BESIII实验和STCF上的超子精细测量

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Outline

- Introduction
- Hyperon Decay
- Measurement Methods
- Experimental Results and Analysis
- Discussion and Outlook
- Summary

Introduction

The imbalance of matter and antimatter:

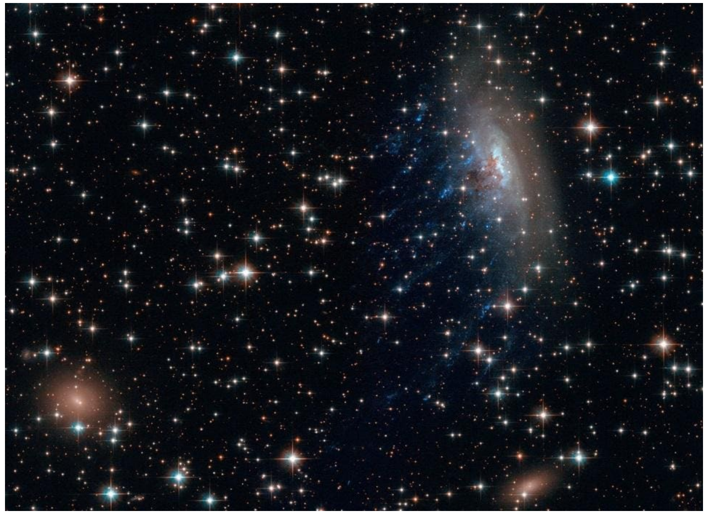
✓The Big Bang should have created equal amounts of matter and antimatter

✓We cannot detect significant amounts of antimatter in the universe

✓Look into the night sky, only matters have been seen

Predict: $n_{matter}/n_{Photon} \sim 0$

Experiment: $n_b/n_\gamma \sim (6.1 +/- 0.3) \times 10^{-10}$



How can this happen?

In 1967, Andrei Sakharov proposed a set of three necessary conditions that a baryon-generating interaction must satisfy to produce matter and antimatter at different rates:

1. Baryon number violation
2. C-symmetry and CP-symmetry violation
3. Deviation from thermal equilibrium

Andrei Sakharov on *Soviet Nobel Peace Prize winners*, the USSR stamp issued on 14 May 1991

CP violation discrovery

- 1964, Cronin and Fitch discovered the violation of CP in the decay of the long-lived, CP-odd neutral K meson into a CP-even final state:

  Br(K_L->$\pi^+\pi^-$) ~0.2% instead of zero

- Staring in 2001, BaBar and Belle experiments observed CP violation in B meson decays

- In 2019, LHCb announced the discovery of CP violation in Charm D^0 decays.

The Nobel Prize in Physics 1980

Photo from the Nobel Foundation archive.
James Watson Cronin
Prize share: 1/2

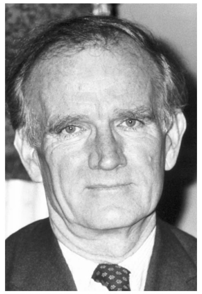
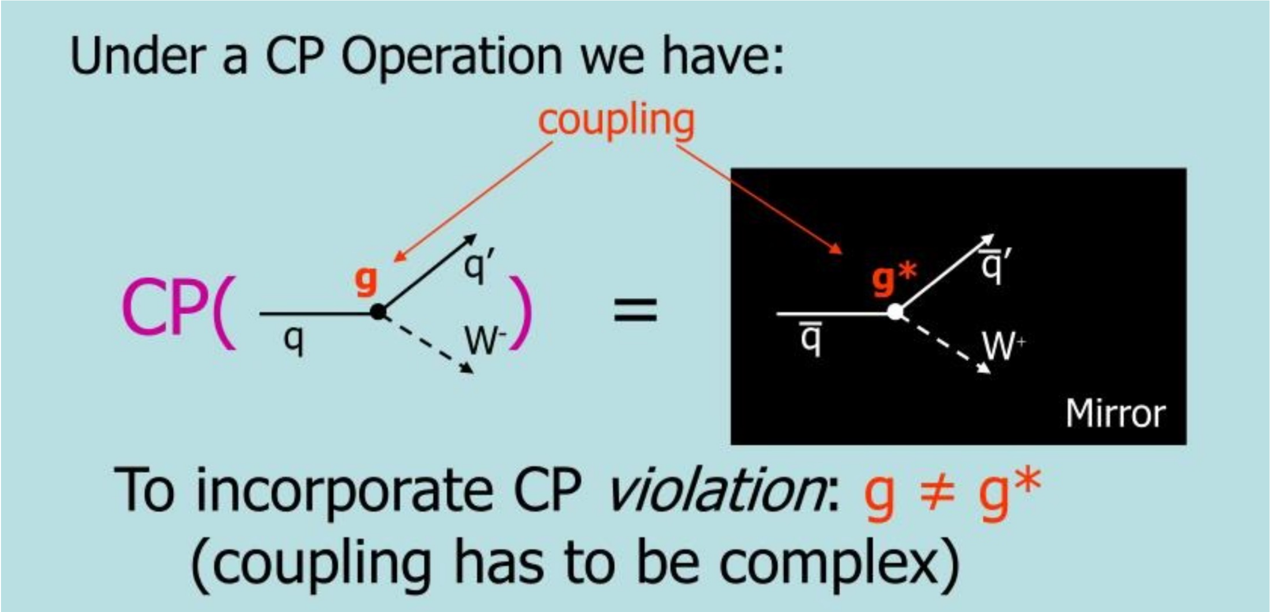


Photo from the Nobel Foundation archive.
Val Logsdon Fitch
Prize share: 1/2

The Nobel Prize in Physics 1980 was awarded jointly to James Watson Cronin and Val Logsdon Fitch "for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"

CP violation in the Standard Model

In the SM, a quark turns into another quark by coupling to a W-boson



It turns out that with 3 generation of quarks we can easily incorporate CP violation into the SM:

The Cabibbo-Kobayashi-Maskawa Marix (1973)

The CKM Matrix

$$V_{\rm CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

The two matrices are not identical (complex elements)
This introduces a phase responsible for CP violation

Weak states CKM matrix Mass states

quarks

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

anti-quarks

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$

CP violation in the K and B meson decay can be explained by the SM: **$n_b/n_\gamma \sim 10^{-20}$ (SM)**

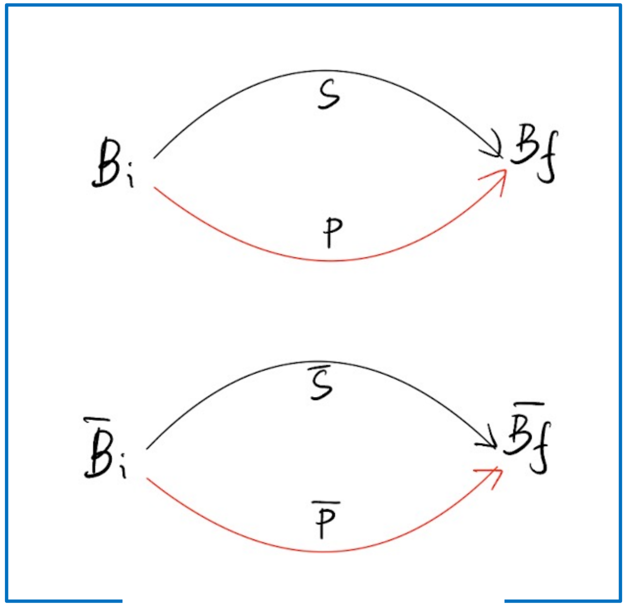
CP violation in the universe: **$n_b/n_\gamma \sim (6.1 +/- 0.3) \times 10^{-10}$ (universe)**

Search for new source for CP violation: Hyperon decays

Hyperon non-leptonic decay

- The Standard Model predicts that if CP violation happens, it must occur through specific kinds of quantum interference effects.
- Hyperon decay into baryon and pion via **S wave** (parity violation) and **P wave** (parity conservation)
- Three decay parameters are defined depending on S and P

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



$$\mathcal{A} \sim S\sigma_0 + P\boldsymbol{\sigma}\cdot\hat{\mathbf{n}}$$

$$\frac{d\Gamma_{\mathcal{B}_i\to\mathcal{B}_f\pi}}{d\Omega_f} = \frac{\Gamma_{\mathcal{B}_i\to\mathcal{B}_f\pi}}{4\pi}\left(1+\alpha\,\boldsymbol{P}_i\cdot\hat{\boldsymbol{p}}_f\right)$$

$$\boldsymbol{P}_f = \frac{(\alpha+\boldsymbol{P}_i\cdot\hat{\boldsymbol{p}}_f)\hat{\boldsymbol{p}}_f + \beta\boldsymbol{P}_i\times\hat{\boldsymbol{p}}_f + \gamma\,\hat{\boldsymbol{p}}_f\times(\boldsymbol{P}_i\times\hat{\boldsymbol{p}}_f)}{1+\alpha\,\boldsymbol{P}_i\cdot\hat{\boldsymbol{p}}_f}$$

CP observables

$$S = \sum_r S_r \, e^{i(\delta_S^r + \xi_S^r)}, \qquad \overline{S} = -\sum_r S_r \, e^{i(\delta_S^r - \xi_S^r)},$$

$$P = \sum_r P_r \, e^{i(\delta_P^r + \xi_P^r)}, \qquad \overline{P} = \sum_r P_r \, e^{i(\delta_P^r - \xi_P^r)},$$

δ designates the CP-conservation phase shift, and ξ stands for weak phase encoding the CP violation.

$$A_{CP} = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}, \qquad B_{CP} = \frac{\beta + \overline{\beta}}{\alpha - \overline{\alpha}}$$

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

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

B_{CP} would exceed A_{CP} in size by up to an order of magnitude

Predictions on CPV in hyperon decays

- S.Okubo, "Decay of the Sigma+ Hyperon and its antiparticle", Phys. Rev. 109 (1958), 984-985
- A. Pais, "Notes on Antibaryon Interaction", Phys. Rev. Lett. 3 (1959),242-244
- T. Brown, S.F. Tuan, and S. Pakvasa, "CP Noconservation in Hyperon Decays", Phy. Rev. Lett. 51 (1983), 1823
- L.L. Chau and H.Y. Chen, "Partial rate differences from CP violation in hyperon nonleptonic decays", Phys. Lett. B 131 (1983), 202-208
- J.F. Donohue, X.G. He, and S. Pakvasa, "Hyperon decays and CP nonconservation", Phys. Rev. D 34 (1986), 833
- …

$$\Delta = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} ,$$

$$A = \frac{\Gamma\alpha + \bar{\Gamma}\bar{\alpha}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}} ,$$

$$B = \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\beta - \bar{\Gamma}\bar{\beta}} ,$$

	Δ	A	B
$\Lambda^0 \to p\pi^-$	-5.4×10^{-7}	-0.5×10^{-4}	3.0×10^{-3}
$\Xi^- \to \Lambda^0\pi^-$	0	-0.7×10^{-4}	8.4×10^{-4}
$\Sigma^- \to n\pi^-$	0	1.6×10^{-4}	-1.2×10^{-2}
$\Sigma^+ \to p\pi^0$	-6.2×10^{-7}	-3.2×10^{-7}	-4.2×10^{-4}
$\Sigma^+ \to n\pi^+$	6.0×10^{-7}	-1.6×10^{-4}	-8.4×10^{-7}

Previous measurements

- Searches for CP violation in hyperon decay started in the mid-1980s.
- The first one: R608 Collaboration "Test of CP invariance in Λ decay".

