$	0.371±0.007±0.002	–	
$\bar{\phi}_\Xi$	−0.021±0.019±0.007 rad	–	
α_Λ	0.757±0.011±0.008	0.750±0.009±0.004	Ref. [4]
$\bar{\alpha}_\Lambda$	−0.763±0.011±0.007	−0.758±0.010±0.007	Ref. [4]
$\xi_P - \xi_S$	$(1.2\pm3.4\pm0.8)\times10^{-2}$ rad	–	
$\delta_P - \delta_S$	$(-4.0\pm3.3\pm1.7)\times10^{-2}$ rad	$(10.2\pm3.9)\times10^{-2}$ rad	Ref. [3]
A_{CP}^{Ξ}	$(6\pm13\pm6)\times10^{-3}$	–	
$\Delta\phi_{CP}^{\Xi}$	$(-5\pm14\pm3)\times10^{-3}$ rad	–	
A_{CP}^{Λ}	$(-4\pm12\pm9)\times10^{-3}$	$(-6\pm12\pm7)\times10^{-3}$	Ref. [4]
$\langle\phi_\Xi\rangle$	0.016±0.014±0.007 rad		

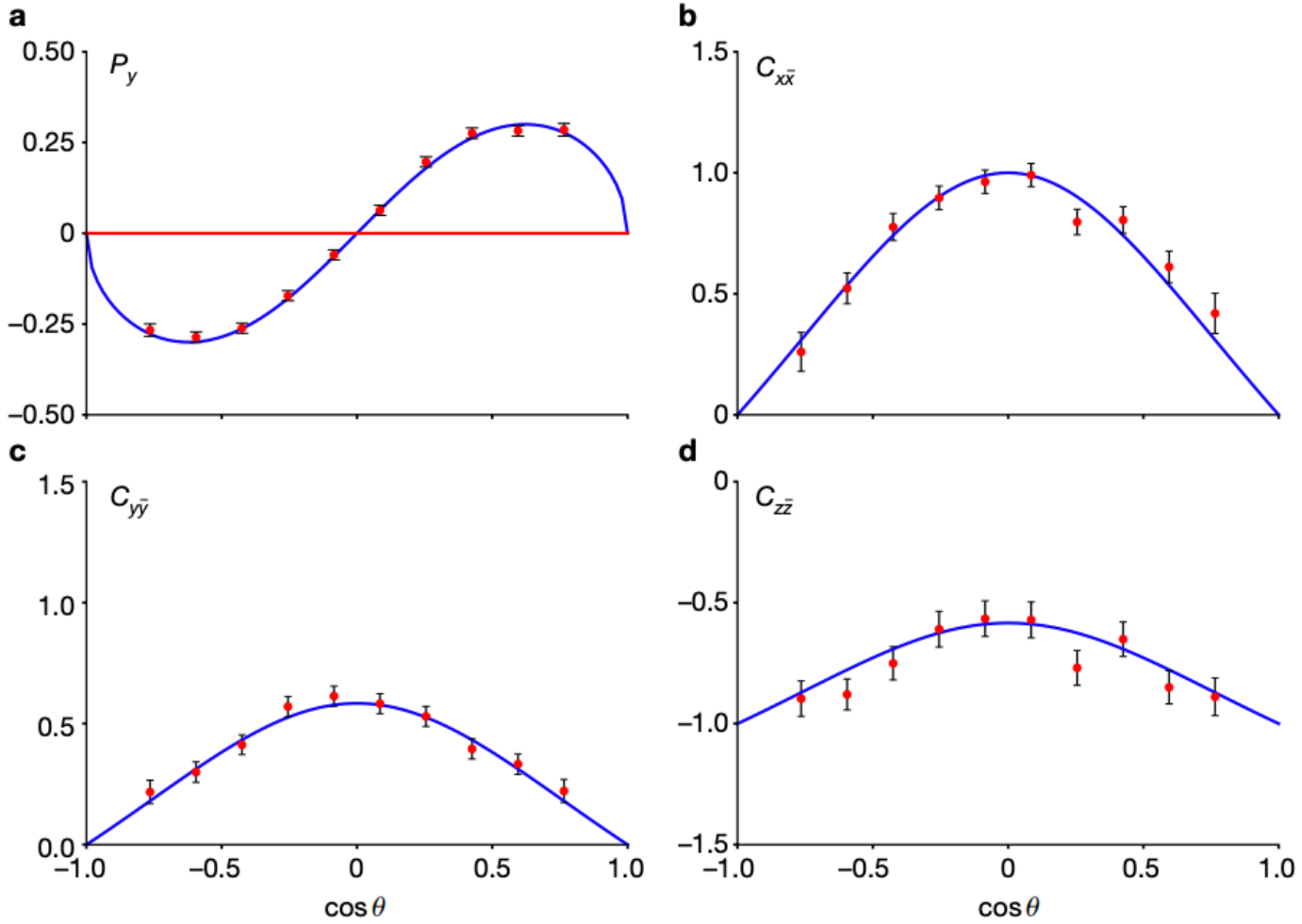
Independent measurement of α_Λ

First measurement of weak phase difference!
strong phase difference

3 CP test

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

Nature 606, pages64–69 (2022)

