Hyperon physics at BESIII

Jingxu Zhang on behalf of BESIII Collaboration
Lanzhou University && IHEP

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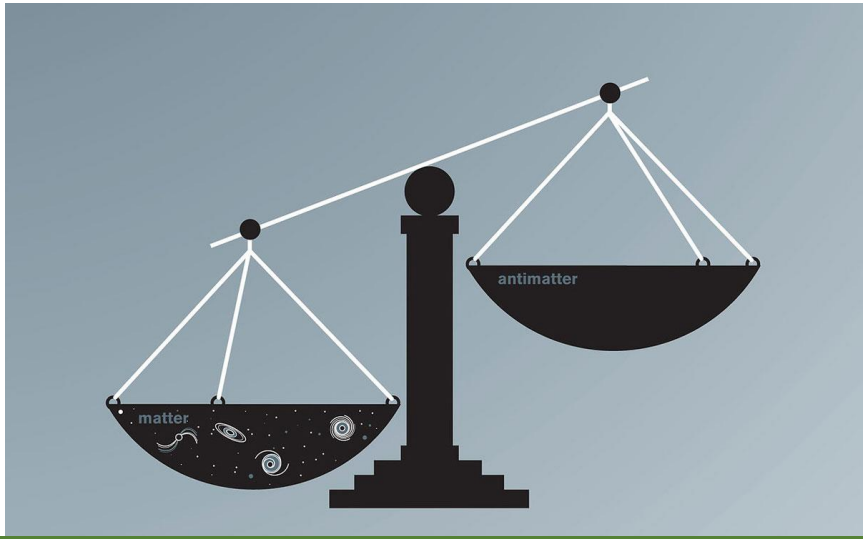
QCD@Work 2024
International Workshop in QCD Theory and Experiment
In Trani - Italy

Outline

- Introduction
- BESIII recent results
  - Hyperon transverse polarization and CP tests
  - Hyperon weak radiative decay
  - Hyperon-nucleon interaction
- Summary

CP violation in Standard Model

Symmetry Magazine



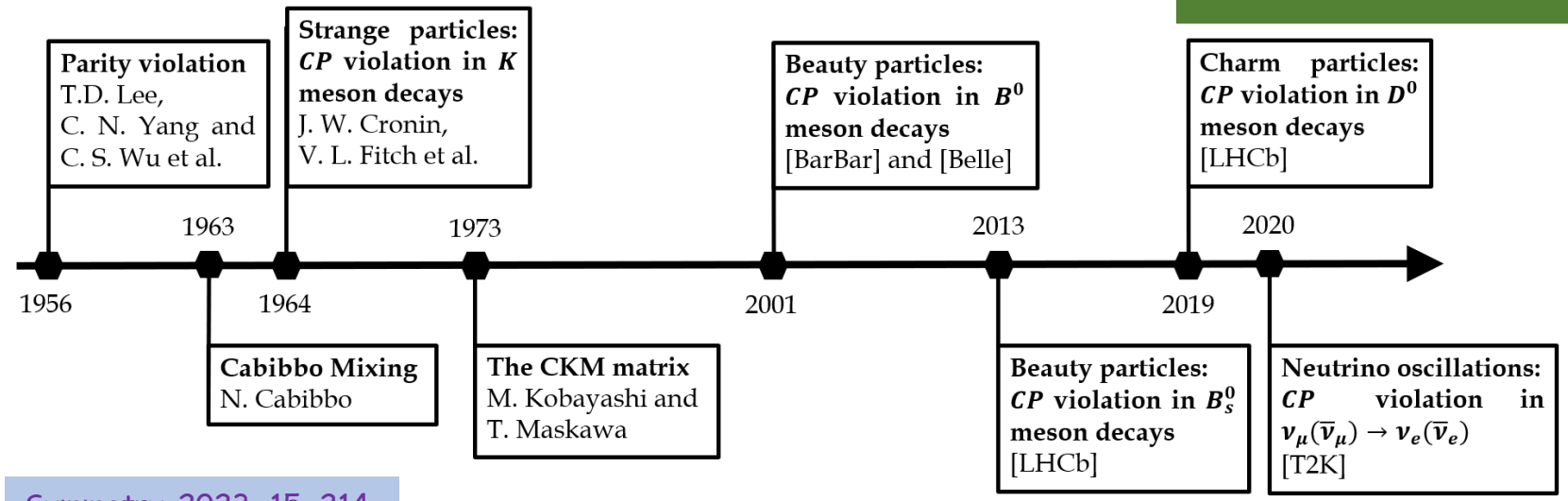
The Big Bang Model:

- **Matter and Anti-matter are produced in equal amounts**
- **Matter and Anti-matter annihilated to energy**

The Sakharov three conditions: Pisma Zh. Eksp. Teor. Fiz., 1967, 5: 32-35

a. **Baryon number (B) violates**
b. **C and CP symmetry violate**
c. **Interactions out of thermal equilibrium**

IF THE BARYON BREAK THE CP SYMMETRY?

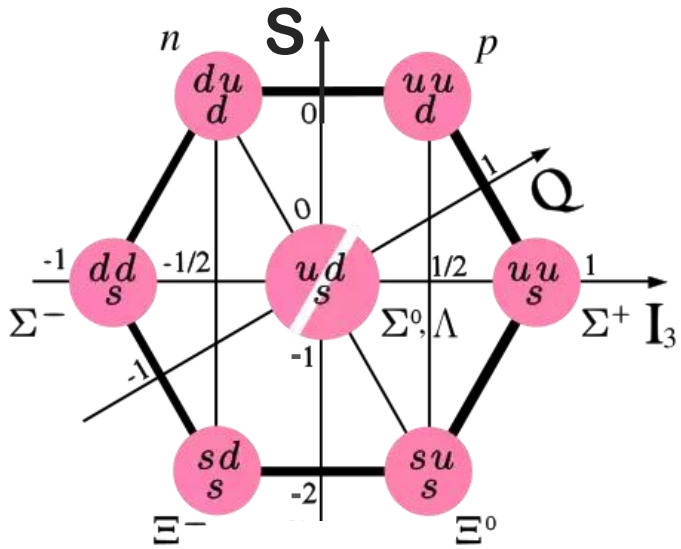


Symmetry 2023, 15, 214.

Phys.Rev.Lett.1963,10,531-533
Phys.Rev.Lett.1964,13,138-140
Prog.Theor.Phys.1973,49,652-657
Phys.Rev.Lett.2001,87,091801
Phys.Rev.Lett.2001,87,091802
Phys.Rev.Lett.2019,122,211803
Nature2020,580,339-344

Weak decay in strange hyperon

- Baryons: Nucleon and hyperons
- The ground hyperons are spin-1/2
- Study hyperon property in the weak decay
  (such as $\Lambda \to p\pi^-$, $\Xi^- \to \Lambda\pi^-$, $\Sigma \to N\pi$)
- Hyperon radiative decay ($\Lambda \to \gamma n, \Sigma \to \gamma\Lambda, \Xi \to \gamma\Lambda$)



- P wave and S wave amplitudes
  in $\frac{1}{2} \to \frac{1}{2} + 0$

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

Strong phases weak phases

$$\mathcal{S} = |\mathcal{S}|e^{i(\delta_S+\xi_S)},$$
$$\mathcal{P} = |\mathcal{P}|e^{i(\delta_P+\xi_P)},$$

Phys.Rev.D1986,34,833

$A_{CP}(\Lambda,\Xi) \approx 10^{-5}$
$A_{CP}(\Sigma^-) \approx 10^{-4}$
$A_{CP}(\Sigma^+) \approx 10^{-7}$

- Weak decay parameters

Phys. Rev. 108, 1645 (1957)

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

$$\beta = \frac{2Im(S*P)}{|S|^2+|P|^2} = \sqrt{1-\alpha^2}\sin\phi$$

- IF CP conserved:

$$\alpha = -\bar{\alpha}, \beta = -\bar{\beta}, \phi = -\bar{\phi}$$

- The CP observables:

$$A_{CP} = \frac{\alpha_B - \alpha_{\bar{B}}}{\alpha_B - \alpha_{\bar{B}}}$$

$$\phi_{CP} = \frac{\phi_B - \phi_{\bar{B}}}{2}$$

Hyperon Polarization in e^+e^- collisions

- The non-zero $\Delta\Phi$ represents the transverse polarization.