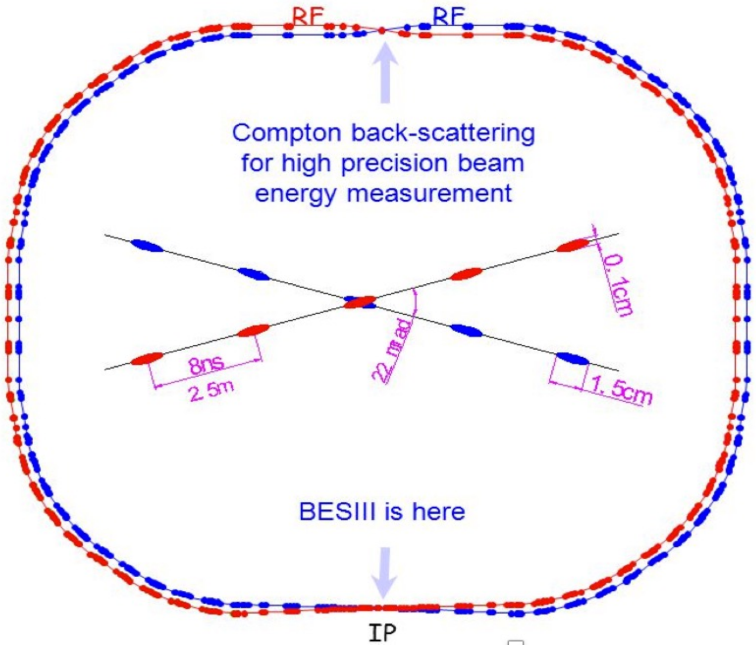
$$(\alpha P)_{\bar{\Lambda}} / (\alpha P)_{\Lambda} = -1.04 \pm 0.29$$

- CERN LEAR and DM2 Collaboration: A ~ 0.1 (uncertainty).
- In 2004, HyperCP Collaboration: Search for CP violation in Charged Ξ and Λ hyperon decays

$$\frac{dN}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha_{\Xi}\alpha_{\Lambda}\cos\theta) \qquad A_{\Xi\Lambda} \equiv \frac{\alpha_{\Xi}\alpha_{\Lambda} - \overline{\alpha}_{\Xi}\overline{\alpha}_{\Lambda}}{\alpha_{\Xi}\alpha_{\Lambda} + \overline{\alpha}_{\Xi}\overline{\alpha}_{\Lambda}}$$

$$[0.0 \pm 5.1(\mathrm{stat}) \pm 4.4(\mathrm{syst})] \times 10^{-4}$$

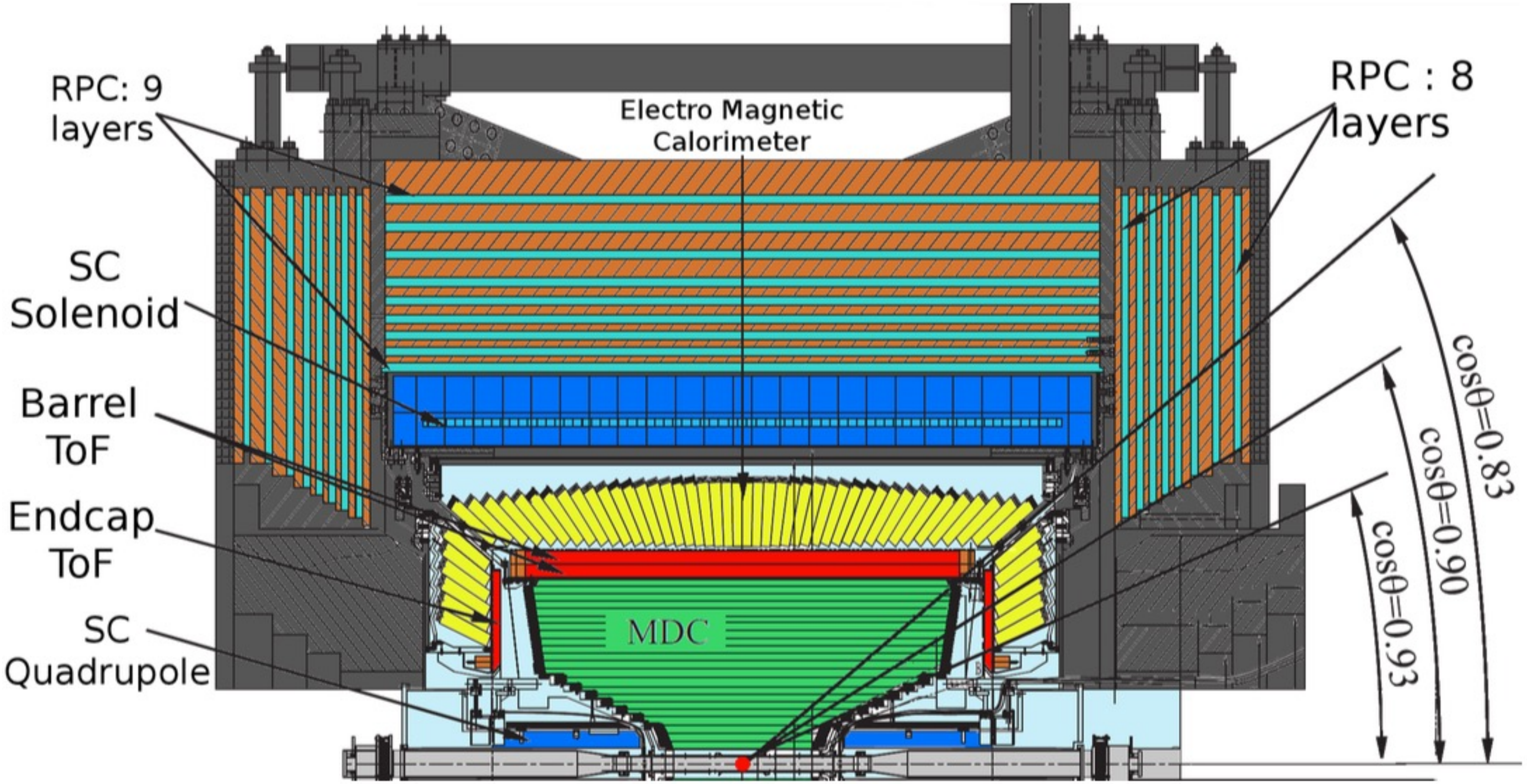
BEPCII storage rings: a τ-charm factory



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

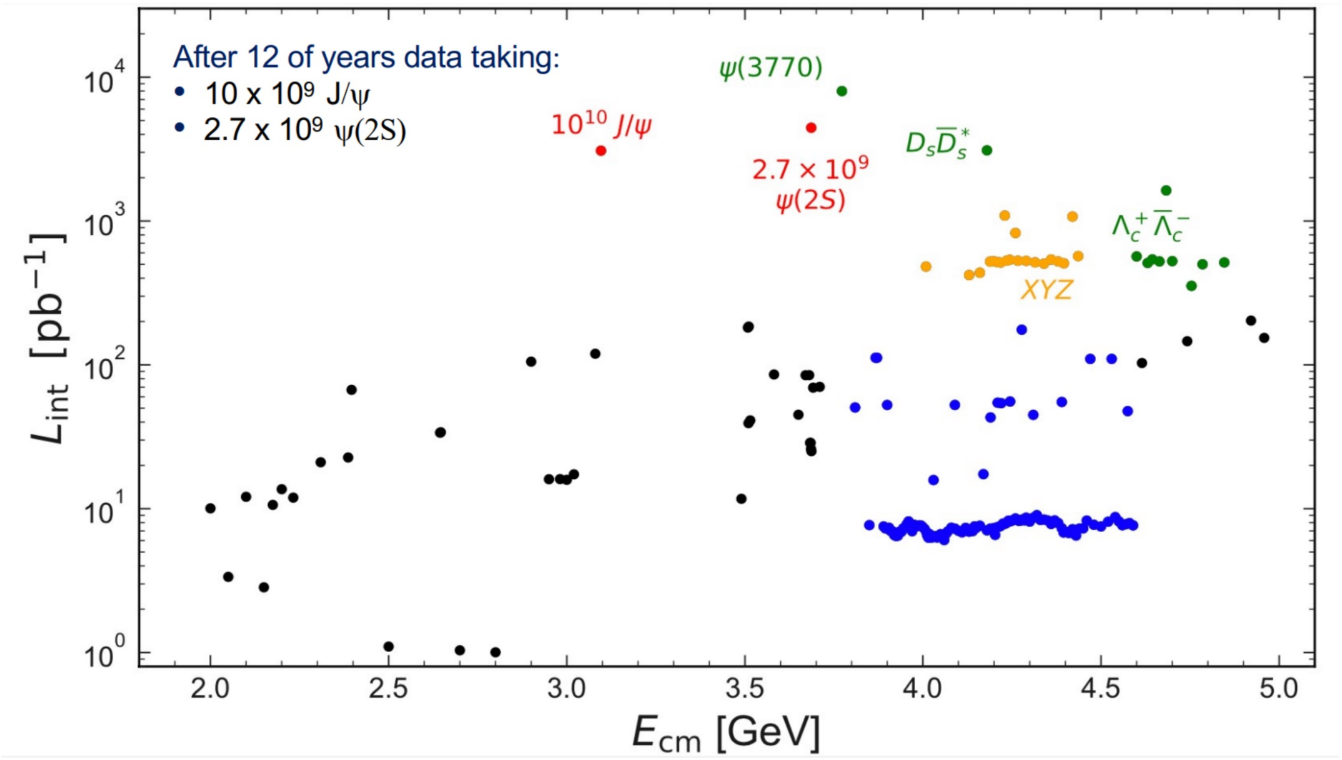
Beam energy	0.92 - 2.475 GeV
Optimum energy	1.89 GeV
Single beam current	0.91 A
Crossing angle	11mrad
Design luminosity	1×10^{33} cm^{-2} s^{-1}
Achieved	1×10^{33} cm^{-2} s^{-1}

