Hyperon Physics at BESIII

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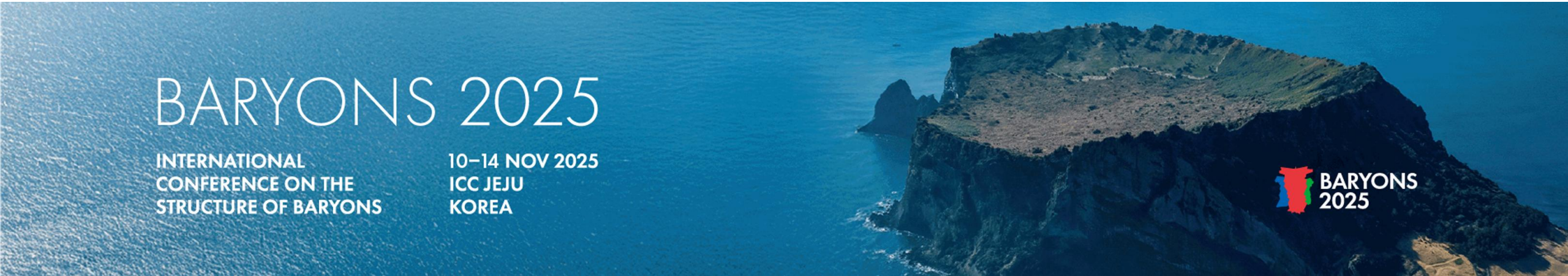
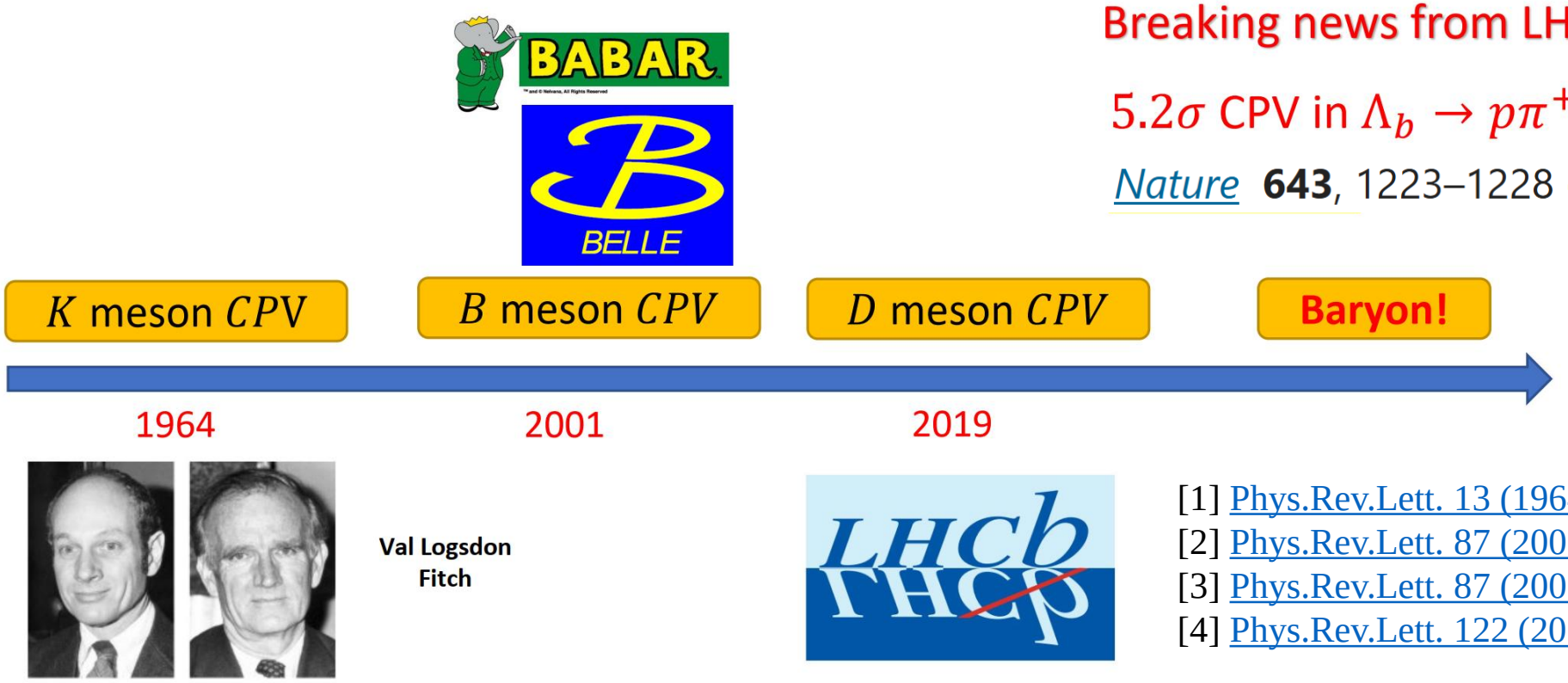


Outline

- Introduction
- Recent results from BESIII
  - CP violation in hyperon decays
  - Hyperon weak radiative decays
- Summary and Outlooks

Roadmap of CP Violation in Flavored Hadrons

- CPV is necessary condition for the matter-antimatter asymmetry
- All consistent with CKM theory but too small to explain the matter-dominant



[1] Phys.Rev.Lett. 13 (1964) 138-140
[2] Phys.Rev.Lett. 87 (2001) 091801
[3] Phys.Rev.Lett. 87 (2001) 091802
[4] Phys.Rev.Lett. 122 (2019) 21, 211803

A new possibility: search for CPV in **entangled** and **polarized** hyperon-antihyperon pairs

Hyperon Non-leptonic Decays


Chen Ning Yang


Tsung-Dao Lee

General Partial Wave Analysis of the Decay of a Hyperon of Spin $\frac{1}{2}$

T. D. LEE* AND C. N. YANG

Institute for Advanced Study, Princeton, New Jersey

(Received October 22, 1957)

Phys. Rev. 108 1645 (1957)