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

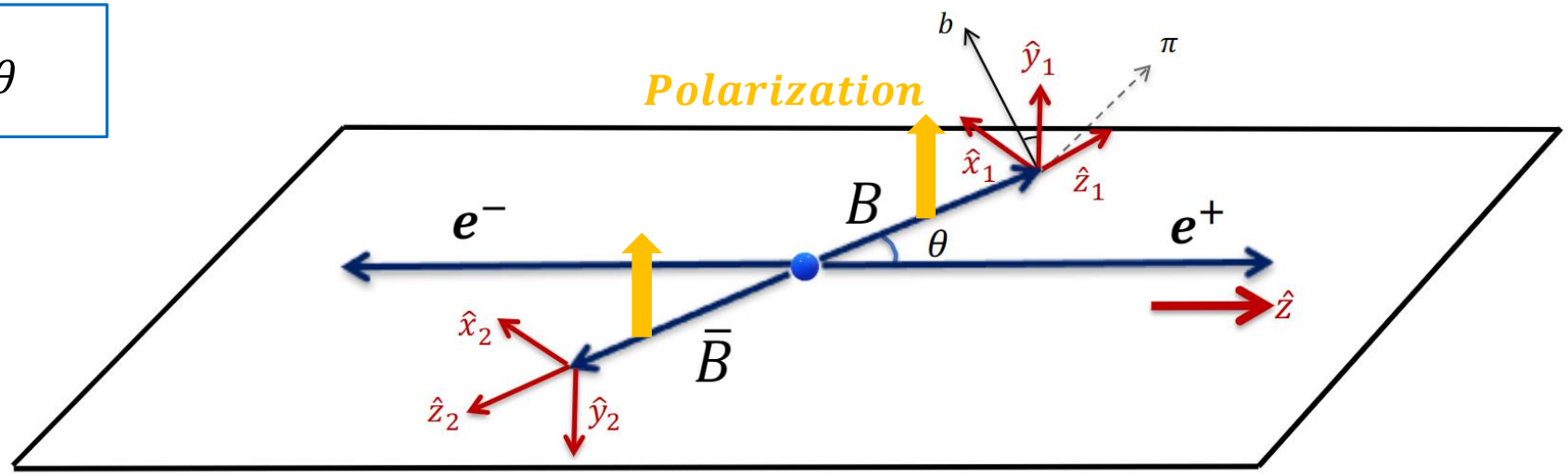
The form factors G_E, G_M construct the production parameters:

$$\alpha_\psi = \frac{s|G_M|^2 - 4M_\Xi^2|G_E|^2}{s|G_M|^2 + 4M_\Xi^2|G_E|^2},$$

$$\Delta\Phi = \arg\left(\frac{G_E}{G_M}\right),$$

- Angular distribution

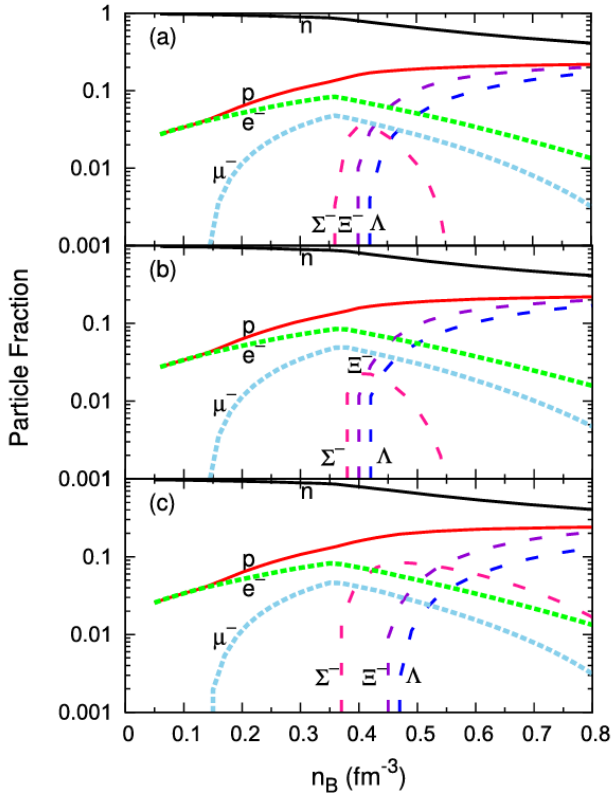
$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_\psi \cos^2\theta$$



Hyperon-Nucleus interaction

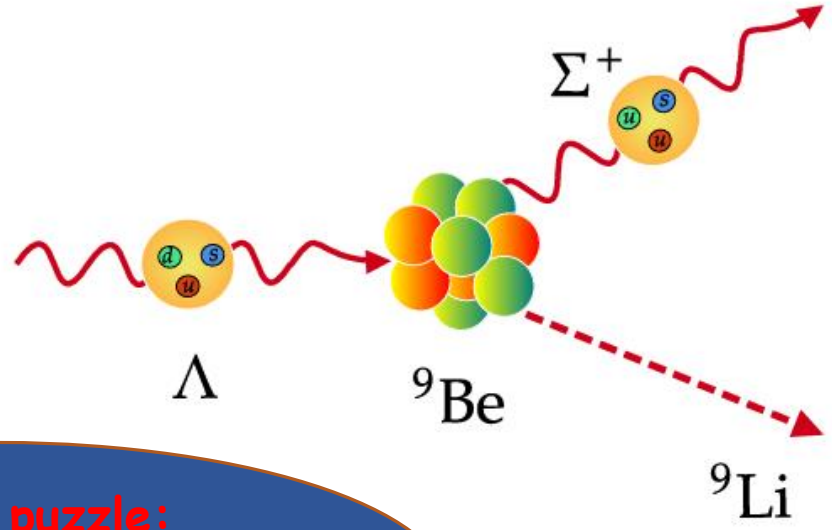
arxiv: 2209.12601

- Hyperon puzzle in neutron stars
- Understanding of hyperon-nucleus is lack
- Study H-N interaction at BESIII