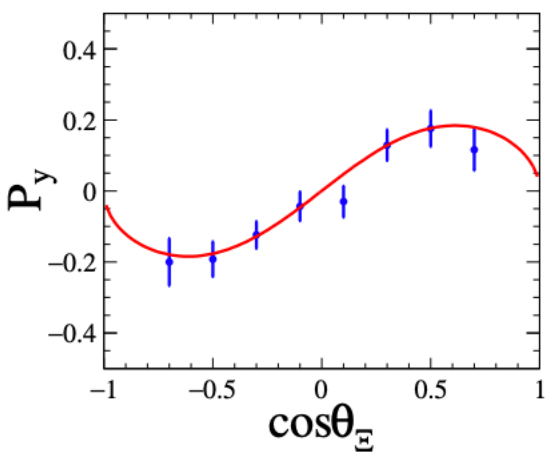


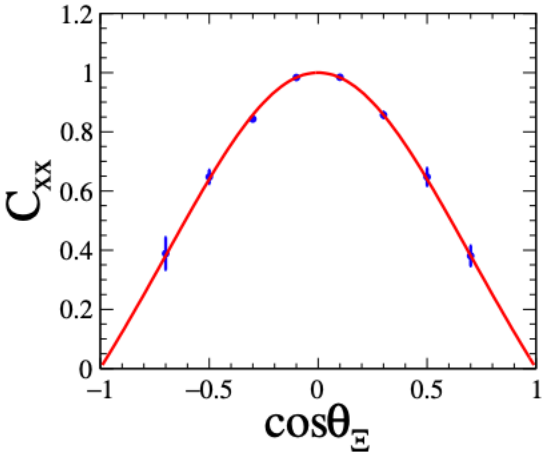
Polarization and spin correlations in the $J/\psi \rightarrow \Xi^- \bar{\Xi}^+$