- Spin ½ hyperon decay

$$\mathcal{A}(Y \to B\pi) \propto S + P\,\sigma \cdot \hat{n}$$

- 3 decay parameters:

$$\alpha_Y = \frac{2Re(S^*P)}{|S|^2+|P|^2}, \qquad \beta_Y = \frac{2Im(S^*P)}{|S|^2+|P|^2}, \qquad \gamma_Y = \frac{|S|^2-|P|^2}{|S|^2+|P|^2}$$

- Two complex amplitudes:

$$S = \sum S_i e^{i(\delta_i^S+\xi_i^S)} \qquad \bar{S} = \sum S_i e^{i(\delta_i^S-\xi_i^S)}$$

CP Transformation

$$P = \sum P_i e^{i(\delta_i^P+\xi_i^P)} \qquad \bar{P} = \sum P_i e^{i(\delta_i^P-\xi_i^P)}$$

- CP conversation: $\alpha_Y = -\bar{\alpha}_Y,\ \phi_Y = -\bar{\phi}_Y$

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

$$\beta_Y = (1-\alpha_Y^2)^{1/2}\sin\phi_Y$$

$$\gamma_Y = (1-\alpha_Y^2)^{1/2}\cos\phi_Y$$

CP observables:

$$A_{CP} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} \approx -\tan(\delta_P-\delta_S)\tan(\xi_P-\xi_S)$$

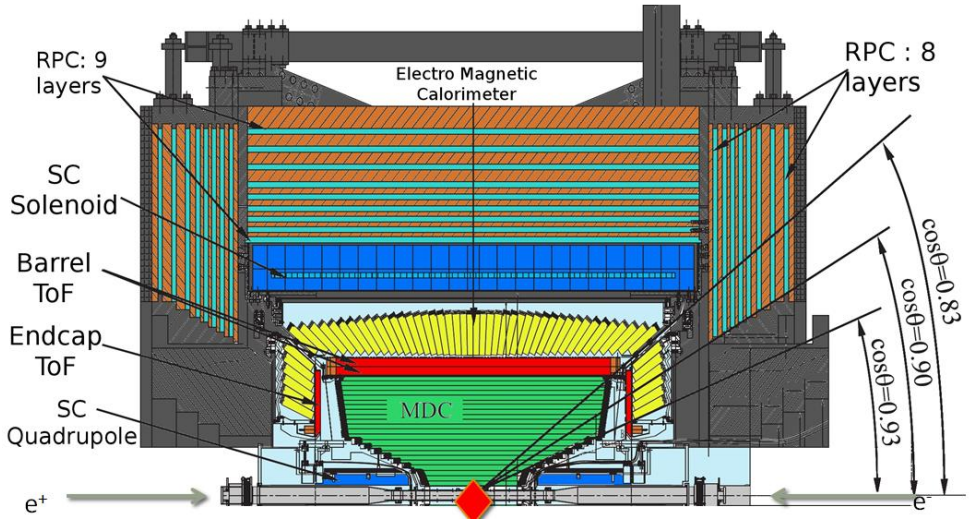
$$B_{CP} = \frac{\beta+\bar{\beta}}{\alpha-\bar{\alpha}} \approx \tan(\xi_P-\xi_S)$$

$$\phi_{CP} = \frac{\phi+\bar{\phi}}{2} \approx \frac{\alpha}{\sqrt{1-\alpha^2}}\cos\phi\,\tan(\xi_P-\xi_S)$$

BESIII: A Hyperon Factory

Electromagnetic Calorimeter
CsI(Tl): L = 28 cm
- Barrel $\sigma_E/E = 2.5\%$ @ 1 GeV
- Endcap $\sigma_E/E = 5.0\%$ @ 1 GeV

Muon Counter RPC
Barrel: 9 layers
Endcaps: 8 layers
- σ_{spatial} = 1.48 cm



Main Drift Chamber
Small cell, 43 layer
- σ_{xy} = 130 μm
- dE/dx ~ 6%
- σ_p/p = 0.5% @ 1 GeV/c

Time Of Flight
Plastic scintillator
- σ_T(barrel) = 68 ps
- σ_T(endcap) = 110 ps

(update to 60 ps with MRPC)

10 billion J/ψ and **2.7 billion $\psi(3686)$** collected at BESIII

- Large branch fraction
- Quantum entangled pair productions
- background free
- Initial 4-momentum known

Front. Phys. 12(5), 121301 (2017)

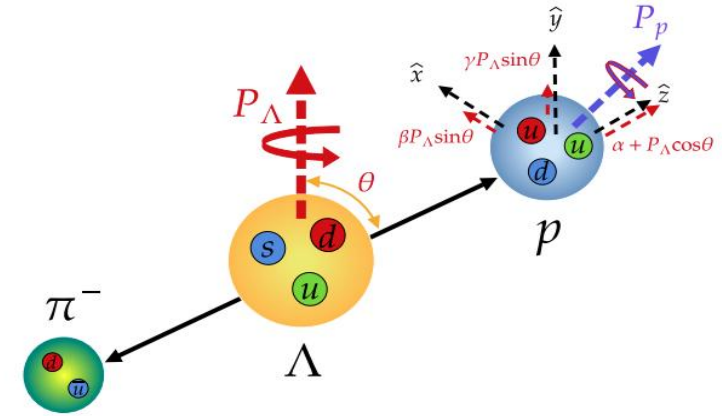
Decay Mode	$\mathcal{B}(\times 10^{-3})$	$N_B(\times 10^6)$
$J/\psi \to \Lambda\bar{\Lambda}$	1.89 ± 0.09	~18.9
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.07 ± 0.04	~10.7
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.17 ± 0.03	~11.7
$J/\psi \to \Xi^-\bar{\Xi}^+$	0.97 ± 0.08	~9.7
$J/\psi \to \Xi^0\bar{\Xi}^0$	1.17 ± 0.04	11.7

Polarized Hyperon Pair in e^+e^- Collisions

Phys.Rev.D 100 (2019) 11, 114005
Phys.Rev.D 99 (2019) 5, 056008

- The **non-zero ΔΦ** represents the transverse polarization:

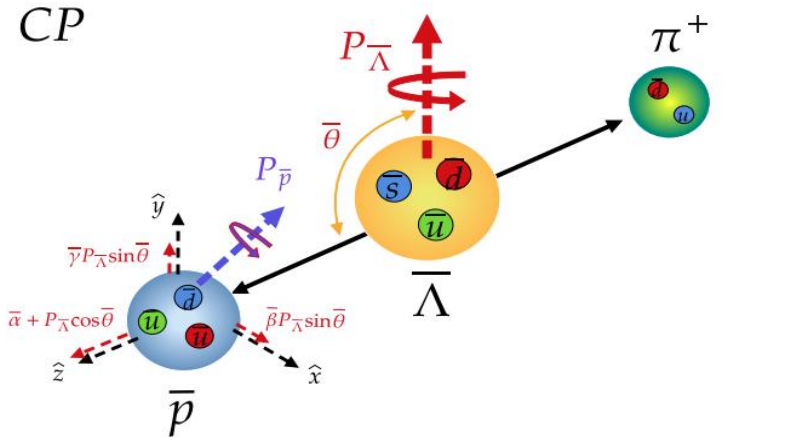
$$P_y(\cos\theta) = \frac{\sqrt{1-\alpha_\psi^2}\,\sin\theta\cos\theta}{1+\alpha_\psi\cos^2\theta}\sin(\mathbf{\Delta\Phi})$$



- Joint angular distribution:

Hyperon Production | Hyperon Decays

- $J/\psi \to \Lambda\bar{\Lambda}/\Sigma\bar{\Sigma}$: $W(\xi;\omega) = Tr\rho_{B,\bar{B}} = \sum_{\mu,\bar{\nu}} C_{\mu\bar{\nu}}\, a^{\Lambda}_{\mu,0} a^{\bar{\Lambda}}_{\bar{\nu},0}$
- $J/\psi \to \Xi\bar{\Xi}$: $W(\xi;\omega) = Tr\rho_{B,\bar{B}} = \sum_{\mu,\bar{\nu}} C_{\mu\bar{\nu}} \sum_{\mu'\bar{\nu}'} a^{\Xi}_{\mu,\mu'} a^{\bar{\Xi}}_{\bar{\nu},\bar{\nu}'} a^{\Lambda}_{\mu',0} a^{\bar{\Lambda}}_{\bar{\nu}',0}$



Based on the **quantum entanglement** between hyperons and antihyperons as well as joint angular analysis, the ϕ_{Ξ^-} precision of **BESIII (73K events)** is comparable with the measurement from **HyperCP (144M events)** in Ξ^- decay, which means that the accuracy of a single event is more than 1000 times higher than HyperCP !

Nature 606 (2022) 7912, 64-69

CP Test in $\Lambda(\to n\pi^0)$ Neural Decay

[1] arXiv:2510.24333

[2] Phys.Rev.Lett. 132 (2024) 10, 101801

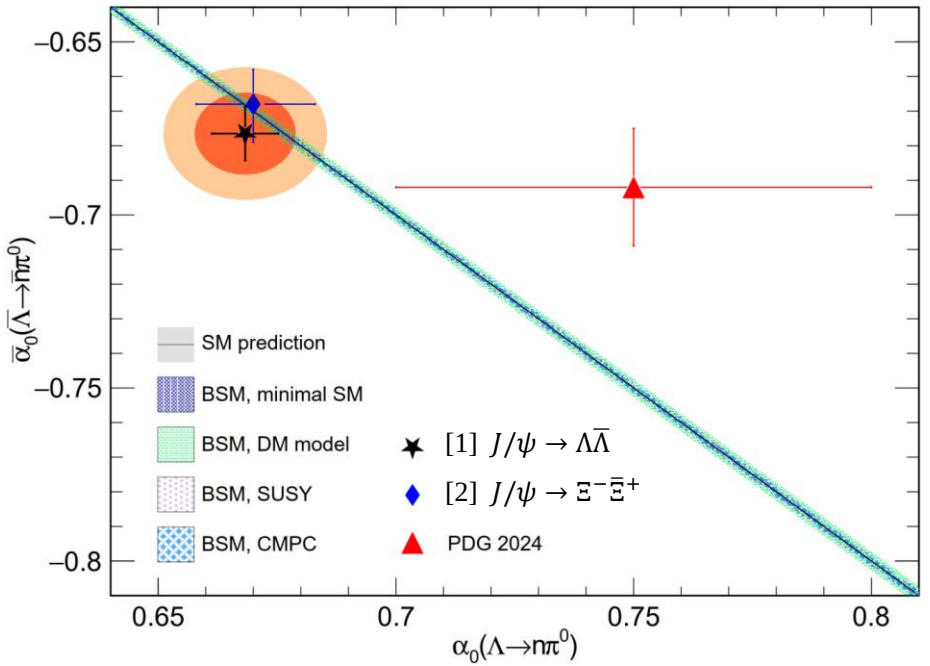
Two channels used to study $\Lambda \to n\pi^0$:

[1] $J/\psi \to \Lambda\bar{\Lambda} \to \boldsymbol{n\pi^0}\bar{p}\pi^+ + c.c$

[2] $J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda(\to \boldsymbol{n\pi^0})\pi^-\bar{\Lambda}(\to \bar{p}\pi^+)\pi^+ + c.c$

4 decay parameters and 2 CP observables measured of Λ

Parameter	[1] $J/\psi \to \Lambda\bar{\Lambda}$	[2] $J/\psi \to \Xi^-\bar{\Xi}^+$
α_-	$0.756 \pm 0.008 \pm 0.003$	$0.764 \pm 0.008^{+0.005}_{-0.006}$
α_+	$-0.764 \pm 0.008 \pm 0.001$	$-0.774 \pm 0.009^{+0.005}_{-0.005}$
α_0	$0.668 \pm 0.007 \pm 0.002$	$0.670 \pm 0.009^{+0.009}_{-0.008}$
$\bar{\alpha}_0$	$-0.677 \pm 0.007 \pm 0.003$	$-0.668 \pm 0.008^{+0.006}_{-0.008}$
A_{CP}^-	$-0.005 \pm 0.007 \pm 0.002$	$-0.007 \pm 0.008^{+0.002}_{-0.003}$
A_{CP}^0	$-0.006 \pm 0.007 \pm 0.002$	$0.001 \pm 0.009^{+0.005}_{-0.007}$
α_0/α_-	$0.884 \pm 0.013 \pm 0.006$	$0.877 \pm 0.015^{+0.014}_{-0.010}$
$\bar{\alpha}_0/\alpha_+$	$0.885 \pm 0.013 \pm 0.004$	$0.863 \pm 0.014^{+0.012}_{-0.008}$