Mounts of hyperons

Phys.Lett.B 747 (2015) 43-47



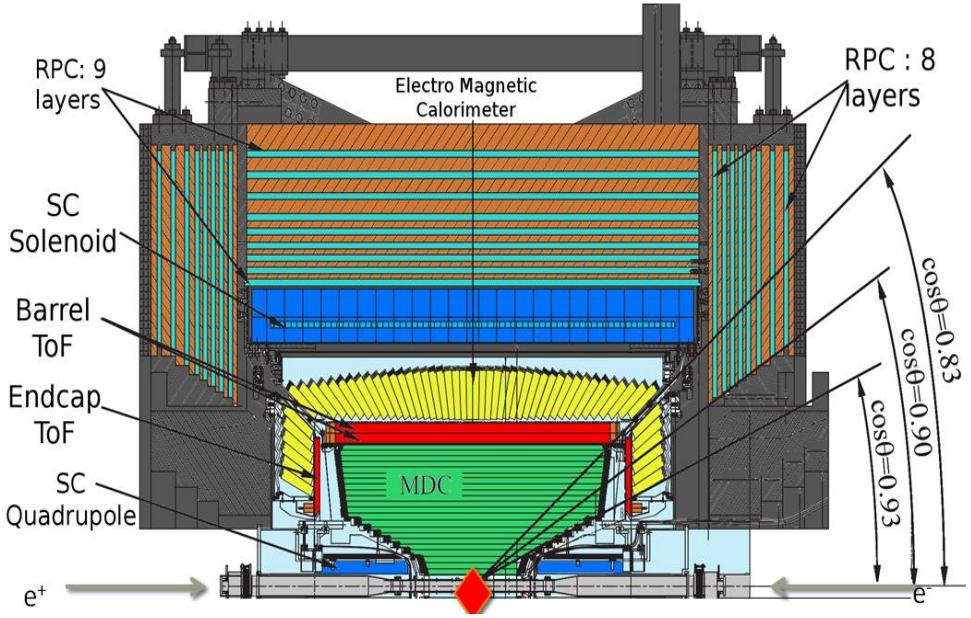
Hyperon puzzle:
Neutron stars need hyperons, but hyperons decrease the density of neutron stars

What role the hyperon play in neutron stars?

Nucl.Phys.News 31 (2021) 3, 17-21
Phys. Rev. Lett. 114, 092301 (2015)

BESIII: A hyperon factory

BESIII
- ✓ Cover 93% of full solid angle
- ✓ 1.0 T supercondacting solenoid
- ✓ Momentum resolution: 0.5% at 1 GeV/c
- ✓ Energy resolution: 2.5%(5%) at 1GeV/c in the barrel (end cap)
- ✓ Time resolution: 68(60) ps in the barrel (end cap)



Nucl. Instrum, Meth. A 598 (2009) 7
arXix: 2111.01597

The world largest J/ψ and $\psi(2S)$ data samples
- ✓ 10 Billion J/ψ
- ✓ 2.7 Billion $\psi(2S)$

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

Decay mode	$\mathcal{B}(\times 10^{-3})$	N_B $(\times 10^6)$
$J/\psi \to \Lambda\bar{\Lambda}$	1.61 ± 0.15	16.1 ± 1.5
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.29 ± 0.09	12.9 ± 0.9
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.50 ± 0.24	15.0 ± 2.4
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}^+$ (or c.c.)	0.31 ± 0.05	3.1 ± 0.5
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$ (or c.c.)	1.10 ± 0.12	11.0 ± 1.2
$J/\psi \to \Xi^0\bar{\Xi}^0$	1.20 ± 0.24	12.0 ± 2.4
$J/\psi \to \Xi^-\bar{\Xi}^+$	0.86 ± 0.11	8.6 ± 1.0
$J/\psi \to \Xi(1530)^0\bar{\Xi}^0$	0.32 ± 0.14	3.2 ± 1.4
$J/\psi \to \Xi(1530)^-\bar{\Xi}^+$	0.59 ± 0.15	5.9 ± 1.5
$\psi(2S) \to \Omega^-\bar{\Omega}^+$	0.05 ± 0.01	0.15 ± 0.03

Hyperon transverse polarization and CP tests

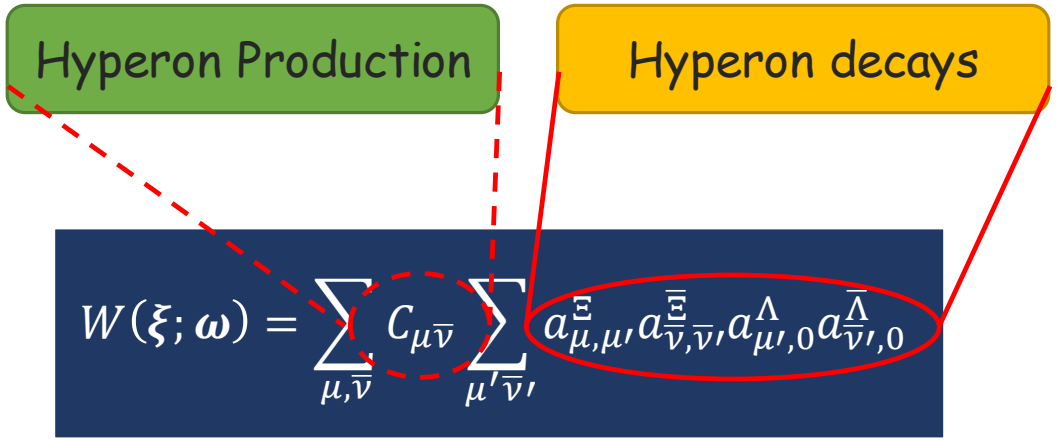
Formulism of amplitude

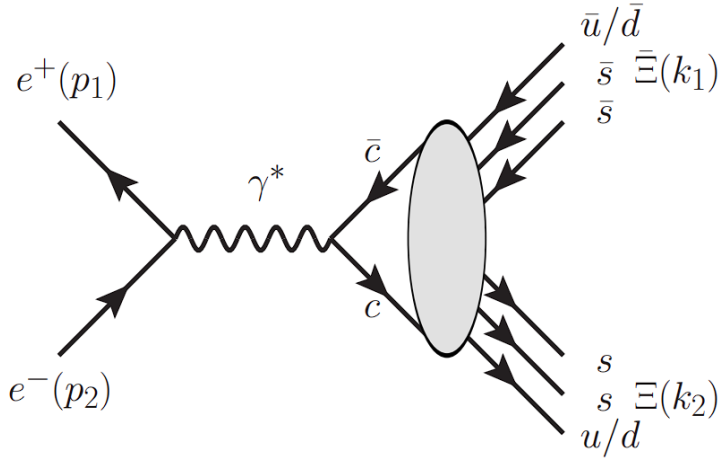
- The 9 kinematical variables – 9 dimension PHSP