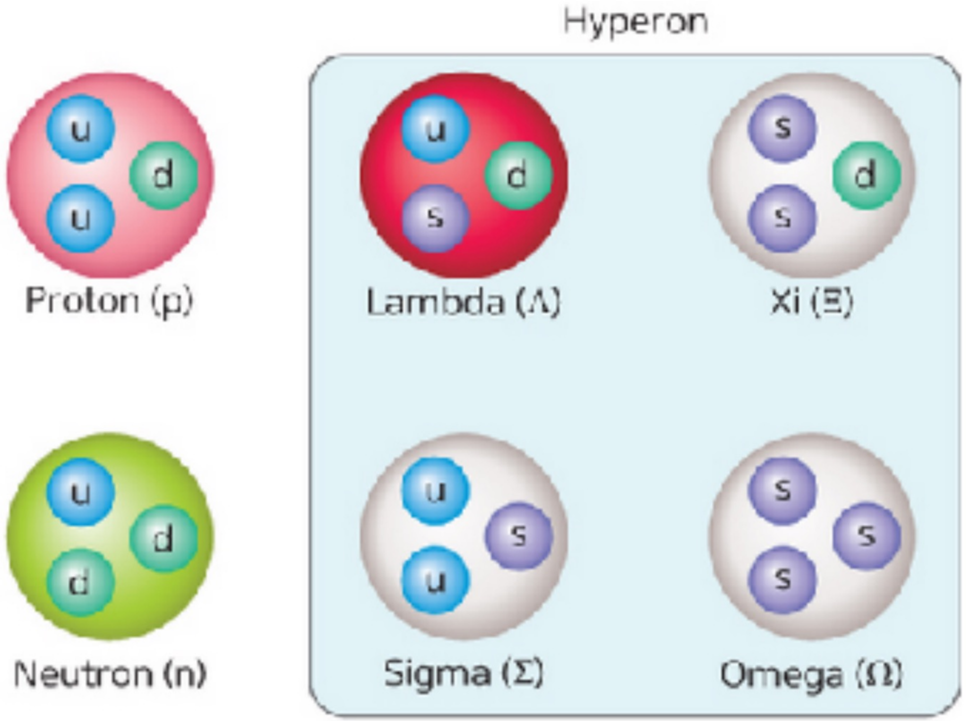
BESIII detectors



- 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

Hyperon pairs at BESIII

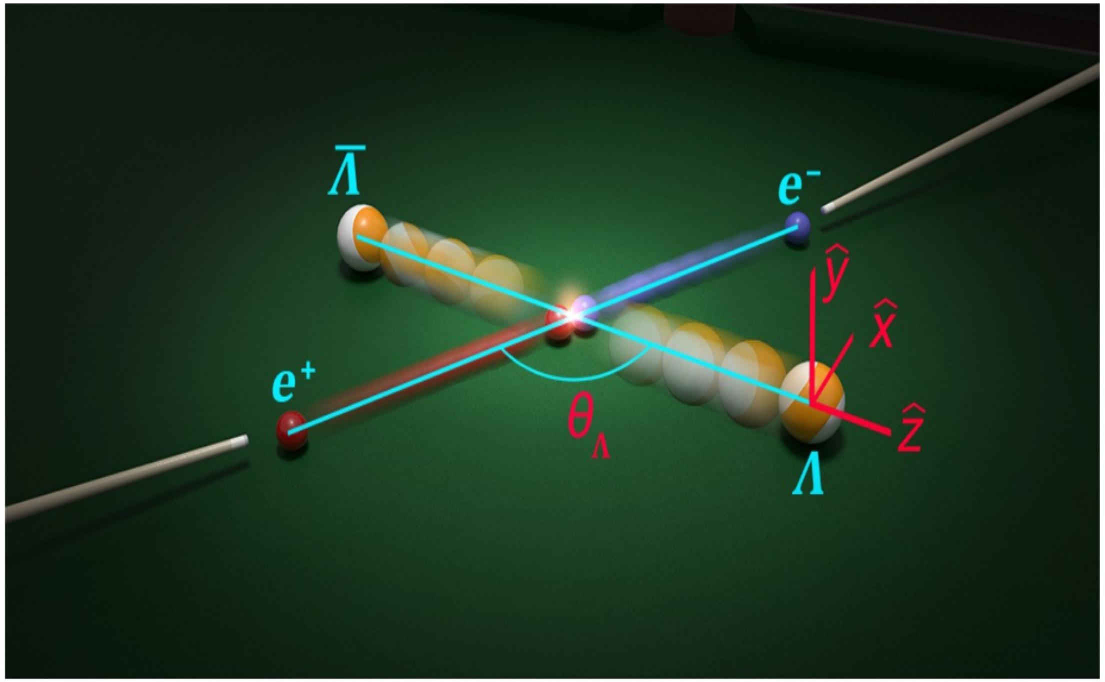




Decay	$\mathcal{B}$ (10^{-5})	Events at BESIII
$J/\psi \to \Lambda\bar{\Lambda}$	189 ± 9	18.9×10^6
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	150 ± 24	15.0×10^6
$J/\psi \to \Xi\bar{\Xi}$	97 ± 8	9.7×10^6
$\psi(2S) \to \Sigma\bar{\Sigma}$	23.2 ± 1.2	116×10^3
$\psi(2S) \to \Omega\bar{\Omega}$	5.66 ± 0.30	28×10^3

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

Nature Phys.15, 631 (2019)



The production process can be parametrized by two complex electromagnetic form factors G_E and G_M.

$\Delta\phi$ is the relative phase between G_E and G_M, which is related to the polarizations of hyperon.

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

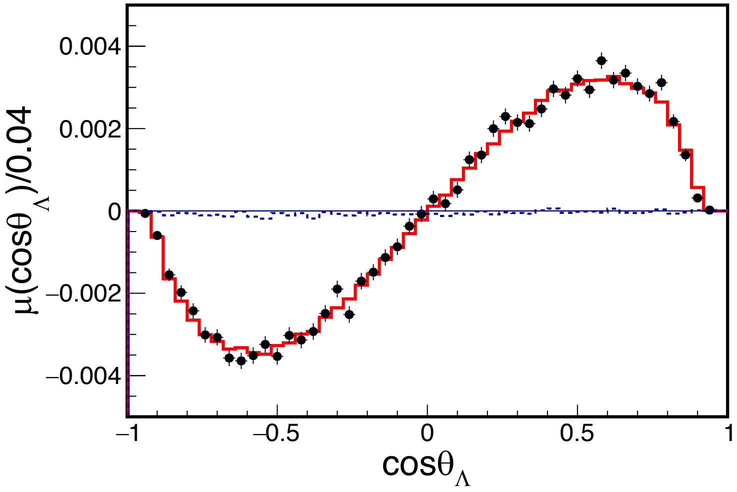
$$+\sqrt{1-\alpha_\psi{}^2}\sin(\Delta\Phi)\left(\alpha_0\mathcal{T}_3(\boldsymbol{\xi}) - \bar{\alpha}_0\mathcal{T}_4(\boldsymbol{\xi})\right)$$

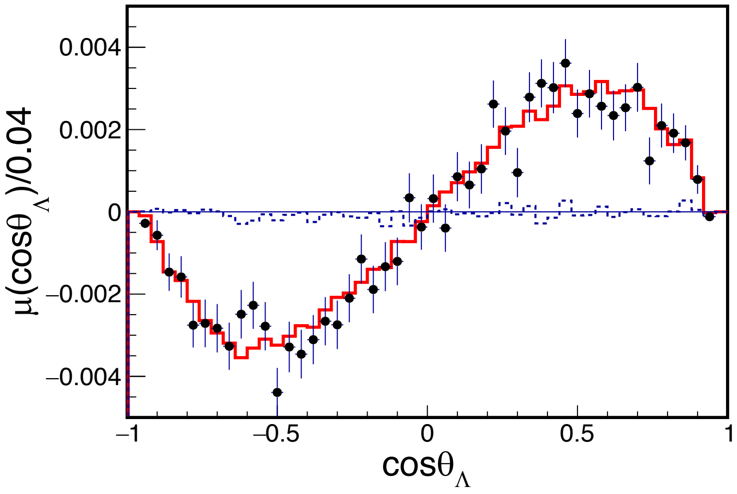
POLARIZATIONS

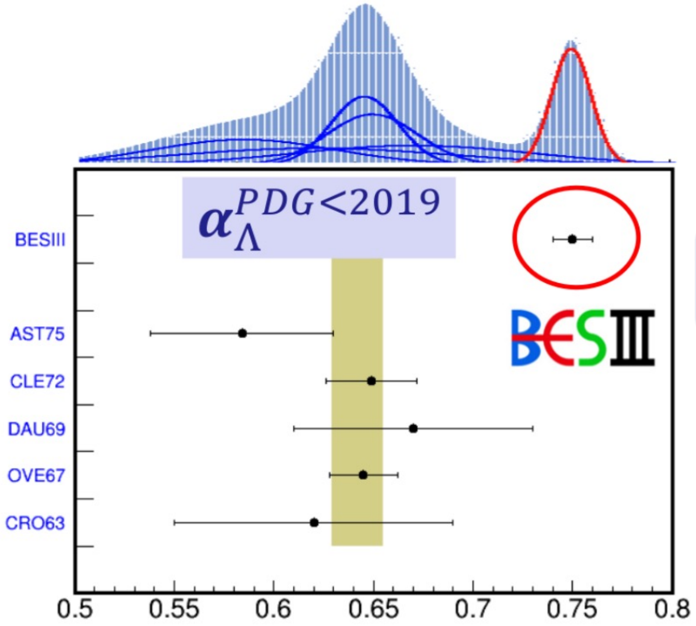
$$\begin{aligned}
\mathcal{T}_0(\boldsymbol{\xi}) &= 1 \\
\mathcal{T}_1(\boldsymbol{\xi}) &= \sin^2\theta \sin\theta_p \sin\theta_{\bar{p}} \cos\phi_p \cos\phi_{\bar{p}} + \cos^2\theta \cos\theta_p \cos\theta_{\bar{p}} \\
\mathcal{T}_2(\boldsymbol{\xi}) &= \sin\theta\cos\theta\,(\sin\theta_p \cos\theta_{\bar{p}}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

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

Nature Phys.15, 631 (2019)







$$< \alpha >= \frac{\alpha - \bar{\alpha}}{2} = 0.754 \pm 0.003 \pm 0.002$$

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

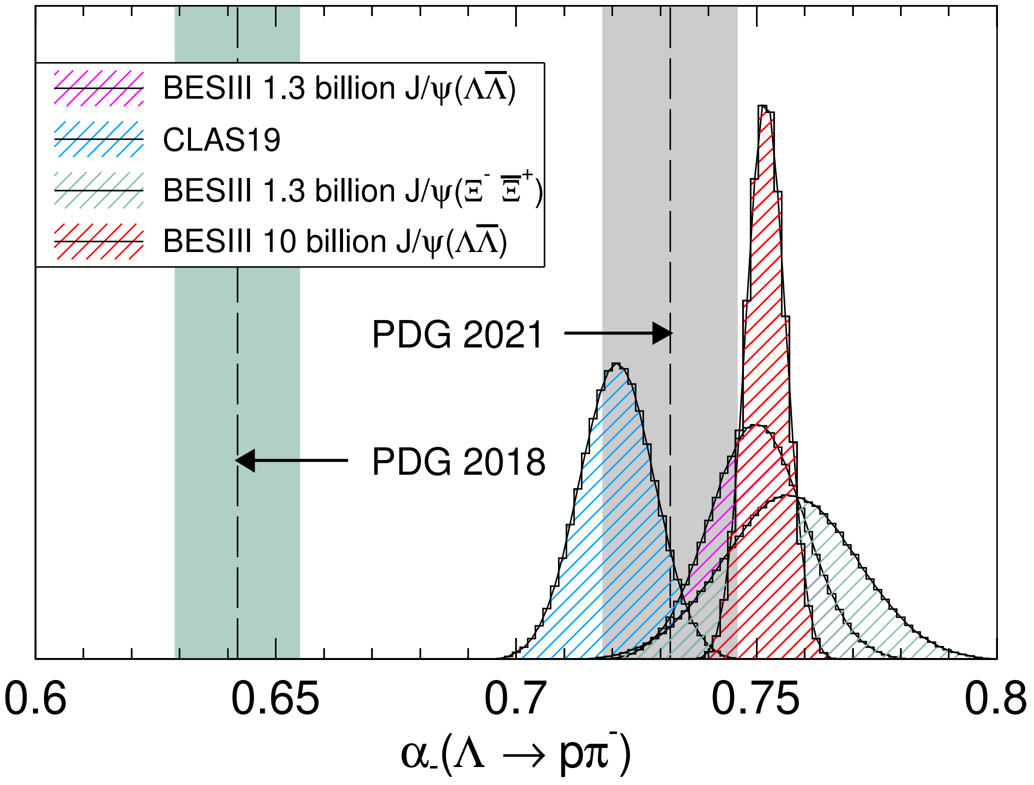
Parameters	This work	Previous results	
α_ψ	$\mathbf{0.461 \pm 0.006 \pm 0.007}$	0.469 ± 0.027	BESIII
$\Delta\Phi$ (rad)	$\mathbf{0.740 \pm 0.010 \pm 0.008}$	–	
α_Λ	$\mathbf{0.750 \pm 0.009 \pm 0.004}$	0.642 ± 0.013	PDG
$\bar{\alpha}_\Lambda$	$\mathbf{-0.758 \pm 0.010 \pm 0.007}$	-0.71 ± 0.08	PDG