The most precise results of Λ neutral decay

43% and 27% improvement in $J/\psi \to \Lambda\bar{\Lambda}$ compared with $J/\psi \to \Xi^-\bar{\Xi}^+$

Most precise CP test in Λ neutral decay

SM prediction: $A_{CP} \sim 10^{-5}$ (PRD 67, 056001(2003))

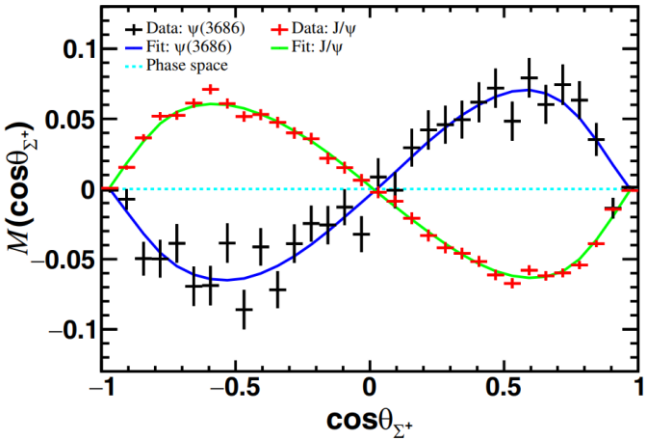
Deviate from unity more than 5σ, indicates the $\Delta I = 3/2$ contributions in Λ decay

CP Test in Σ^+ Decay

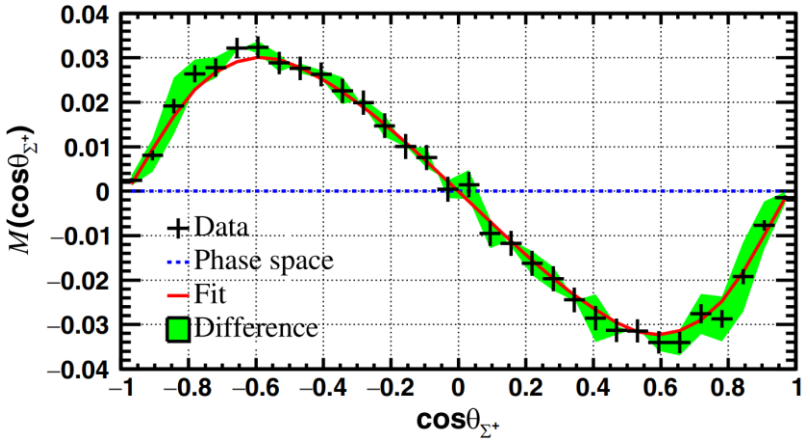
[1] Phys.Rev.Lett. 135 (2025) 14, 141804

[2] Phys.Rev.Lett. 131 (2023) 19, 191802

[1] $J/\psi[\psi(3686)] \to \Sigma^+\bar{\Sigma}^- \to p\pi^0\bar{p}\pi^0$



[2] $J/\psi \to \Sigma^+(\to n\pi^+)\bar{\Sigma}^-(\to \bar{p}\pi^0) + c.c.$



Polarization of Σ^+

Opposite direction of the Σ^+ polarization in J/ψ and $\psi(3686)$

Parameter	10B J/ψ and 2.7B $\psi(3686)$ [1] $\Sigma^+ \to p\pi^0, \bar{\Sigma}^- \to \bar{p}\pi^0$	10B J/ψ [2] $\Sigma^+ \to p\pi^0, \bar{\Sigma}^- \to \bar{n}\pi^- + c.c.$
$\alpha_{J/\psi}$	$-0.5047 \pm 0.0018 \pm 0.0010$	$-0.5156 \pm 0.0030 \pm 0.0061$
$\Delta\Phi_{J/\psi}$	$-0.2744 \pm 0.0033 \pm 0.0010$	$-0.2772 \pm 0.0044 \pm 0.0041$
$\alpha_{\psi(3686)}$	$0.7133 \pm 0.0094 \pm 0.0065$	–
$\Delta\Phi_{\psi(3686)}$	$0.427 \pm 0.022 \pm 0.003$	–
$\alpha_0(\Sigma^+ \to p\pi^0)$	$-0.975 \pm 0.011 \pm 0.002$	–
$\bar{\alpha}_0(\bar{\Sigma}^- \to \bar{p}\pi^0)$	$0.999 \pm 0.011 \pm 0.004$	–
$\alpha_+(\Sigma^+ \to n\pi^+)$	–	$0.0481 \pm 0.0031 \pm 0.0019$
$\alpha_-(\bar{\Sigma}^- \to \bar{n}\pi^-)$	–	$-0.0565 \pm 0.0047 \pm 0.0022$

The most precise CP test in Σ sector:

$$A_{CP}(\Sigma^+ \to p\pi^0) = \frac{\alpha_0 + \bar{\alpha}_0}{\alpha_0 - \bar{\alpha}_0} = -0.0118 \pm 0.0083 \pm 0.0028$$

$$A_{CP}(\Sigma^+ \to n\pi^+) = \frac{\alpha_+ + \bar{\alpha}_-}{\alpha_+ - \bar{\alpha}_-} = -0.080 \pm 0.052 \pm 0.028$$