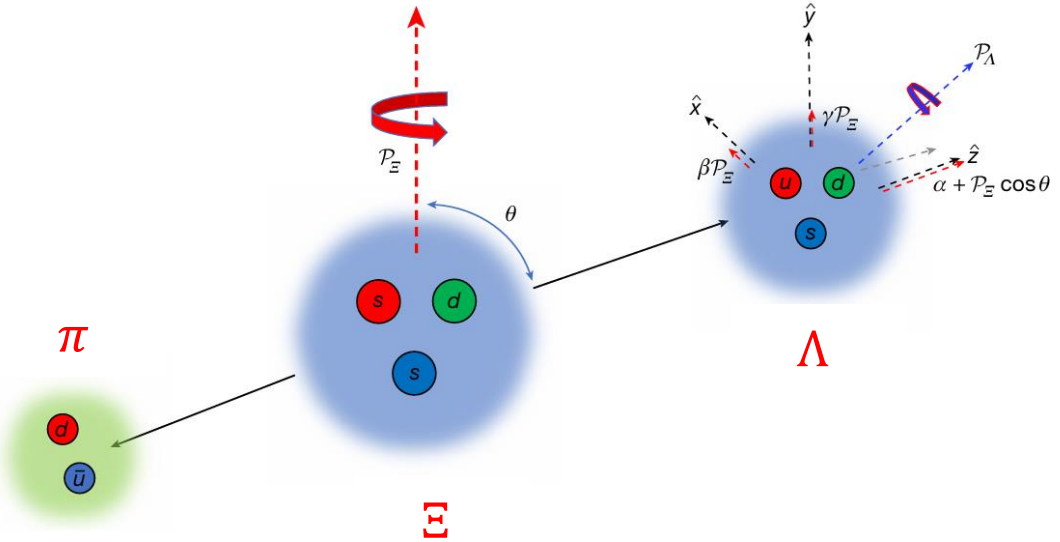
$$\xi = (\theta_\Xi, \theta_\Lambda, \phi_\Lambda, \theta_{\bar{\Lambda}}, \phi_{\bar{\Lambda}}, \theta_p, \phi_p, \theta_{\bar{p}}, \phi_{\bar{p}})$$

- The 8 free parameters

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







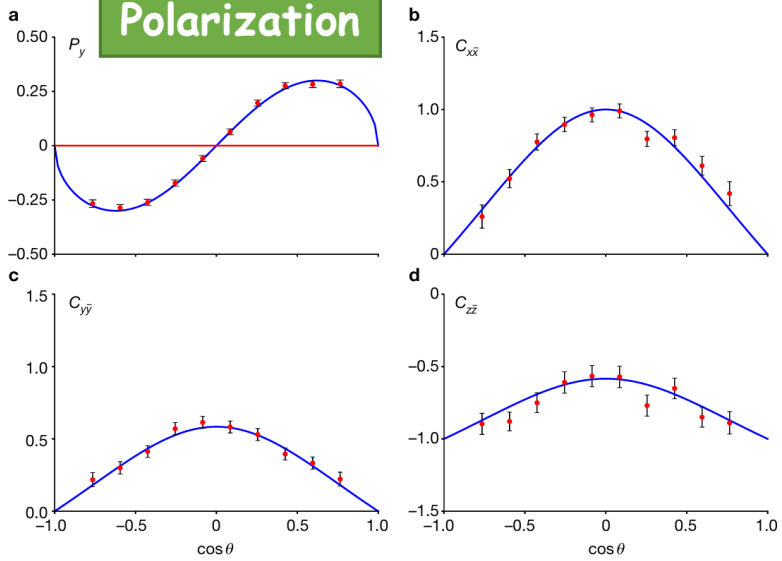
Phys. Rev. D 99, 056008 (2019)

$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+, \Xi^-(\bar{\Xi}^+) \to \Lambda\pi^-(\bar{\Lambda}\pi^+)$

Nature Vol 606 2 June 2022 | 65

1.3 Billion J/ψ

Polarization



$$C_{\mu\nu} = (1+\alpha_\psi\cos^2\theta)\begin{pmatrix} 1 & 0 & P_y & 0 \\ 0 & C_{xx} & 0 & C_{xz} \\ -P_y & 0 & C_{yy} & 0 \\ 0 & -C_{xz} & 0 & C_{zz} \end{pmatrix}.$$

Spin Correlation

Parameter	This work	Previous result
α_ψ	0.586±0.012±0.010	0.58±0.04±0.08 [1]
$\Delta\Phi$	1.213±0.046±0.016 rad	–
α_Ξ	−0.376±0.007±0.003	−0.401±0.010 [2]
ϕ_Ξ	0.011±0.019±0.009 rad	−0.037±0.014 rad [2]
$\bar{\alpha}_\Xi$	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 [3]
$\bar{\alpha}_\Lambda$	−0.763±0.011±0.007	−0.758±0.010±0.007 [3]
$\xi_P - \xi_S$	$(1.2\pm3.4\pm0.8)\times10^{-2}$ rad	–
$\delta_P - \delta_S$	$(-4.0\pm3.3\pm1.7)\times10^{-2}$ rad	$(10.2\pm3.9)\times10^{-2}$ rad [4]
A_{CP}^{Ξ}	$(6\pm13\pm6)\times10^{-3}$	–
$\Delta\phi_{CP}^{\Xi}$	$(-5\pm14\pm3)\times10^{-3}$ rad	–
A_{CP}^{Λ}	$(-4\pm12\pm9)\times10^{-3}$	$(-6\pm12\pm7)\times10^{-3}$ [3]
$\langle\phi_\Xi\rangle$	0.016±0.014±0.007 rad	

1. Phys. Rev. D 93, 072003 (2016) 2. PDG 2020 3. Nat. Phys. 15, 631-634 (2019) 4. Phys. Rev. Lett. 93, 011802 (2004)

$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+, \Xi^-(\bar{\Xi}^+) \to \Lambda\pi^-(\bar{\Lambda}\pi^+)$

Nature Vol 606 2 June 2022 | 65

1.3 Billion J/ψ

- ✓ First measurement of Ξ polarization
- ✓ First determination of entangled $\Xi\bar{\Xi}$ decay parameters
- ✓ Independent measurement of the Λ decay parameters: in agreement with previous BESIII results
- ✓ First measurement of weak phase difference

$(\xi_P - \xi_S)_{SM} = (-2.1 \pm 1.7) \times 10^{-4}$ rad

Phys. Rev. D 105, 116022 (2022)

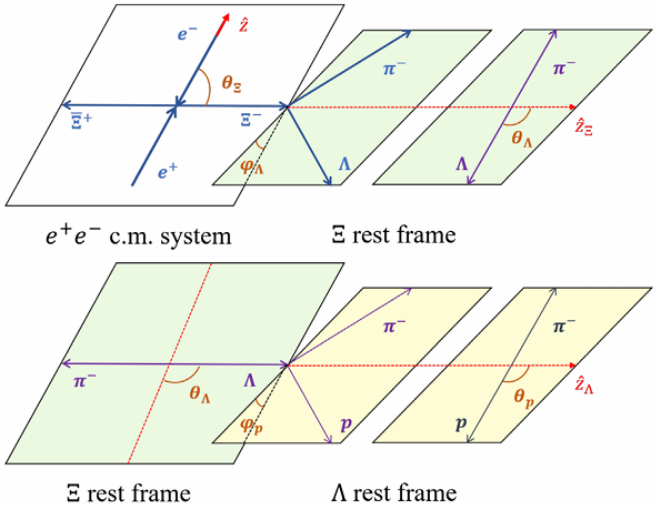
- ✓ First direct CP tests for Ξ hyperon

Parameter	This work	Previous result
α_ψ	0.586±0.012±0.010	0.58±0.04±0.08 [1]
$\Delta\Phi$	1.213±0.046±0.016 rad	–
α_Ξ	−0.376±0.007±0.003	−0.401±0.010 [2]
ϕ_Ξ	0.011±0.019±0.009 rad	−0.037±0.014 rad [2]
$\bar{\alpha}_\Xi$	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 [3]
$\bar{\alpha}_\Lambda$	−0.763±0.011±0.007	−0.758±0.010±0.007 [3]
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ 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 [4]
A_{CP}^{Ξ}	$(6 \pm 13 \pm 6) \times 10^{-3}$	–
$\Delta\phi_{CP}^{\Xi}$	$(-5 \pm 14 \pm 3) \times 10^{-3}$ rad	–
A_{CP}^{Λ}	$(-4 \pm 12 \pm 9) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$ [3]
$\langle\phi_\Xi\rangle$	0.016±0.014±0.007 rad	