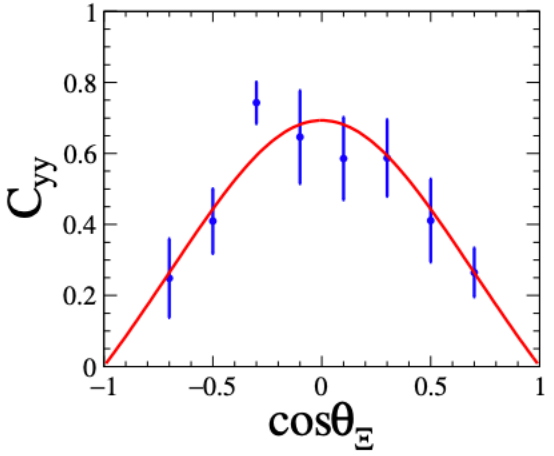
$\Psi(3686) \to \Xi^- \bar{\Xi}^+$

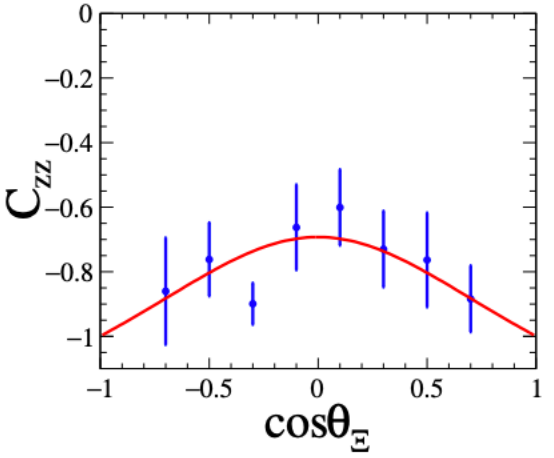
arXiv:2204.11058

Parameter	$\psi(3686) \to \Xi^-\bar{\Xi}^+$	$J/\psi \to \Xi^-\bar{\Xi}^+$
α_ψ	$0.693 \pm 0.048 \pm 0.049$	$0.586 \pm 0.012 \pm 0.010$
$\Delta\Phi$ (rad)	$0.667 \pm 0.111 \pm 0.058$	$1.213 \pm 0.046 \pm 0.016$
α_{Ξ^-}	$-0.344 \pm 0.025 \pm 0.007$	$-0.376 \pm 0.007 \pm 0.003$
$\alpha_{\bar{\Xi}^+}$	$0.355 \pm 0.025 \pm 0.002$	$0.371 \pm 0.007 \pm 0.002$
ϕ_{Ξ^-} (rad)	$0.023 \pm 0.074 \pm 0.003$	$0.011 \pm 0.019 \pm 0.009$
$\phi_{\bar{\Xi}^+}$ (rad)	$-0.123 \pm 0.073 \pm 0.004$	$-0.021 \pm 0.019 \pm 0.007$
$\delta_p - \delta_s$ (10^{-2} rad)	$-19.5 \pm 13.4 \pm 0.7$	$-4.0 \pm 3.3 \pm 1.7$
$A_{CP,\Xi}$ (10^{-3})	$-14.7 \pm 50.8 \pm 10.3$	$6.0 \pm 13.4 \pm 5.6$
$\Delta\phi_{CP}$ (10^{-3} rad)	$-49.9 \pm 52.1 \pm 2.6$	$-4.8 \pm 13.7 \pm 2.9$







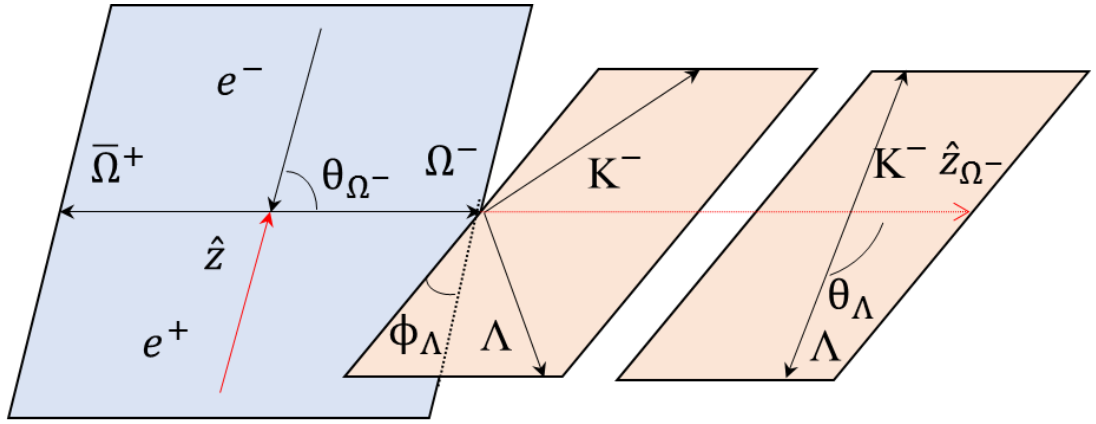


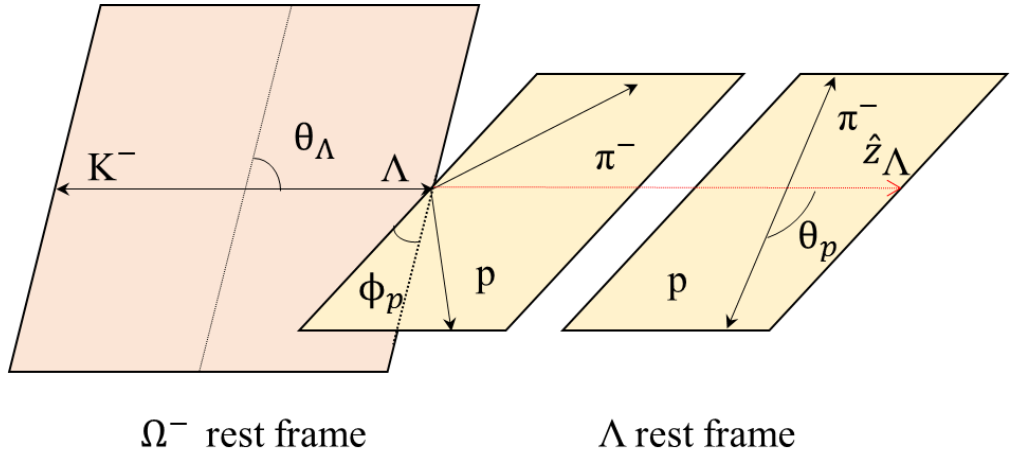
Polarization and spin correlations in the J/ψ -> Ξ^- Ξ^+

$\psi(3686)\text{->}\Omega^-\ \Omega^+$

Phys. Rev. Lett. 126, 092002 (2021)