CP Test in Σ^0 Decay

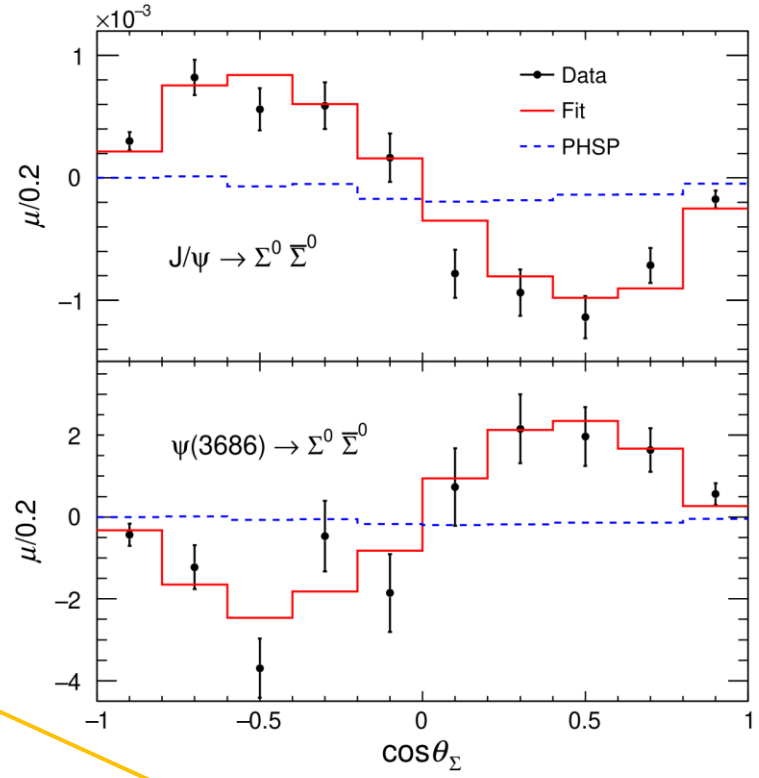
Phys.Rev.Lett. 133 (2024) 10, 101902

The CPV source in SM:

- Weak interaction, CKM (observed, but too small)
- Strong interaction, θ-term (not yet observed)

10B J/ψ and 2.7B $\psi(3686)$

Parameter	This Letter
$\alpha_{J/\psi}$	$-0.4133 \pm 0.0035 \pm 0.0077$
$\Delta\Phi_{J/\psi}$ (rad)	$-0.0828 \pm 0.0068 \pm 0.0033$
$\alpha_{\psi(3686)}$	$0.814 \pm 0.028 \pm 0.028$
$\Delta\Phi_{\psi(3686)}$ (rad)	$0.512 \pm 0.085 \pm 0.034$
α_{Σ^0}	$-0.0017 \pm 0.0021 \pm 0.0018$
$\bar{\alpha}_{\Sigma^0}$	$0.0021 \pm 0.0020 \pm 0.0022$
α_Λ	$0.730 \pm 0.051 \pm 0.011$
$\bar{\alpha}_\Lambda$	$-0.776 \pm 0.054 \pm 0.010$
A_{CP}^{Σ}	$(0.4 \pm 2.9 \pm 1.3) \times 10^{-3}$
A_{CP}^{Λ}	$(-3.0 \pm 6.9 \pm 1.5) \times 10^{-2}$



Polarization of Σ^0

Similar behavior is observed in Σ^+, but not in Λ or Ξ

Opposite directions of Σ^0 polarization

The first attempt to measure the P-violation decay parameter of $\Sigma^0 \to \Lambda\gamma$

The first strong-CP test in hyperon decays

CP Test in Ξ Decay

[1] Phys.Rev.Lett. 132 (2024) 10, 101801

[2] Phys.Rev.D 108 (2023) 3, L031106

[1] $J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda(\to n\pi^0)\pi^-\bar{\Lambda}(\to \bar{p}\pi^+)\pi^+ + c.c$

Parameters	This work
$\alpha_{J/\psi}$	$0.611 \pm 0.007^{+0.013}_{-0.007}$
$\Delta\Phi_{J/\psi}$ (rad)	$1.30 \pm 0.03^{+0.02}_{-0.03}$
α_Ξ	$-0.367 \pm 0.004^{+0.003}_{-0.004}$
ϕ_Ξ (rad)	$-0.016 \pm 0.012^{+0.004}_{-0.008}$
$\bar{\alpha}_\Xi$	$0.374 \pm 0.004^{+0.003}_{-0.004}$
$\bar{\phi}_\Xi$ (rad)	$0.010 \pm 0.012^{+0.003}_{-0.013}$
$\alpha_{\Lambda-}$	$0.764 \pm 0.008^{+0.005}_{-0.006}$
$\alpha_{\Lambda+}$	$-0.774 \pm 0.009^{+0.005}_{-0.005}$
$\alpha_{\Lambda 0}$	$0.670 \pm 0.009^{+0.009}_{-0.008}$
$\bar{\alpha}_{\Lambda 0}$	$-0.668 \pm 0.008^{+0.006}_{-0.008}$
$\delta_P - \delta_S$ (rad)	$0.033 \pm 0.020^{+0.008}_{-0.012}$
$\xi_P - \xi_S$ (rad)	$0.007 \pm 0.020^{+0.018}_{-0.005}$
A_{CP}^{Ξ}	$-0.009 \pm 0.008^{+0.007}_{-0.002}$
$\Delta\phi_{CP}^{\Xi}$ (rad)	$-0.003 \pm 0.008^{+0.003}_{-0.007}$
A_{CP}^{-}	$-0.007 \pm 0.008^{+0.002}_{-0.003}$
A_{CP}^{0}	$0.001 \pm 0.009^{+0.005}_{-0.007}$
A_{CP}^{Λ}	$-0.004 \pm 0.007^{+0.003}_{-0.004}$