1. Phys. Rev. D 93, 072003 (2016) 2. PDG 2020 3. Nat. Phys. 15, 631-634 (2019) 4. Phys. Rev. Lett. 93, 011802 (2004)

$e^+e^- \to \psi(2S) \to \Xi^-\bar{\Xi}^+, \Xi^-(\bar{\Xi}^+) \to \Lambda\pi^-(\bar{\Lambda}\pi^+)$

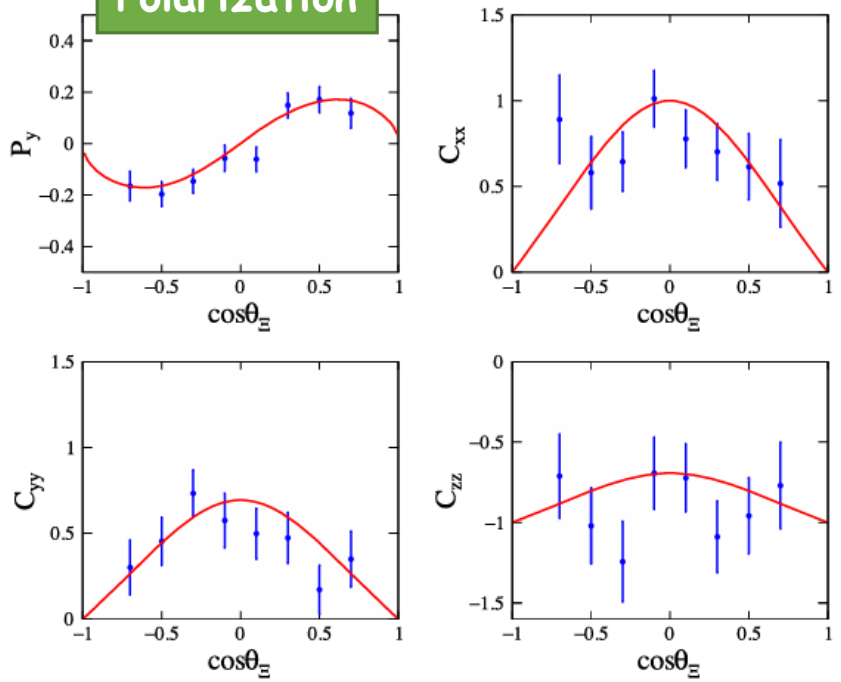
	$\psi(2S)$	J/ψ
N_ψ	0.45 B	1.3B
signals	5.3k	73.2k



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)	$-0.123 \pm 0.073 \pm 0.004$	$-0.021 \pm 0.019 \pm 0.007$
$\delta_p - \delta_s$ ($\times 10^{-1}$ rad)	$-2.0 \pm 1.3 \pm 0.1$	$-0.40 \pm 0.33 \pm 0.17$
$A_{CP,\Xi}$ ($\times 10^{-2}$)	$-1.5 \pm 5.1 \pm 1.0$	$0.60 \pm 1.34 \pm 0.56$
$\Delta\phi_{CP}$ ($\times 10^{-2}$rad)	$-5.0 \pm 5.2 \pm 0.3$	$-0.48 \pm 1.37 \pm 0.29$

Phys. Rev. D 106, L091101

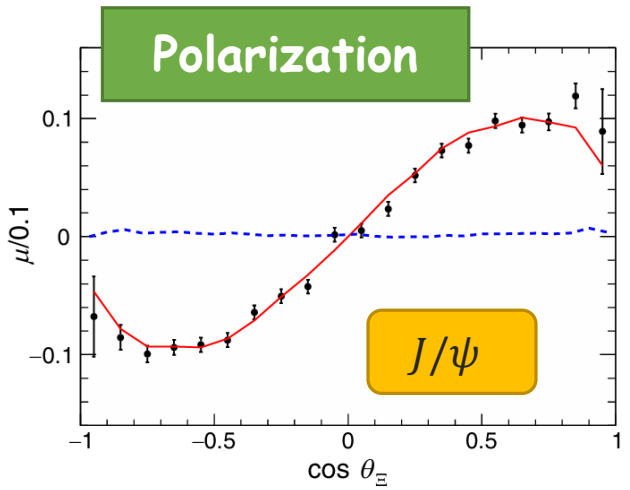
Polarization

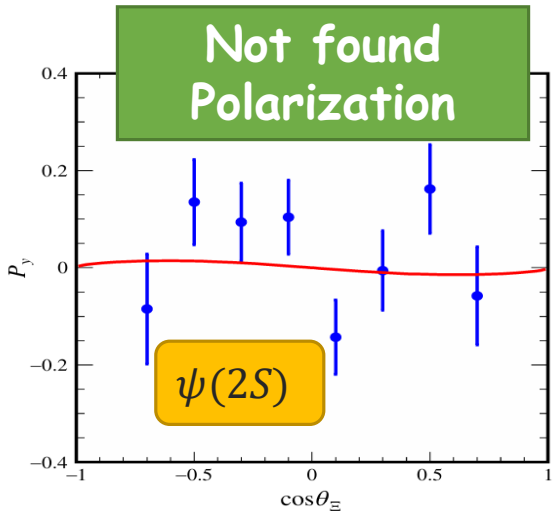


- Hyperon decay parameters are in agreement with previous BESIII report.
- The different production parameters in $\psi(2S)$ and J/ψ.

$e^+e^- \to J/\psi, \psi(2S) \to \Xi^0\bar{\Xi}^0, \Xi^0(\bar{\Xi}^0) \to \Lambda\pi^0(\bar{\Lambda}\pi^0)$