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

Phys. Rev. Lett. 129, 131801 (2022)

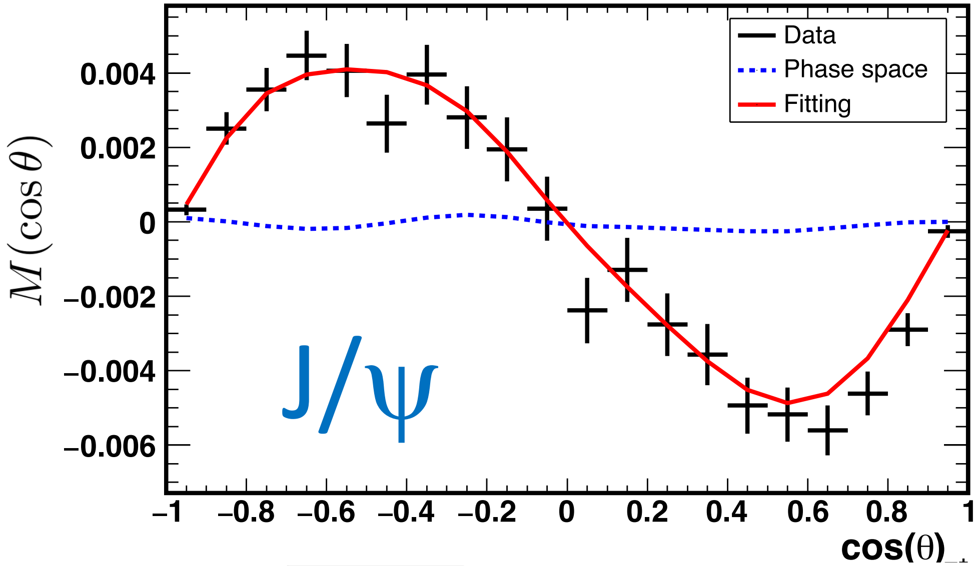
- 10 Billion J/psi events are used to update the results.
- The decay parameters are consistent with previous measurements.
- Acp value is improved with both statistical and systematical uncertainties.

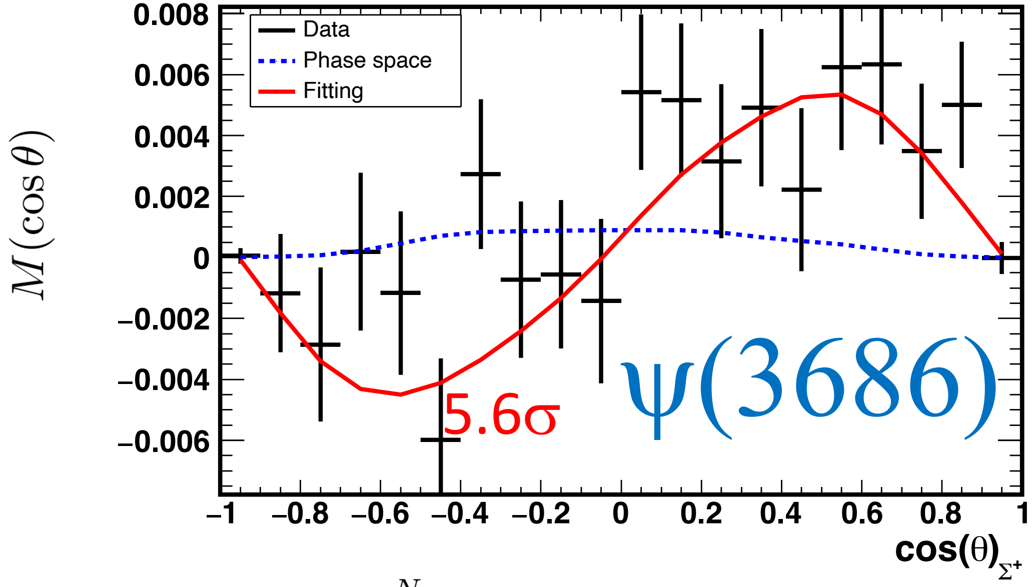
Par.	This work	Previous results [8]
$\alpha_{J/\psi}$	$0.4748 \pm 0.0022 \pm 0.0024$	$0.461 \pm 0.006 \pm 0.007$
$\Delta\Phi$	$0.7521 \pm 0.0042 \pm 0.0080$	$0.740 \pm 0.010 \pm 0.009$
α_-	$0.7519 \pm 0.0036 \pm 0.0019$	$0.750 \pm 0.009 \pm 0.004$
α_+	$-0.7559 \pm 0.0036 \pm 0.0029$	$-0.758 \pm 0.010 \pm 0.007$
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)





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

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

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	$-0.998 \pm 0.037 \pm 0.009$
$\bar{\alpha}_0$	$0.990 \pm 0.037 \pm 0.011$

The first CP test for Σ+

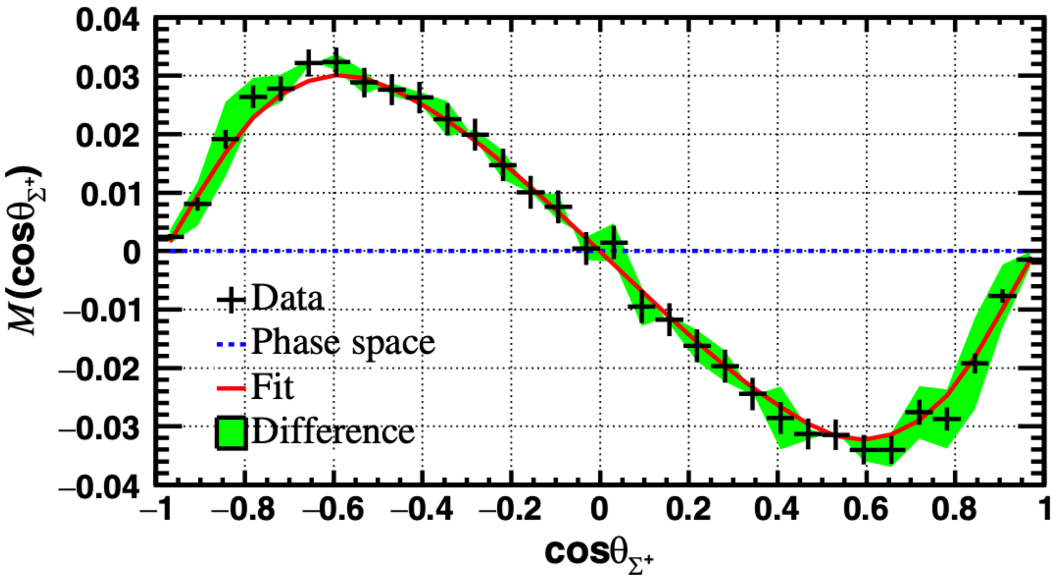
CP asymmetry $-0.004 \pm 0.037 \pm 0.010$

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

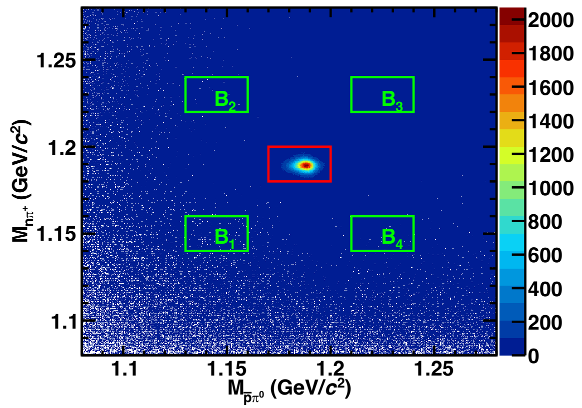
Hyperon to Neutron Decays

Phys. Rev. Lett. 131, 191802 (2023)

- First CP precision test of any hyperon decaying into neutron
- Select event $\Sigma^+ \to n\,\pi^+$ and anti-Σ^- ->pbar π^0 or c.c. with tagging methods
- Utilizing the polarized and entangled Σ^+ anti-Σ^- pair in J/ψ decay

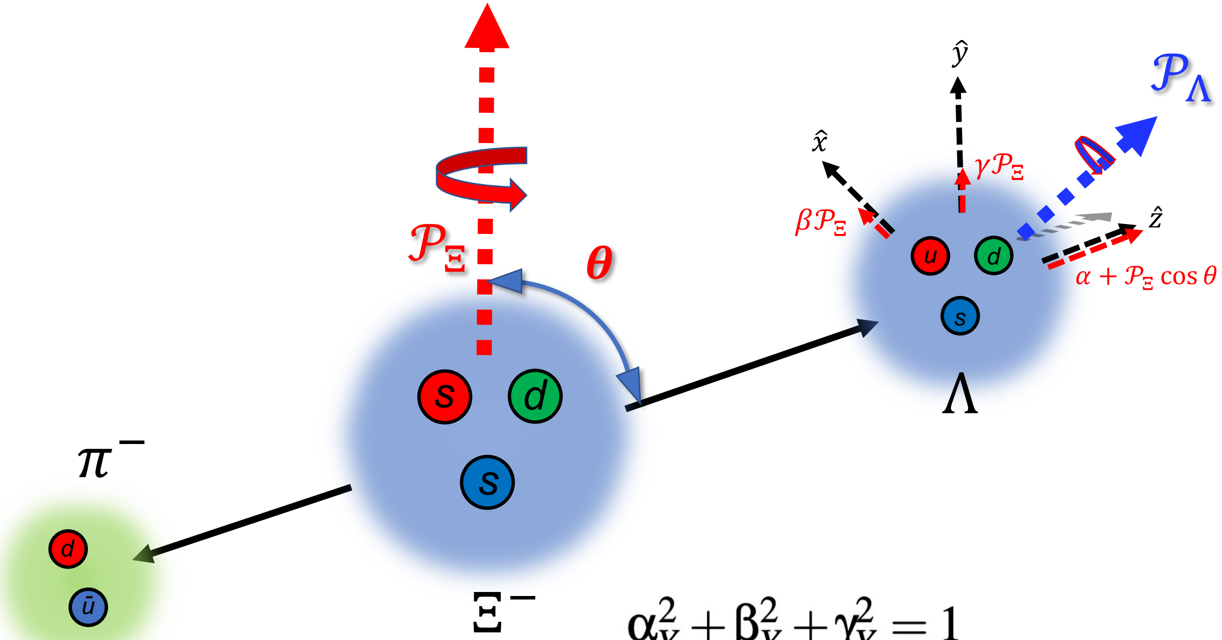


Parameter	This Letter	Previous result
$\alpha_{J/\psi}$	$-0.5156 \pm 0.0030 \pm 0.0061$	$-0.508 \pm 0.006 \pm 0.004$ [26]
$\Delta\Phi_{J/\psi}$ (rad)	$-0.2772 \pm 0.0044 \pm 0.0041$	$-0.270 \pm 0.012 \pm 0.009$ [26]
α_+	$0.0481 \pm 0.0031 \pm 0.0019$	0.069 ± 0.017 [18]
$\bar{\alpha}_-$	$-0.0565 \pm 0.0047 \pm 0.0022$	...
α_+/α_0	$-0.0490 \pm 0.0032 \pm 0.0021$	-0.069 ± 0.021 [33]
$\bar{\alpha}_-/\bar{\alpha}_0$	$-0.0571 \pm 0.0053 \pm 0.0032$	...
A_{CP}	$-0.080 \pm 0.052 \pm 0.028$	...
$\langle\alpha_+\rangle$	$0.0506 \pm 0.0026 \pm 0.0019$	...