Determination of all ΞΞ̄ decay parameters

Weak and strong phase differences measured in Ξ decays

5 and 3 CP observables measured with high precision

[2] $J/\psi \to \Xi^0\bar{\Xi}^0 \to \Lambda\pi^0\bar{\Lambda}\pi^0$

Parameter	This work
$\alpha_{J/\psi}$	$0.514 \pm 0.006 \pm 0.015$
$\Delta\Phi$(rad)	$1.168 \pm 0.019 \pm 0.018$
α_Ξ	$-0.3750 \pm 0.0034 \pm 0.0016$
$\bar{\alpha}_\Xi$	$0.3790 \pm 0.0034 \pm 0.0021$
ϕ_Ξ(rad)	$0.0051 \pm 0.0096 \pm 0.0018$
$\bar{\phi}_\Xi$(rad)	$-0.0053 \pm 0.0097 \pm 0.0019$
α_Λ	$0.7551 \pm 0.0052 \pm 0.0023$
$\bar{\alpha}_\Lambda$	$-0.7448 \pm 0.0052 \pm 0.0017$
$\xi_P - \xi_S$(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}	$(-5.4 \pm 6.5 \pm 3.1) \times 10^{-3}$
$\Delta\phi_{CP}^{\Xi}$(rad)	$(-0.1 \pm 6.9 \pm 0.9) \times 10^{-3}$
A_{CP}^{Λ}	$(6.9 \pm 5.8 \pm 1.8) \times 10^{-3}$
$\langle\alpha_\Xi\rangle$	$-0.3770 \pm 0.0024 \pm 0.0014$
$\langle\phi_\Xi\rangle$(rad)	$0.0052 \pm 0.0069 \pm 0.0016$
$\langle\alpha_\Lambda\rangle$	$0.7499 \pm 0.0029 \pm 0.0013$

Hyperon Weak Radiative Decays

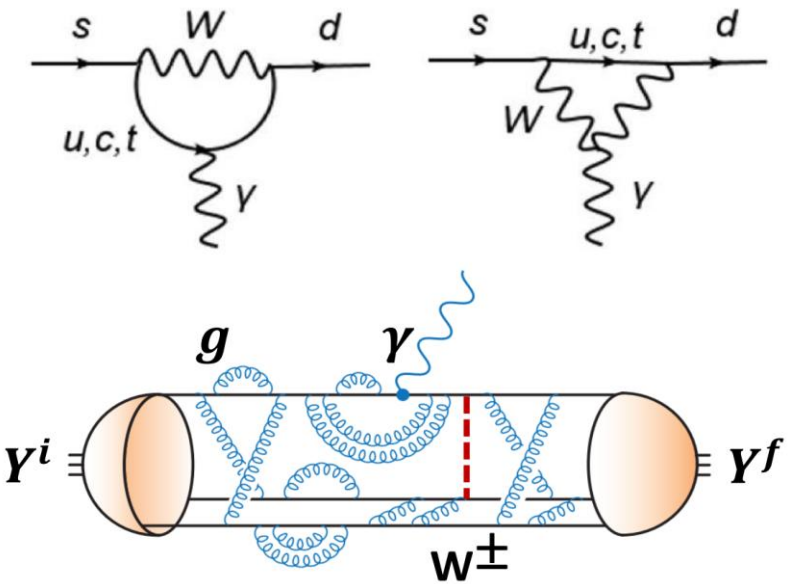
Prog.Part.Nucl.Phys. 91 (2016) 1-100
Sci.Bull. 67 (2022) 2298-2304

- Flavor changing neutral current process ($s \to d\gamma$ transition)
- A symphony of strong, weak and EM interaction
- Decay width & decay asymmetry parameter:

$$\Gamma = \frac{e^2 G_F^2}{\pi}(|a|^2 + |b|^2) \cdot \left|\vec{k}\right|^3 \qquad \alpha_\gamma = \frac{2\mathrm{Re}(ab^*)}{|a|^2 + |b|^2}$$

a: parity conserved amplitude; ***b***: parity violated amplitude

- Hara's theorem: $\alpha_\gamma = 0$ under SU(3) symmetry.
- α_γ values are large in experiment
  - Various phenomenological models?
  - ChPT !!!
  - Need more precise measurements



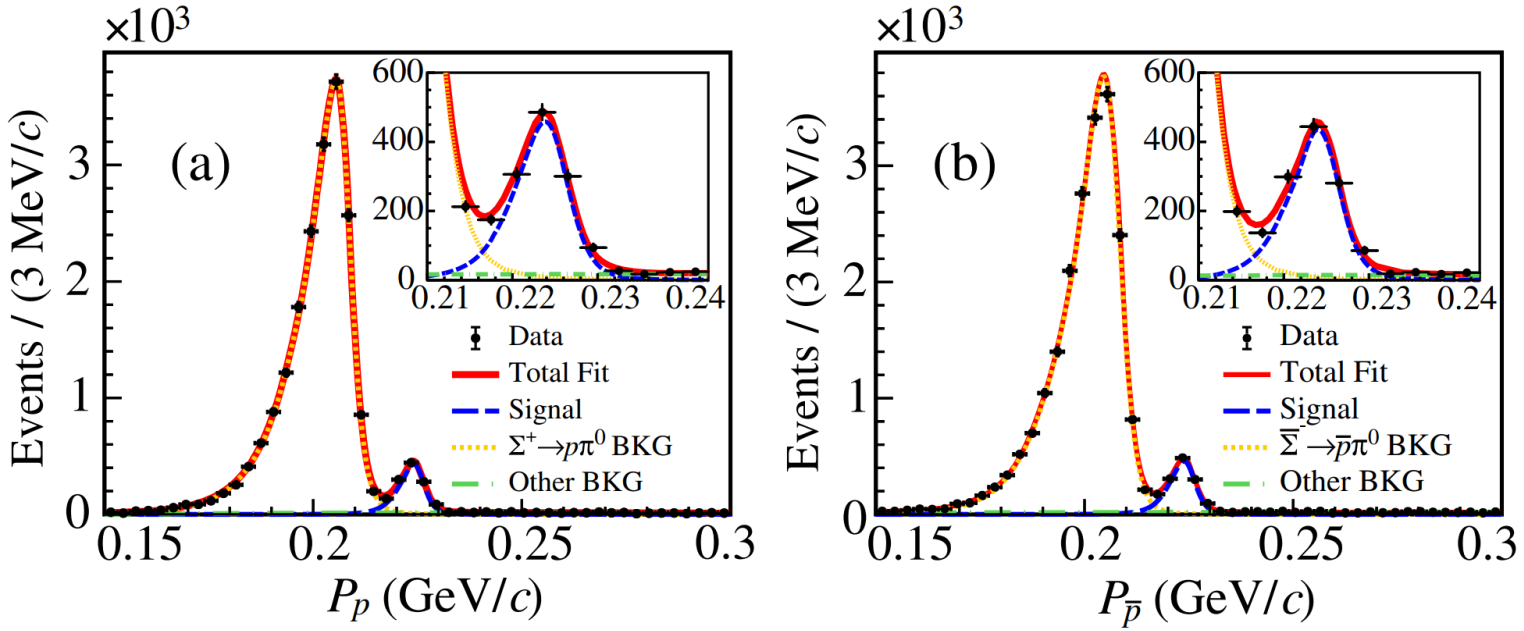
CP observables in HWRD:

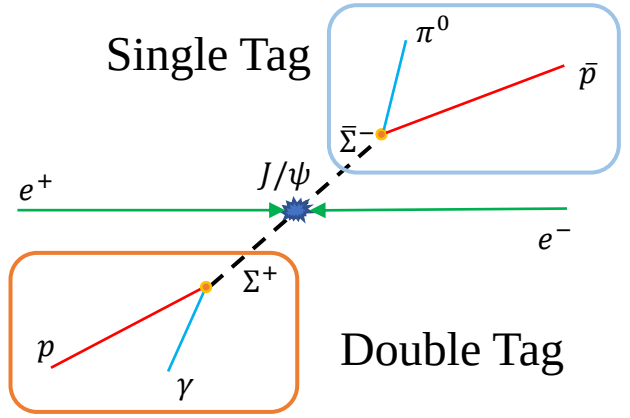
$$A_{CP} = \frac{\alpha_+ + \alpha_-}{\alpha_+ - \alpha_-}$$

$$\Delta_{CP} = \frac{\mathrm{BF}_- - \mathrm{BF}_+}{\mathrm{BF}_- - \mathrm{BF}_+}$$

Radiative Decay: $\Sigma^+ \to p\gamma$ in $J/\psi \to \Sigma^+\bar{\Sigma}^-$

Phys.Rev.Lett. 130 (2023) 21, 211901





$$\mathcal{B}(\Sigma^+ \to p\gamma) = \frac{N_{DT}}{N_{ST}} \times \frac{\epsilon_{ST}}{\epsilon_{DT}}$$

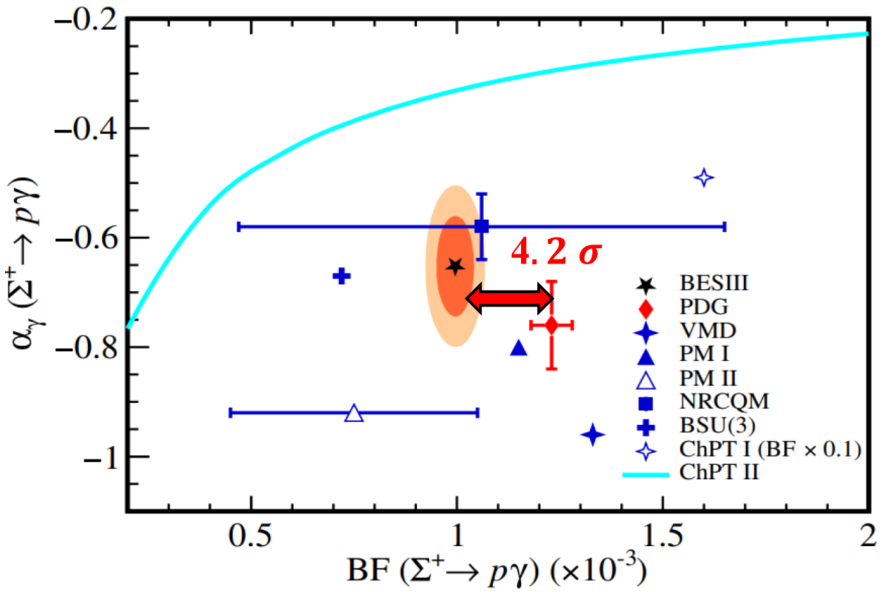
The most precise branching fraction and decay parameter of $\Sigma^+ \to p\gamma$:

- $\mathcal{B}(\Sigma^+ \to p\gamma) = (0.996 \pm 0.021 \pm 0.018) \times 10^{-3}$
- $\alpha_\gamma = -0.652 \pm 0.056 \pm 0.020$

Deviate from previous value by 4.2σ

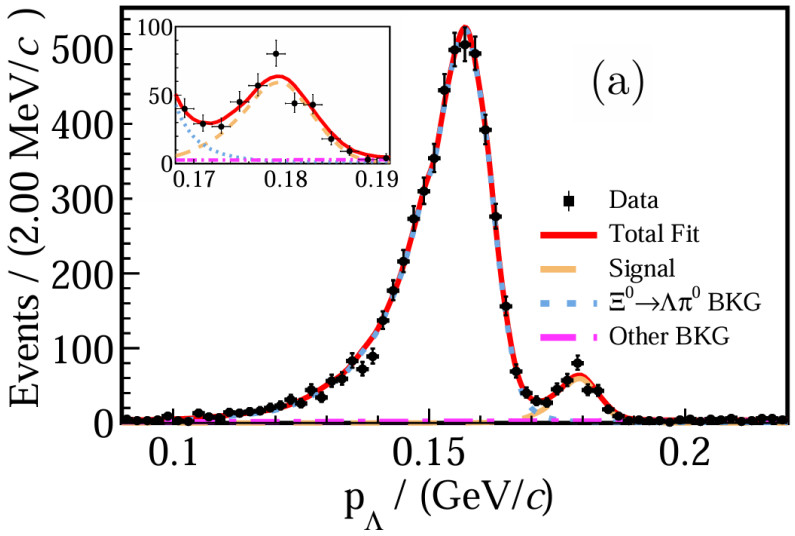
The CP asymmetry is calculated to be:

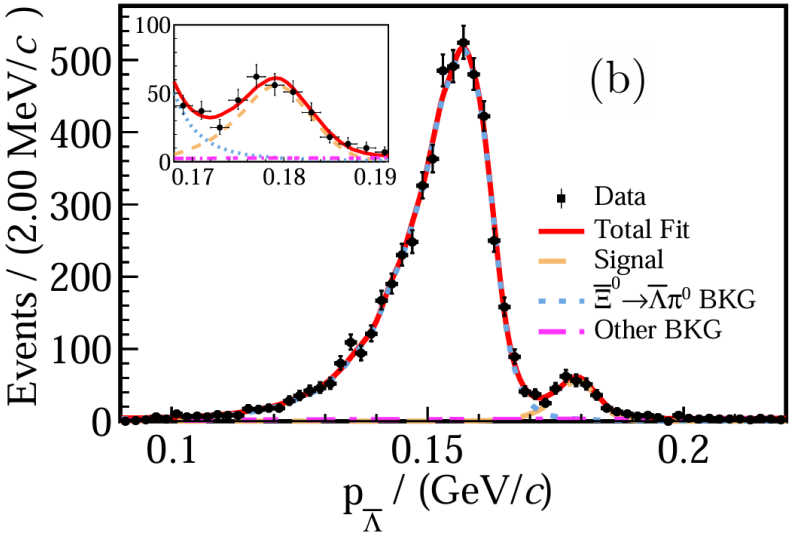
- $A_{CP} = (\alpha_- + \alpha_+)/(\alpha_- - \alpha_+) = 0.095 \pm 0.087 \pm 0.018$
- $\Delta_{CP} = (\mathcal{B}_+ - \mathcal{B}_-)/(\mathcal{B}_+ + \mathcal{B}_-) = 0.006 \pm 0.011 \pm 0.004$

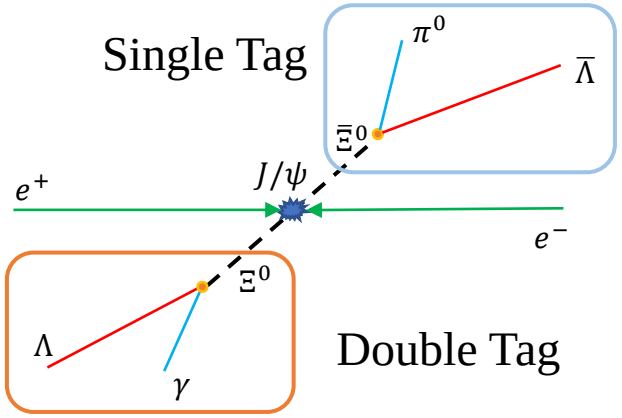


Radiative Decay: $\Xi^0 \to \Lambda\gamma$ in $J/\psi \to \Xi^0\bar{\Xi}^0$

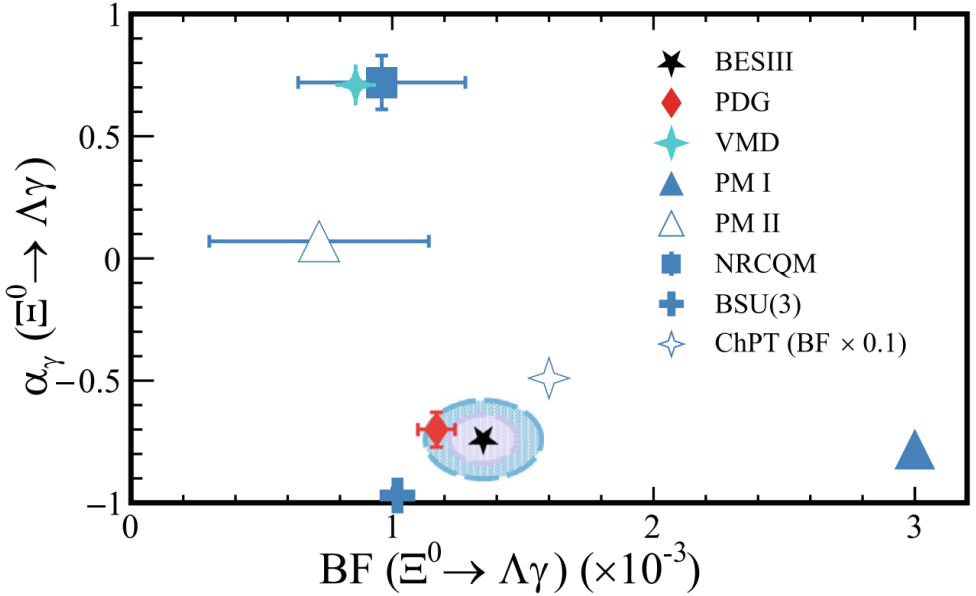
Sci.Bull. 70 (2025) 454-459







$$\mathcal{B}(\Xi^0 \to \Lambda\gamma) = \frac{N_{DT}}{N_{ST}} \times \frac{\epsilon_{ST}}{\epsilon_{DT}} \times \frac{1}{\mathcal{B}(\Lambda \to p\pi^-)}$$



Channels	$\Xi^0 \to \Lambda\gamma$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$
Individual BF(10^{-3})	$1.348 \pm 0.090 \pm 0.054$	$1.326 \pm 0.098 \pm 0.066$
Combined BF(10^{-3})	$1.347 \pm 0.066 \pm 0.054$	
Individual $\alpha_\gamma(\bar{\alpha}_\gamma)$	$-0.652 \pm 0.092 \pm 0.016$	$0.830 \pm 0.080 \pm 0.044$
Combined α_γ	$-0.741 \pm 0.062 \pm 0.019$	

First CP test in $\Xi^0 \to \Lambda\gamma$: $A_{CP} = -0.120 \pm 0.084 \pm 0.029$

Summary

- BESIII has collected a large number of J/ψ and $\psi(3686)$ data events
  - Large hyperon pair production ($\Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}$)
  - Hyperon polarization measurements and CP violation searches
  - Hyperon radiative decays
- More interesting results are on schedule base on 10 billion J/ψ and 2.7 billion $\psi(3686)$ data sets at BESIII
- Look forward to future STCF !

Thank you !