	$\psi(2S)$	J/ψ
N_ψ	0.45 B	10B
signals	1.9k	327.3k





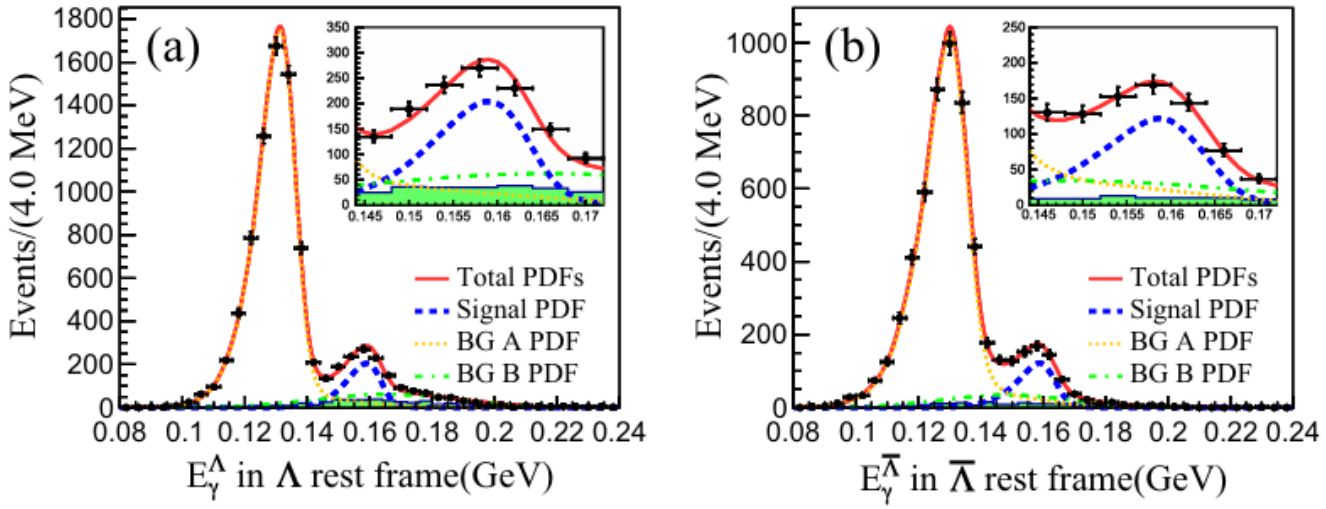
Parameter	$J/\psi \to \Xi^0\bar{\Xi}^0$	$\psi(3686) \to \Xi^0\bar{\Xi}^0$
α_ψ	$0.514 \pm 0.006 \pm 0.015$	$0.665 \pm 0.086 \pm 0.081$
$\Delta\Phi$ (rad)	$1.168 \pm 0.019 \pm 0.018$	$-0.050 \pm 0.150 \pm 0.020$
α_Ξ	$-0.3750 \pm 0.0034 \pm 0.00016$	$-0.358 \pm 0.042 \pm 0.013$
$\alpha_{\bar{\Xi}}$	$0.3790 \pm 0.0034 \pm 0.0021$	$0.363 \pm 0.042 \pm 0.013$
ϕ_Ξ (rad)	$0.0051 \pm 0.0096 \pm 0.0018$	$0.027 \pm 0.117 \pm 0.011$
$\phi_{\bar{\Xi}}$ (rad)	$-0.0053 \pm 0.0097 \pm 0.0019$	$-0.185 \pm 0.116 \pm 0.017$
α_Λ	$0.7557 \pm 0.0052 \pm 0.0023$	-
$\alpha_{\bar{\Lambda}}$	$-0.7448 \pm 0.0052 \pm 0.0017$	-
$\xi_P - \xi_S$ (rad)	$0.000 \pm 0.017 \pm 0.002$	-
$\delta_P - \delta_S$ (rad)	$-0.013 \pm 0.017 \pm 0.004$	-
$A_{CP}^{\Xi}(\times 10^{-3})$	$-5.4 \pm 6.5 \pm 3.1$	$-7 \pm 82 \pm 25$
$A_{CP}^{\Lambda}(\times 10^{-3})$	$6.9 \pm 5.8 \pm 1.8$	-
$\Delta\phi_{CP}^{\Xi}(\times 10^{-3}$ rad)	$-0.1 \pm 6.9 \pm 0.9$	$-79 \pm 82 \pm 10$
$\langle\alpha_\Xi\rangle$	$-0.3770 \pm 0.0024 \pm 0.0014$	-
$\langle\phi_\Xi\rangle$ (rad)	$0.0052 \pm 0.0069 \pm 0.0016$	-
$\langle\alpha_\Lambda\rangle$	$0.7499 \pm 0.0029 \pm 0.0013$	-

- Hyperon polarization and decay parameters for $\Xi^0\bar{\Xi}^0$ are reported for the first time.
- The CP tests and weak/strong phase difference are determined.

Phys. Rev. D 108, L011101 (2023)
Phys. Rev. D 108, L031106 (2023)

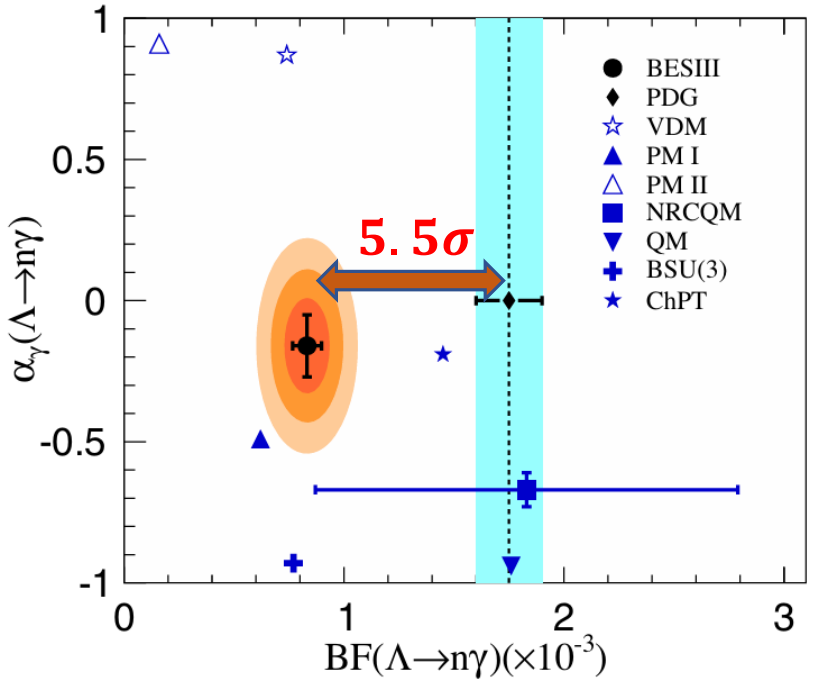
Hyperon weak radiative decay

Radiative decay: $\Lambda \to n\gamma$



Decay mode	$\Lambda \to n\gamma$	$\bar\Lambda \to \bar n\gamma$
N_{ST} $(\times 10^3)$	6853.2 ± 2.6	7036.2 ± 2.7
ε_{ST} (%)	51.13 ± 0.01	52.53 ± 0.01
N_{DT}	723 ± 40	498 ± 41
ε_{DT} (%)	6.58 ± 0.04	4.32 ± 0.03
BF $(\times 10^{-3})$	$0.820 \pm 0.045 \pm 0.066$	$0.862 \pm 0.071 \pm 0.084$
	$\mathbf{0.832 \pm 0.038 \pm 0.054}$	
α_γ	$-0.13 \pm 0.13 \pm 0.03$	$0.21 \pm 0.15 \pm 0.06$
	$\mathbf{-0.16 \pm 0.10 \pm 0.05}$	

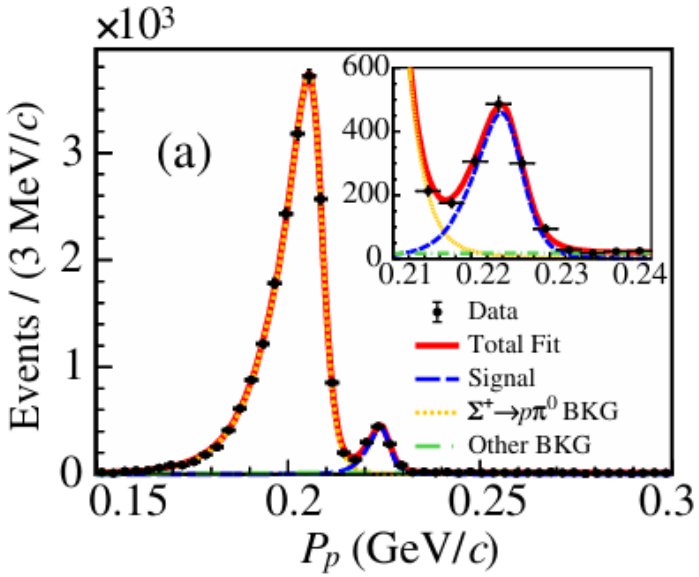
Stag method: $Br(\Lambda \to n\gamma) = \frac{N_{DT}\epsilon_{ST}}{N_{ST}\epsilon_{DT}}$