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

Nature 606,7912 (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:

Production

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

Decay

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

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

Nature 606,7912 (2022)

Parameter	This work	Previous result	
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$	[39]
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad	–	
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010	[21]
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009$ rad	-0.037 ± 0.014 rad	[21]
$\bar{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	–	
$\bar{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007$ rad	–	
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$	[14]
$\bar{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$	[14]
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ 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	[17]
A_{CP}^{Ξ}	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–	
$\Delta\phi_{CP}^{\Xi}$	$(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ rad	–	
A_{CP}^{Λ}	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$	[14]
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad		

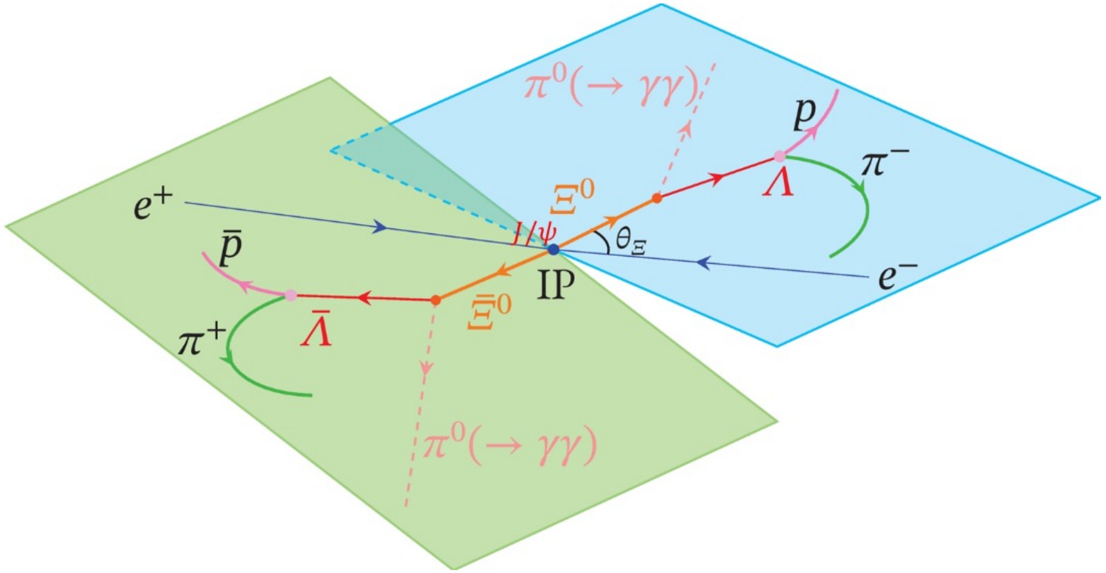
Independent measurement of α_Λ

First measurement of weak phase difference!

3 CP test

$J/\psi \to \Xi^0 \bar{\Xi}^0$ and $\psi(2S) \to \Xi^- \bar{\Xi}^+$

Phys. Rev. D 106, L091101 (2022)
Phys. Rev. D 108, L031106 (2023)



Based on 10 billion J/ψ events collected at BESIII, About 320000 quantum-entangled Ξ^0-Ξbar^0 pairs are reconstructed

A detailed study of quantum entangled Ξ^0-Ξbar^0 pairs has been performed through the process $e^+e^- \to J/\psi \to \Xi^0$ Ξbar^0, $\Xi^0 \to \Lambda(\to p\pi^-)\pi^0$, Ξbar$^0 \to$ Λbar(→pbar π^+)π^0

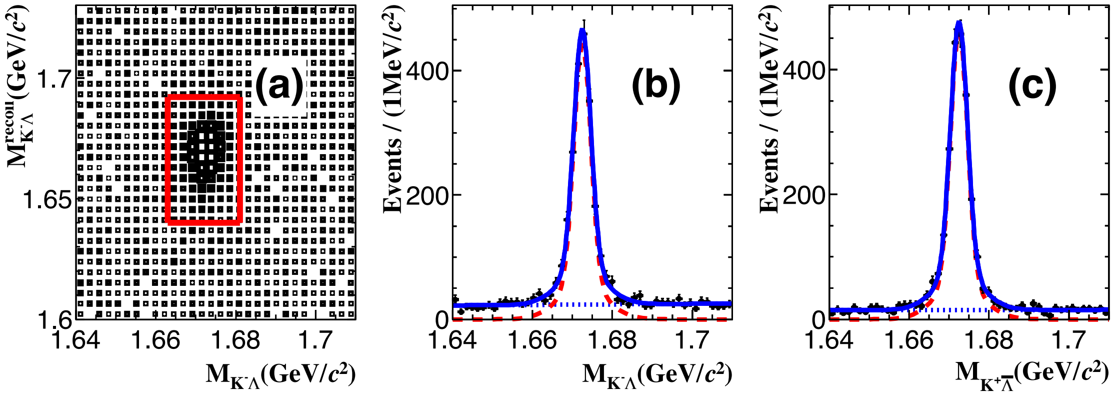
Parameter	This work	Previous result
$\alpha_{J/\psi}$	$0.514 \pm 0.006 \pm 0.015$	0.66 ± 0.06 [42]
$\Delta\Phi$(rad)	$1.168 \pm 0.019 \pm 0.018$	...
α_Ξ	$-0.3750 \pm 0.0034 \pm 0.0016$	-0.358 ± 0.044 [49]
$\bar{\alpha}_\Xi$	$0.3790 \pm 0.0034 \pm 0.0021$	0.363 ± 0.043 [49]
ϕ_Ξ(rad)	$0.0051 \pm 0.0096 \pm 0.0018$	0.03 ± 0.12 [49]
$\bar{\phi}_\Xi$(rad)	$-0.0053 \pm 0.0097 \pm 0.0019$	-0.19 ± 0.13 [49]
α_Λ	$0.7551 \pm 0.0052 \pm 0.0023$	0.7519 ± 0.0043 [20]
$\bar{\alpha}_\Lambda$	$-0.7448 \pm 0.0052 \pm 0.0017$	-0.7559 ± 0.0047 [20]
$\xi_P - \xi_S$(rad)	$(0.0 \pm 1.7 \pm 0.2) \times 10^{-2}$	...
$\delta_P - \delta_S$(rad)	$(-1.3 \pm 1.7 \pm 0.4) \times 10^{-2}$	...
A_{CP}^{Ξ}	$(-5.4 \pm 6.5 \pm 3.1) \times 10^{-3}$	$(-0.7 \pm 8.5) \times 10^{-2}$ [49]
$\Delta\phi_{CP}^{\Xi}$(rad)	$(-0.1 \pm 6.9 \pm 0.9) \times 10^{-3}$	$(-7.9 \pm 8.3) \times 10^{-2}$ [49]
A_{CP}^{Λ}	$(6.9 \pm 5.8 \pm 1.8) \times 10^{-3}$	$(-2.5 \pm 4.8) \times 10^{-3}$ [20]
$\langle\alpha_\Xi\rangle$	$-0.3770 \pm 0.0024 \pm 0.0014$	...
$\langle\phi_\Xi\rangle$(rad)	$0.0052 \pm 0.0069 \pm 0.0016$	...
$\langle\alpha_\Lambda\rangle$	$0.7499 \pm 0.0029 \pm 0.0013$	0.7542 ± 0.0026 [20]

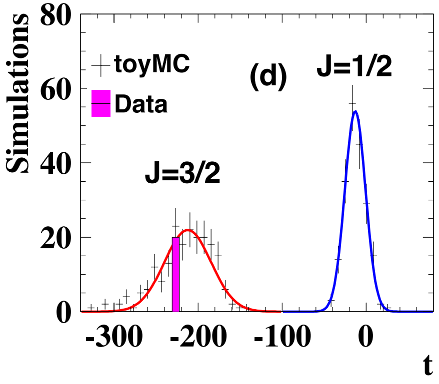
Parameter	$\psi(3686) \to \Xi^-\bar{\Xi}^+$
α_ψ	$0.693 \pm 0.048 \pm 0.049$
$\Delta\Phi$ (rad)	$0.667 \pm 0.111 \pm 0.058$
α_{Ξ^-}	$-0.344 \pm 0.025 \pm 0.007$
$\alpha_{\bar{\Xi}^+}$	$0.355 \pm 0.025 \pm 0.002$
ϕ_{Ξ^-} (rad)	$0.023 \pm 0.074 \pm 0.003$
$\phi_{\bar{\Xi}^+}$ (rad)	$-0.123 \pm 0.073 \pm 0.004$
$\delta_p - \delta_s$ ($\times 10^{-1}$ rad)	$-2.0 \pm 1.3 \pm 0.1$
$A_{CP,\Xi}$ ($\times 10^{-2}$)	$-1.5 \pm 5.1 \pm 1.0$
$\Delta\phi_{CP}$ ($\times 10^{-2}$ rad)	$-5.0 \pm 5.2 \pm 0.3$

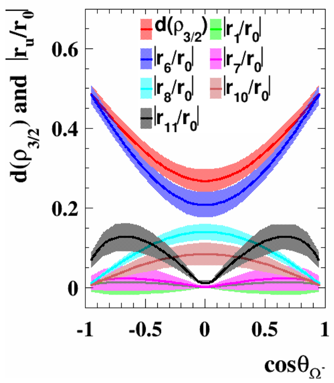
$\psi(3686) \to \Omega^- \Omega^+$

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.