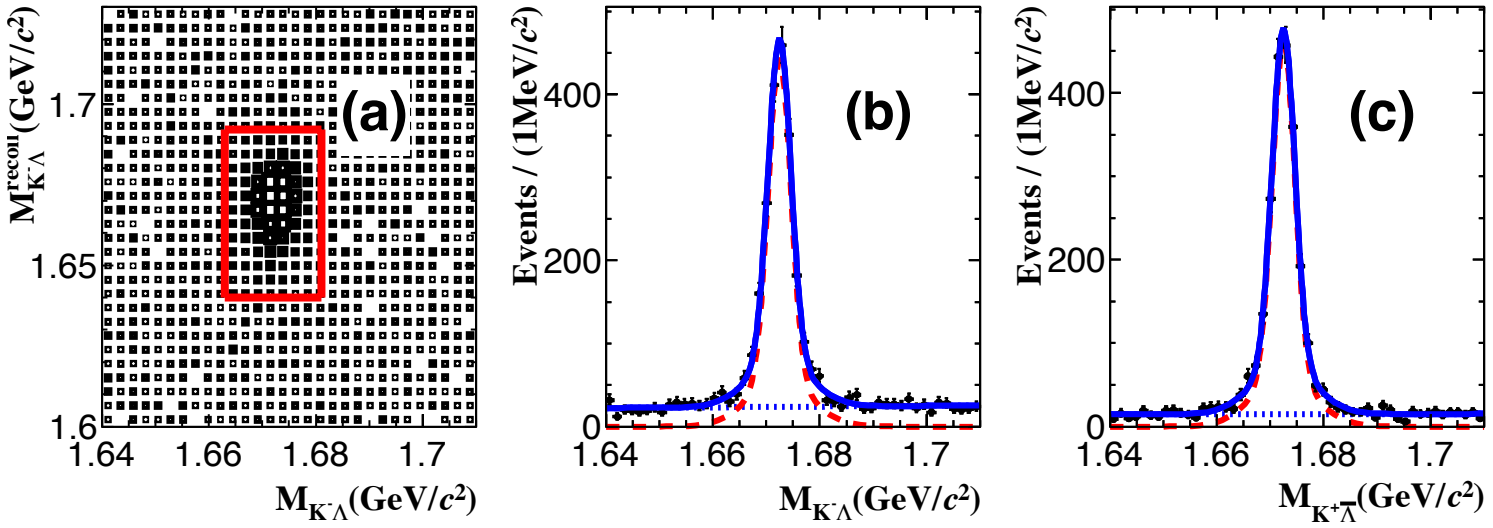
- The spin of Ω^- J= 3/2 has never unambiguously confirmed by experiments directly.
- Polarization of the Ω^- can be studied with the Ω^- weak decay chains, and decay parameters could be measured.
- Helicity amplitude method is used.

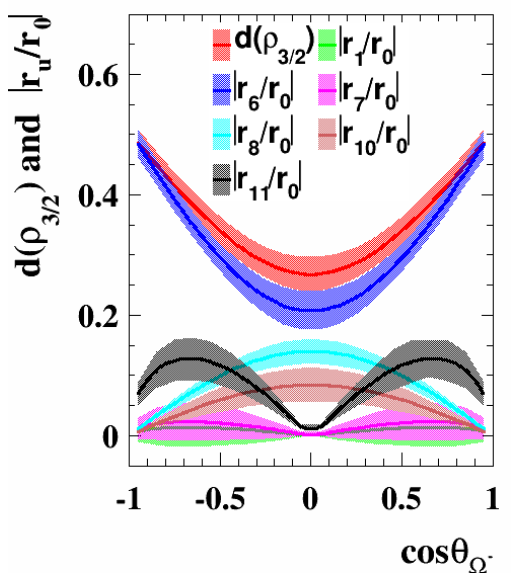




$\psi(3686)\text{->}\Omega^-\ \Omega^+$

Phys. Rev. Lett. 126, 092002 (2021)





Not only observe vector polarization(r1), but also quadrupole (r6, r7, r8) and octupole(r10, r11) polarizations

Br($\psi(3686)\text{->}\Omega^+\ \Omega^-$) =
$(5.85 \pm 0.12 \pm 0.25) \times 10^{-5}$
$\alpha = 0.24 \pm 0.10$

Summary

- Hyperons are an important probe to study QCD, fundamental symmetries, and form factors.

- 10 Billion J/ψ data and 2.7 Billion $\psi(3686)$ data collected will bring more exciting results ($\Sigma^0, \Sigma^-, \Sigma^+, \Xi^0, \Xi^-$, and Ω^-).

- More hyperons study results come soon.

THANK YOU

BACK UP