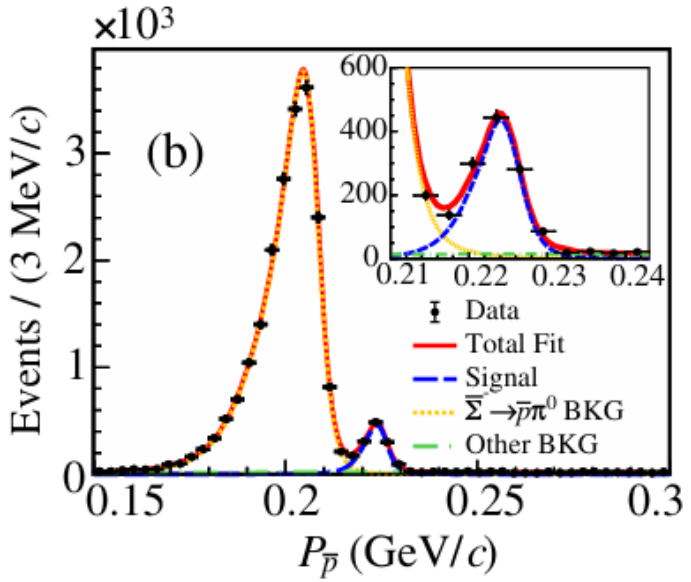


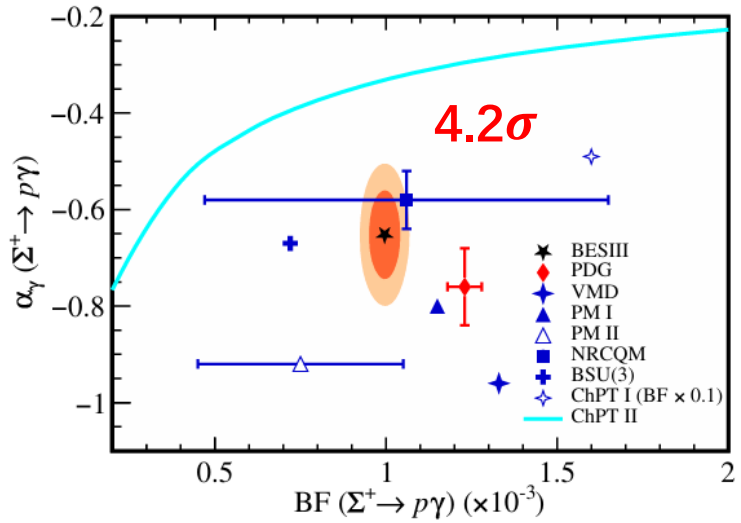
- More precise in branch fraction $\Lambda \to n\gamma$
- Less than PDG 5.5σ

PRL 129, 212002 (2022)

Radiative decay: $\Sigma^+ \to p\gamma$







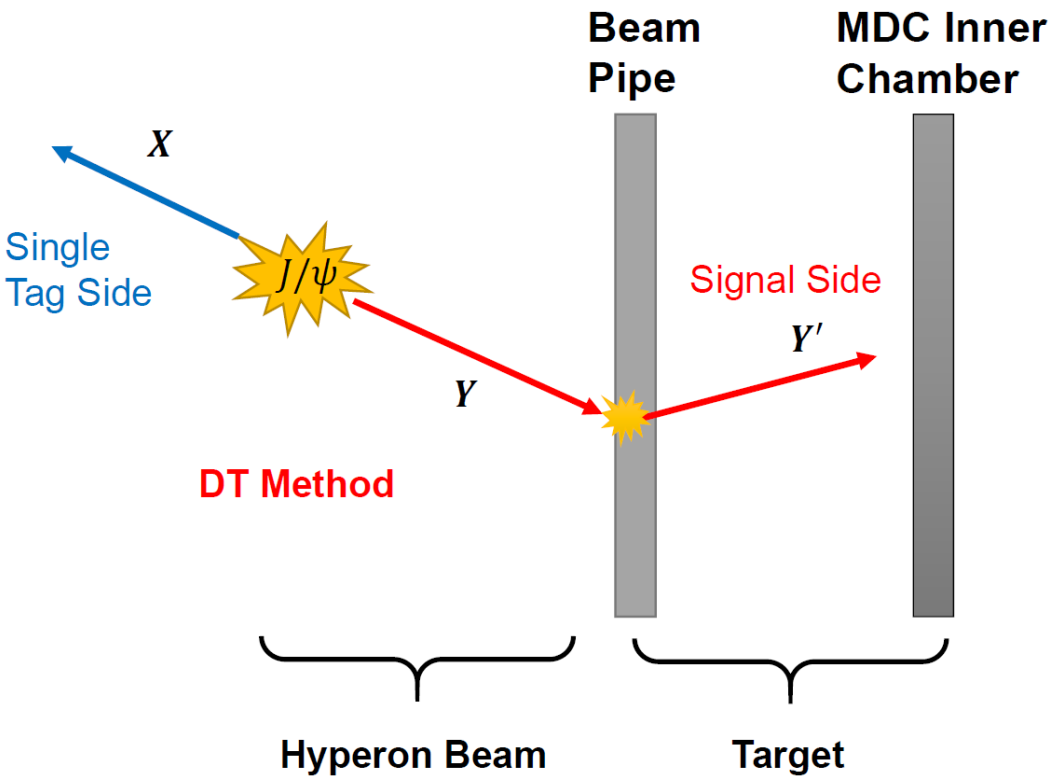
Mode	$\Sigma^+ \to p\gamma$	$\bar{\Sigma}^- \to \bar{p}\gamma$
N_{ST}^{obs}	$2\,177\,771 \pm 2285$	$2\,509\,380 \pm 2301$
ε_{ST} (%)	39.00 ± 0.04	44.31 ± 0.04
N_{DT}^{obs}	1189 ± 38	1306 ± 39
ε_{DT} (%)	21.16 ± 0.03	23.20 ± 0.03
Individual BF (10^{-3})	1.005 ± 0.032	0.993 ± 0.030
Simultaneous BF (10^{-3})	$0.996 \pm 0.021 \pm 0.018$	
Individual α_γ	-0.587 ± 0.082	0.710 ± 0.076
Simultaneous α_γ	$-0.651 \pm 0.056 \pm 0.020$	