3/2 is preferred over 1/2 with significance more than 14σ

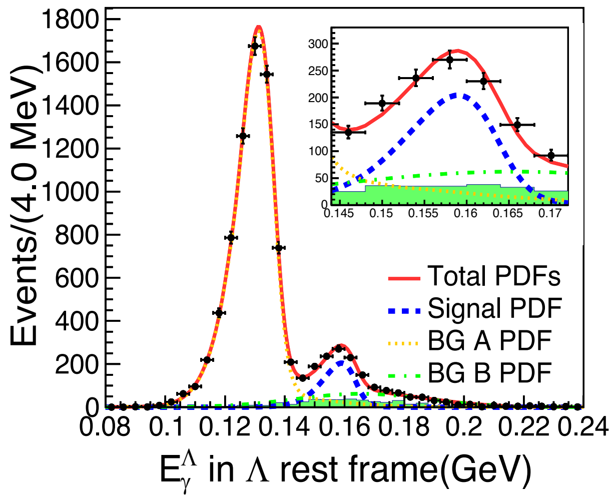
Not only observe vector polarization(r1), but also quadrupole (r6, r7, r8) and octupole(r10, r11) polarizations

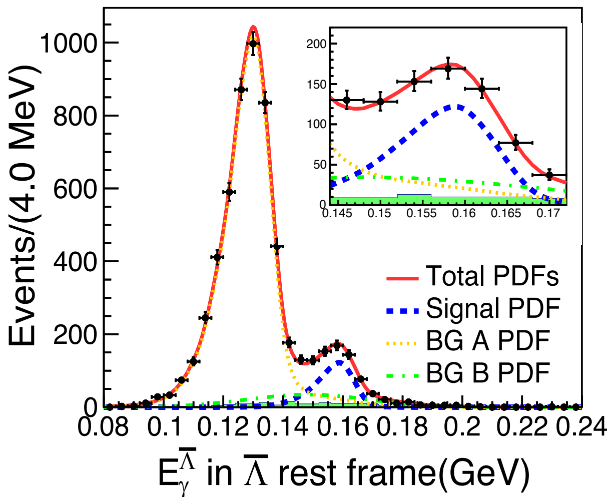
$Br(\psi(3686) \to \Omega^+ \Omega^-) =$
$(5.85 \pm 0.12 \pm 0.25)$ X 10^{-5}
$\alpha = 0.24 \pm 0.10$

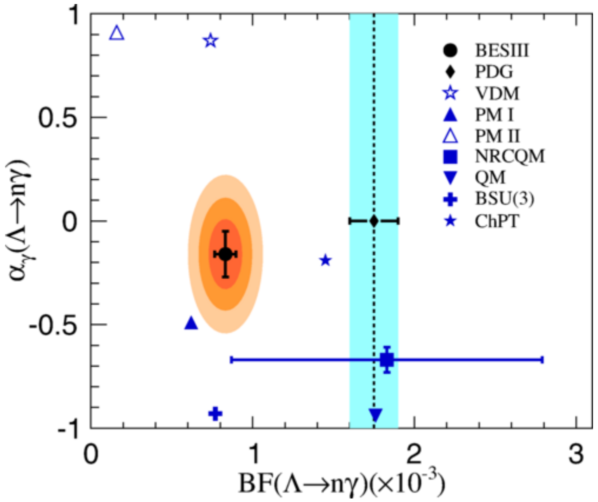
Hyperon radiative decay

Phys. Rev. Lett. 129, 212002 (2022)

Phys. Rev. Lett. 130, 211901 (2023)

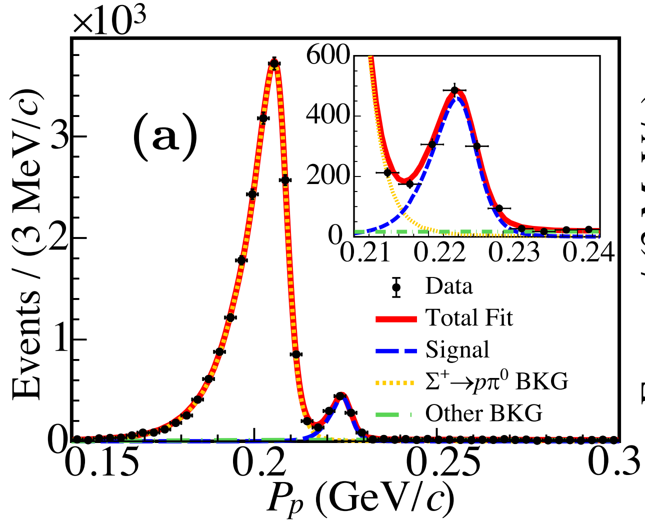


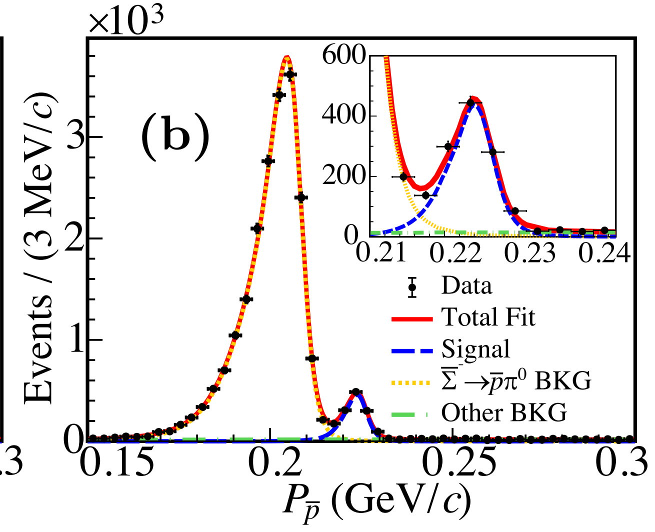


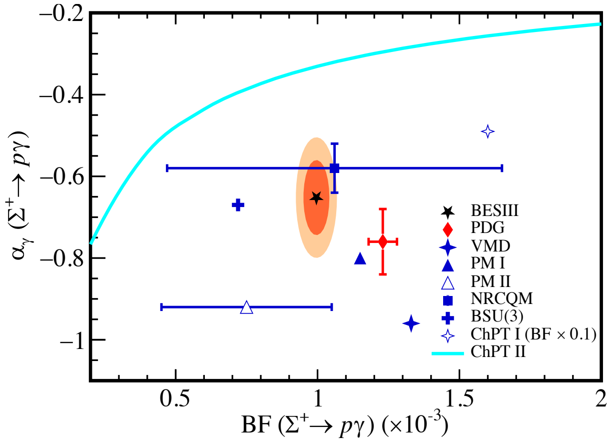


The BF of Λ->γ n, smaller than PDG value by 5.5σ

$(0.832 \pm 0.038 \pm 0.054) \times 10^{-3}$







The BF of Σ⁺->γ p, deviates from the previous value by 4.2σ

$(0.996 \pm 0.021 \pm 0.018) \times 10^{-3}$

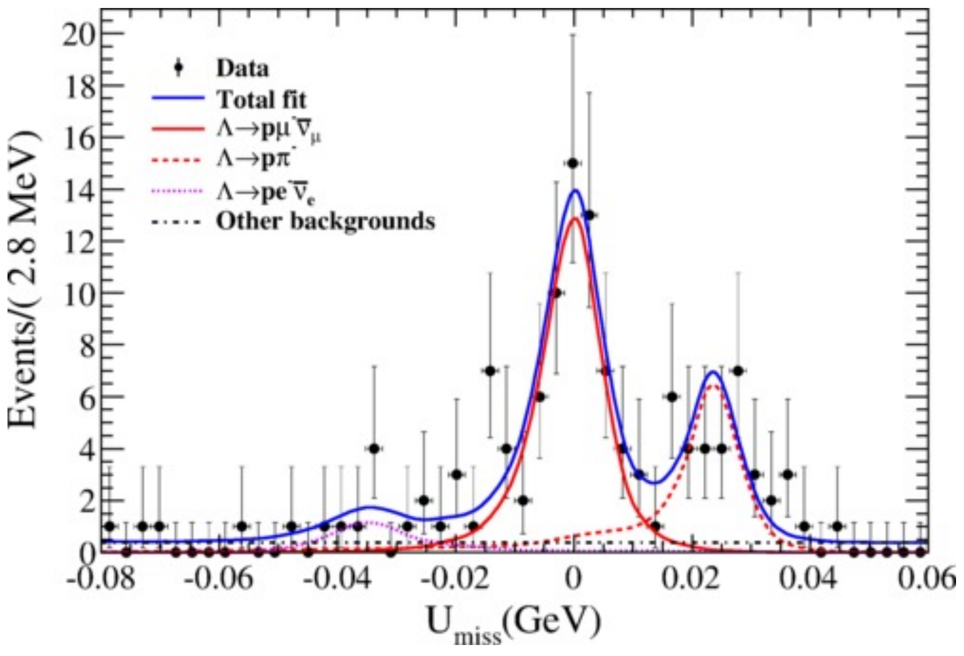
Hyperon semi-leptonic decay

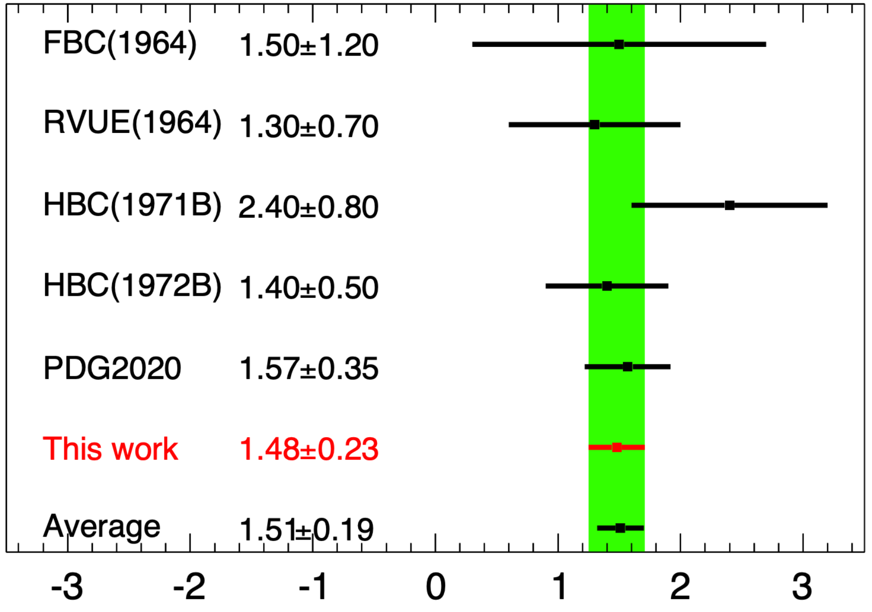
Phys. Rev. Lett. 127, 121802 (2021)

- Absolute BF measurement of the branching fraction of $\Lambda \to p\mu^-\bar{\nu}_\mu$ with DT method.
- Test lepton flavor universality
- Search for CP violation

SM Prediction $$R^{\mu e}_{SM} = \frac{\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda \to pe^-\bar{\nu}_e)} = 0.153 \pm 0.008$$

Experimental results $$R^{\mu e} = \frac{\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda \to pe^-\bar{\nu}_e)} = 0.178 \pm 0.028$$





$B(\Lambda \to p\mu^-\bar{\nu}_\mu)\times 10^{-4}$

Hyperon rare decay

Front. Phys. 12(5), 121301 (2017)
DOI 10.1007/s11467-017-0691-9

PERSPECTIVE

Prospects for rare and forbidden hyperon decays at BESIII

Hai-Bo Li[1,2,†]

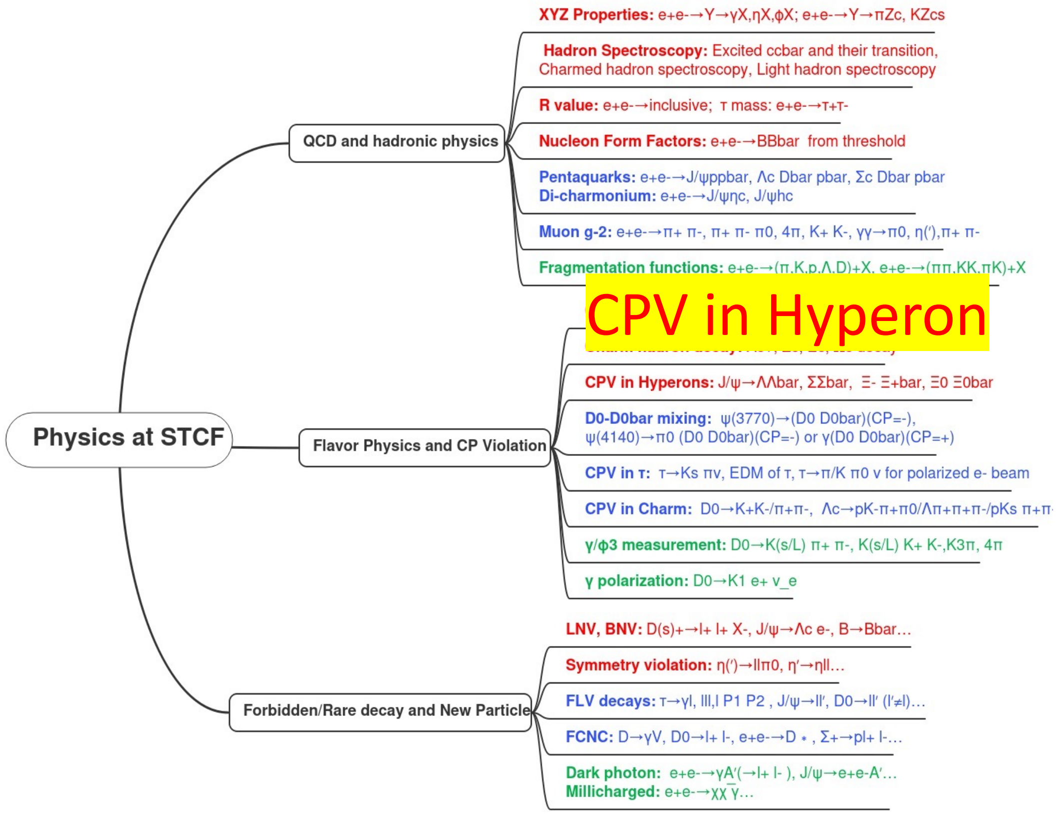
The study of hyperon decays at the Beijing Electron Spectrometer III (BESIII) is proposed to investigate the events of J/ψ decay into hyperon pairs, which provide a pristine experimental environment at the Beijing Electron–Positron Collider II. About 10^6–10^8 hyperons, i.e., Λ, Σ, Ξ, and Ω, will be produced in the J/ψ and $\psi(2S)$ decays with the proposed data samples at BESIII. Based on these samples, the measurement sensitivity of the branching fractions of the hyperon decays is in the range of 10^{-5}–10^{-8}. In addition, with the known center-of-mass energy and "tag technique", rare decays and decays with invisible final states can be probed.

Decay mode	Current data $\mathcal{B}$ ($\times 10^{-6}$)	Sensitivity $\mathcal{B}$ (90% C.L.) ($\times 10^{-6}$)	Type
$\Lambda \to n e^+ e^-$	–	< 0.8	
$\Sigma^+ \to p e^+ e^-$	< 7	< 0.4	
$\Xi^0 \to \Lambda e^+ e^-$	7.6 ± 0.6	< 1.2	
$\Xi^0 \to \Sigma^0 e^+ e^-$	–	< 1.3	EM decay
$\Xi^- \to \Sigma^- e^+ e^-$	–	< 1.0	
$\Omega^- \to \Xi^- e^+ e^-$	–	< 26.0	
$\Sigma^+ \to p \mu^+ \mu^-$	$(0.09^{+0.09}_{-0.08})$	< 0.4	
$\Omega^- \to \Xi^- \mu^+ \mu^-$	–	< 30.0	
$\Lambda \to n \nu \bar{\nu}$	–	< 0.3	
$\Sigma^+ \to p \nu \bar{\nu}$	–	< 0.4	
$\Xi^0 \to \Lambda \nu \bar{\nu}$	–	< 0.8	
$\Xi^0 \to \Sigma^0 \nu \bar{\nu}$	–	< 0.9	FCNC
$\Xi^- \to \Sigma^- \nu \bar{\nu}$	–	–*	
$\Omega^- \to \Xi^- \nu \bar{\nu}$	–	< 26.0	
$\Sigma^- \to \Sigma^+ e^- e^-$	–	< 1.0	
$\Sigma^- \to p e^- e^-$	–	< 0.6	
$\Xi^- \to p e^- e^-$	–	< 0.4	
$\Xi^- \to \Sigma^+ e^- e^-$	–	< 0.7	
$\Omega^- \to \Sigma^+ e^- e^-$	–	< 15.0	
$\Sigma^- \to p \mu^- \mu^-$	–	< 1.1	Neutrinoless double beta decay
$\Xi^- \to p \mu^- \mu^-$	< 0.04	< 0.5	
$\Omega^- \to \Sigma^+ \mu^- \mu^-$	–	< 17.0	
$\Sigma^- \to p e^- \mu^-$	–	< 0.8	
$\Xi^- \to p e^- \mu^-$	–	< 0.5	
$\Xi^- \to \Sigma^+ e^- \mu^-$	–	< 0.8	
$\Omega^- \to \Sigma^+ e^- \mu^-$	–	< 17.0	

Search for hyperon $\Delta S - \Delta Q$ violating decay PRD 107,012002 (2023)
Search for the lepton number violation decay PRD 103,052011(2021)
Λ invisible decays PRD 105,L071101 (2022)

Most of them never studied

Physics Program at STCF



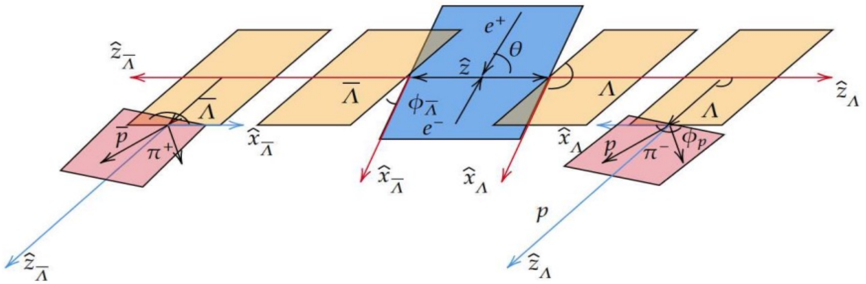
- **Leading role**
- In Competition with Belle II/LHCb
- **Synergy with BelleII/LHCb/EicC**

M. Achasov, et al., STCF conceptual design report (Volume 1): Physics & detector, Front. Phys. 19(1), 14701 (2024)

关于横向极化见近物所曹须报告
周二上午物理分会

CP Test in Λ Decay with Polarized Electron Beam

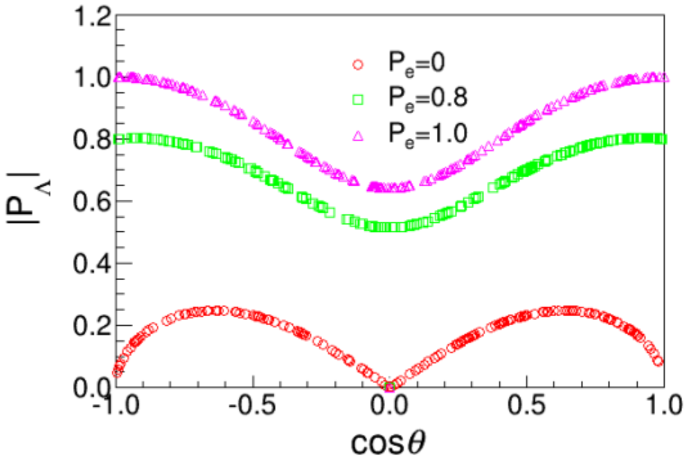
Chinese Physics C 47, 113001 (2023)

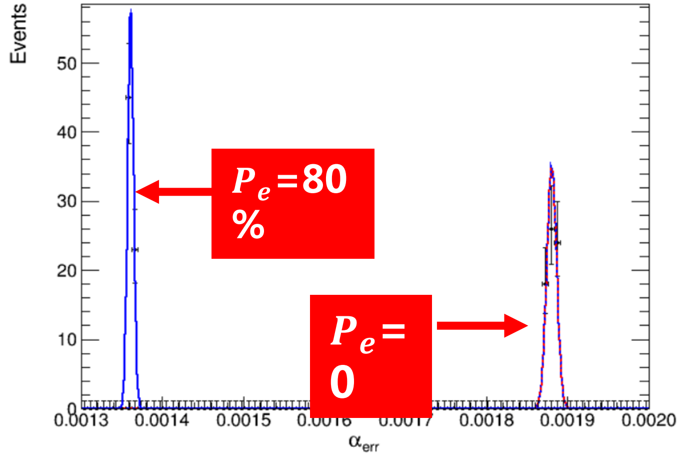


$$\rho_{\Lambda\bar{\Lambda}} = \sum_{\mu\upsilon=0}^{3} C_{\mu\upsilon}\sigma_{\mu}^{\Lambda} \otimes \sigma_{\upsilon}^{\bar{\Lambda}}$$

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

$$\mathbf{P}_\Lambda = \frac{\gamma_\psi P_e\sin\theta\hat{x}_1 - \beta_\psi\sin\theta\cos\theta\hat{y}_1 - (1+\alpha_\psi)P_e\cos\theta\hat{z}_1}{1+\alpha_\psi\cos^2\theta}.$$





- **Large statistics and electron polarization will improve the sensitivity of CPV significantly**
- **The sensitivity of CPV follows :** $\sigma_{A_{CP}} \approx \sqrt{\frac{3}{2}}\frac{1}{\alpha_1\sqrt{N_{sig}}\sqrt{\langle P_B^2\rangle}}.$

$1\times10^9\ \Lambda\bar{\Lambda},\ \langle P_B^2\rangle=0.1 \Longrightarrow \sigma_{A_{CP}}\sim1.4\times10^{-4}$

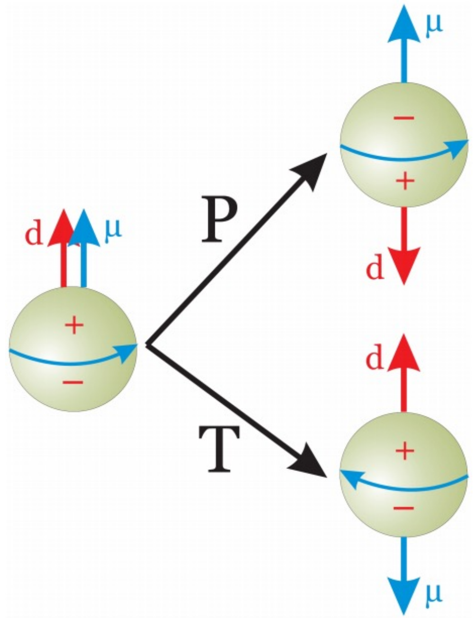
$1\times10^9\ \Lambda\bar{\Lambda},\ \langle P_B^2\rangle=0.8 \Longrightarrow \sigma_{A_{CP}}\sim 5\times10^{-5}$

详细内容见上海交大杜勇报告
周二上午物理分会

Searching for Hyperon EDM

X. G. He, J. P. Ma, Phys. Lett. B 839, 137834 (2023)

J. Fu, H.B.Li, J.P. Wang, F. S. Yu and J. Zhang, Phys. Rev. D 108, 9 (2023)



μ: magnetic dipole moment

d: electric dipole moment

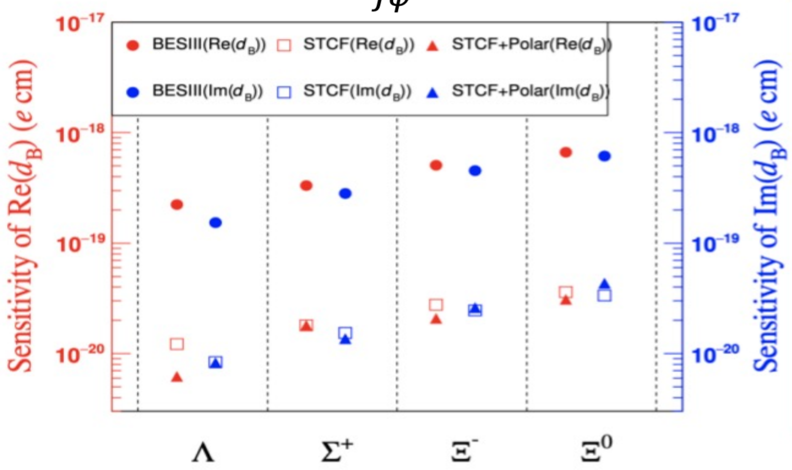
Non-zero EDM will violate P and T symmetry:
T violation ↔ CP violation,
if CPT holds.