◆ Less than PDG 4.2σ

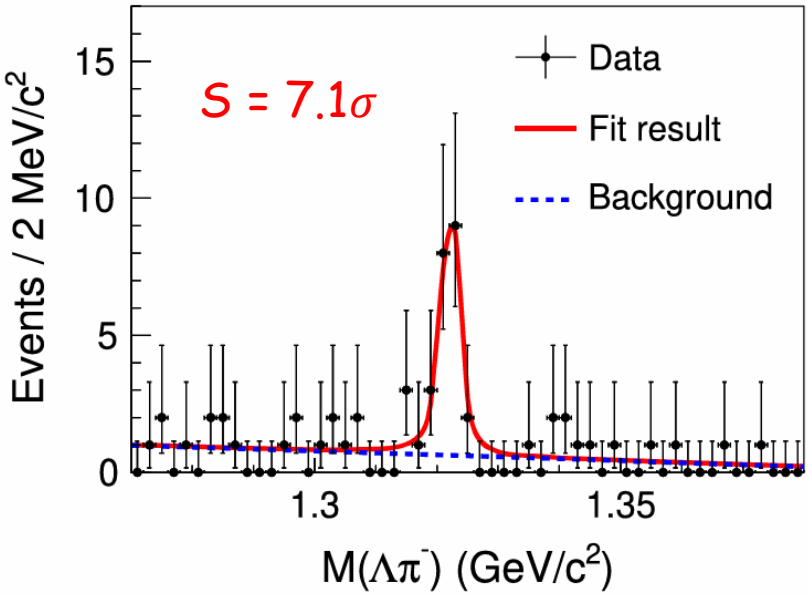
PRL 130, 211901 (2023)

Study Hyperon-Nucleus interaction at BESIII

Hyperon-Nucleus interaction in $\Xi^0 - N$



PRL 130 (2023) 251902



$\Xi^0 n \to \Xi^- p$ is observed for the first time

$$\sigma(\Xi^0 n \to \Xi^- p) = (7.4 \pm 1.8_{\text{stat}} \pm 1.5_{\text{sys}})\ \text{mb}$$

$$\sigma(\Xi^0 + {}^9\text{Be} \to \Xi^- + p + {}^8\text{Be}) = (22.1 \pm 5.3_{\text{stat}} \pm 4.5_{\text{sys}})\ \text{mb}$$

Results are consistent with theory prediction.

arxiv: 2209.12601

Hyperon-Nucleus interaction in $\Lambda - N$

J/ψ, $\psi(2S)$ →

- $p K^- \bar{\Lambda}$
- $\Lambda\bar{\Lambda}$
- $\Sigma^+\bar{\Sigma}^-$
- $\Xi^-\bar{\Xi}^+$
- $\Omega^-\bar{\Omega}^+$

Hyperon beam

Possible reactions

- $\Lambda + p$ → $\Sigma^+ n$, $K^+\Lambda\Lambda$, $K^+\Xi^- p$
- $\Lambda + n \longrightarrow \Sigma^- p$
- $\Sigma^0 + p \longrightarrow \Sigma^+ n$
- $\Sigma^- + p \longrightarrow \Sigma^0 n, \Lambda n$
- $\Sigma^+ + n \longrightarrow \Sigma^0 p, \Lambda p$

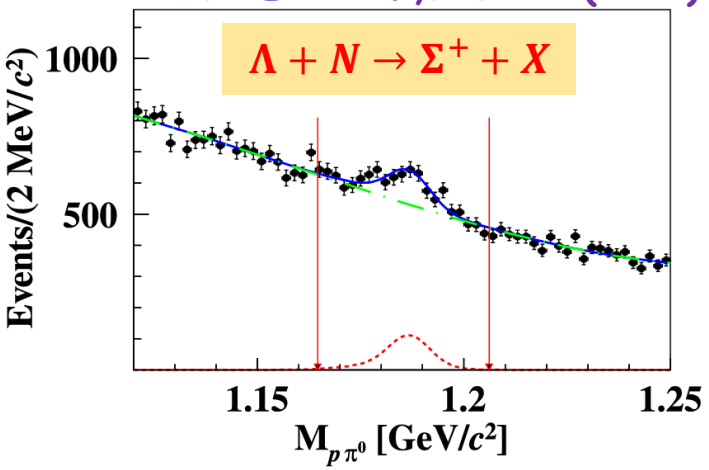
arxiv: 2209.12601

- $\Xi^- + p \longrightarrow \Xi^0 n, \Lambda\Lambda$
- $\Xi^0 + n \longrightarrow \Lambda\Lambda$

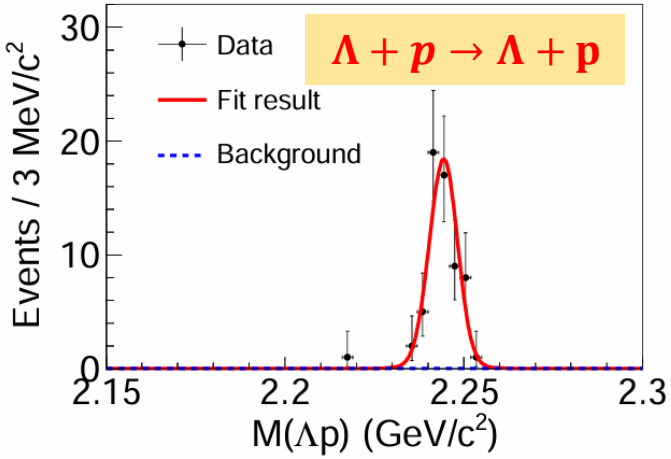
Many results are available

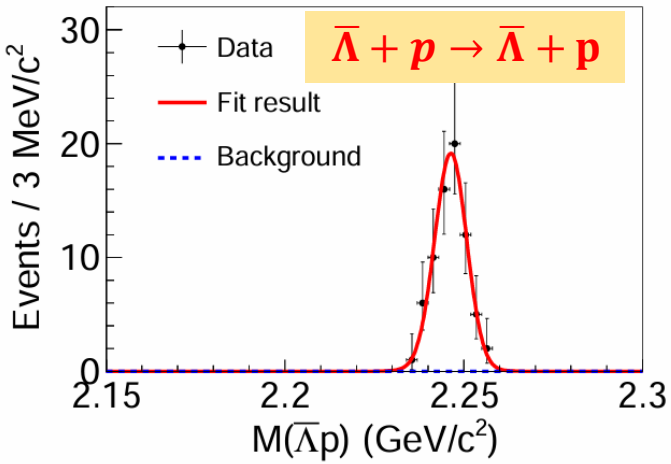
Decay	σ (mb)
$\Lambda p \to \Lambda p$	12.2±1.6±1.1
$\bar{\Lambda} p \to \bar{\Lambda} p$	17.5±2.1±1.6
$\Lambda p \to \Sigma^+ X$	19.3±2.4±1.8
$\Lambda^9 Be \to \Sigma^+ X$	37.3±4.7±3.5

PHYs REV C109,L052201(2024)



Phys. Rev. Lett. 132, 231902 (Published 4 June 2024)





- First to investigate Λ-nucleus interactions at e^+e^- collider
- Significant signals in Λ-nucleus interactions .

Summary

- BESIII has collected large number of J/ψ and $\psi(2S)$ data events at e^+e^- annihilation.
  - large hyperon pairs production ($\Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}$)
  - hyperon polarization measurement and precise CP tests
  - Precise hyperon radiative branch ratio and angular distribution measurement
  - Hyperon-Nucleus interaction studies
- More interesting results are on schedule based on 10 Billion J/ψ and 2.7 Billion $\psi(2S)$ data sets at BESIII.
- Look forward to future Super J/ψ Factory.

Thank you!