Detailed dynamics in J/ψ decay to hyperon pair have been studied:

$$\mathcal{A} = \epsilon_\mu(\lambda)\bar{u}(\lambda_1)\left(F_V\gamma^\mu + \frac{i}{2M_\Lambda}\sigma^{\mu\nu}q_\nu H_\sigma + \gamma^\mu\gamma^5 F_A + \sigma^{\mu\nu}\gamma^5 q_\nu H_T\right)v(\lambda_2)$$

Systematic measurement of the EDMs of the hyperon family!

$$H_T(q^2) = \frac{2e}{3m_{J\psi}^2} g_V d_B(q^2)$$



(a)Sensitivity of $Re(d_B)$ and $Im(d_B)$

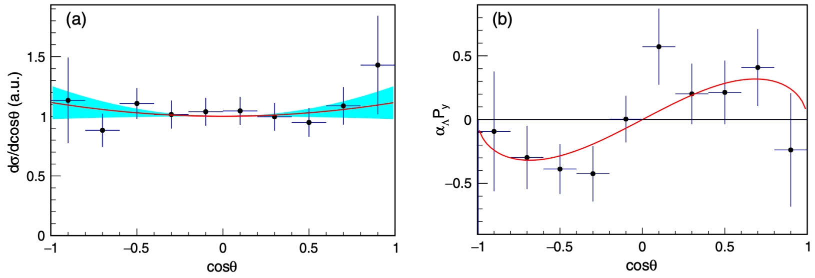
SM: $\sim 10^{-26}$ e cm

BESIII: milestone for hyperon EDM measurement
Λ 10^{-19}e cm (FermiLab 10^{-16} e cm)
first achievement for Σ^+,Ξ^- and Ξ^0 at level of 10^{-19}e cm
a litmus test for new physics

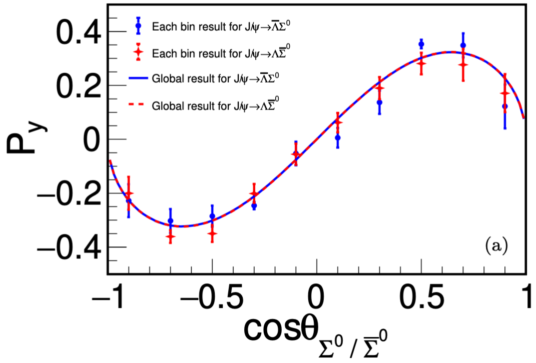
STCF: improved by 2 order of magnitude

Discussion and outlook

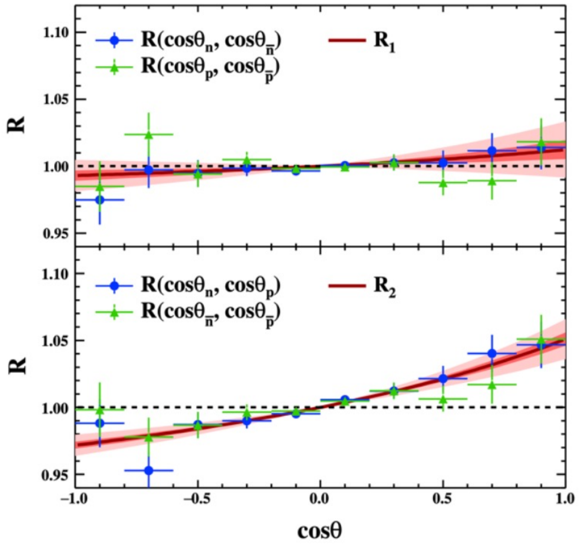
- A similar method could be used in the other c.m. energies for polarization and form factor studies.
- Study the $\Delta I = 1/2$ rule in Ξ and Ω decay
- Study the charm baryon decay



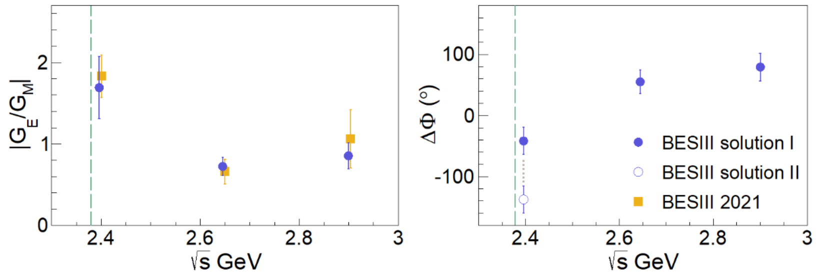
Phys. Rev. Lett. **123**, 122003 (2019)



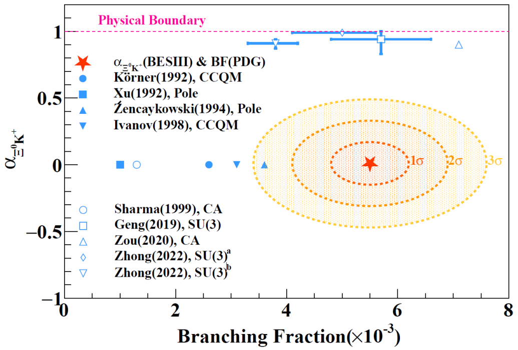
arXiv: 2309.04139



Phys. Rev. Lett. **132**, 101801 (2024)



Phys. Rev. Lett. **132**, 081904 (2024)

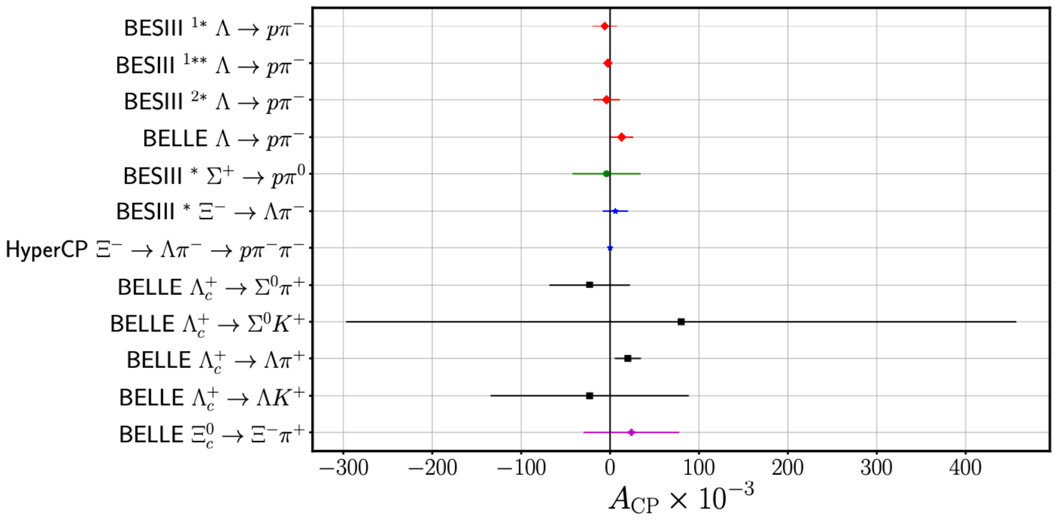


Phys. Rev. Lett. **132**, 031801 (2024)

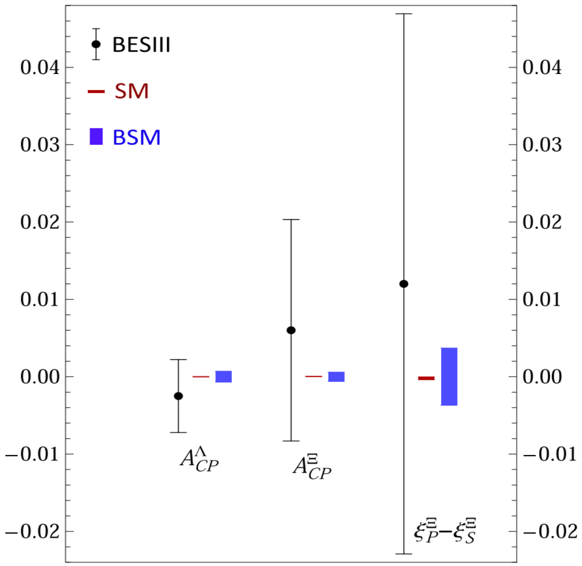
BFs	$\mathcal{B}_{\Omega^- \to \Xi^0\pi^-}$	$\mathcal{B}_{\Omega^- \to \Xi^-\pi^0}$	$\mathcal{B}_{\Omega^- \to \Lambda K^-}$
This work	$25.03 \pm 0.44 \pm 0.53$	$8.43 \pm 0.52 \pm 0.28$	$66.3 \pm 0.8 \pm 2.0$
PDG	23.6 ± 0.7	8.6 ± 0.4	67.8 ± 0.7

Phys. Rev. D. **108**, L091101 (2023)

Discussion and outlook

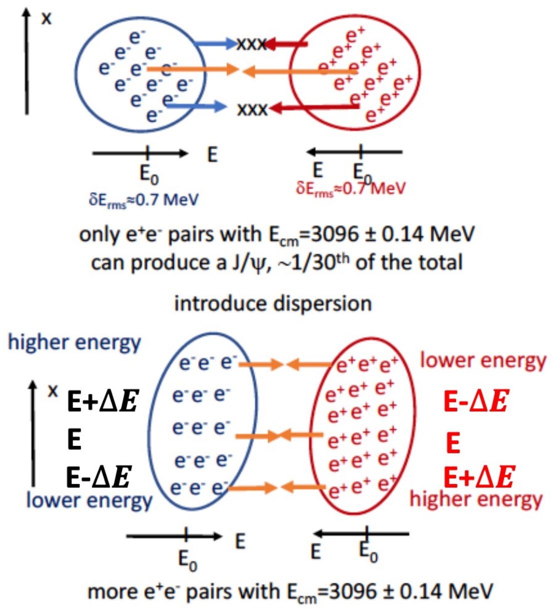


K. Schonning *et al*. Chin.Phys.C 47, 052002 (2023)



X.G. He *et al*. Sci.Bull. 67, 1840-1843 (2022)

Monochromatic collision



A.A.Zholents, CERN-SL-92-27-AP

The SM predictions are below BESIII measurements by 2 orders of magnitude
If the presence of BSM, as a new source of CP violation, enhances the value in size concerning SM prediction
Polarized beam or Monochromatic collision could improve the sensitivity of CP test.

STCF as the future facility has the potential to challenge the SM and BSM

Summary

- The Quantum entangle system supplies a good laboratory to study hyperon properties.
- Many interesting studies have been performed including the CP test, polarization, and isospin rules.
- The precision in CP violation measurements below SM and BSM on the order of magnitude.
- More data and new techniques are needed in the hyperon studies.

THANK YOU