Hyperon physics at BESIII

Wenjing Zheng on behalf of BESIII Collaboration

Institute of High Energy Physics, Chinese Academy of Sciences

2024-07-18

42nd International Conference on High Energy Physics(ICHEP2024)

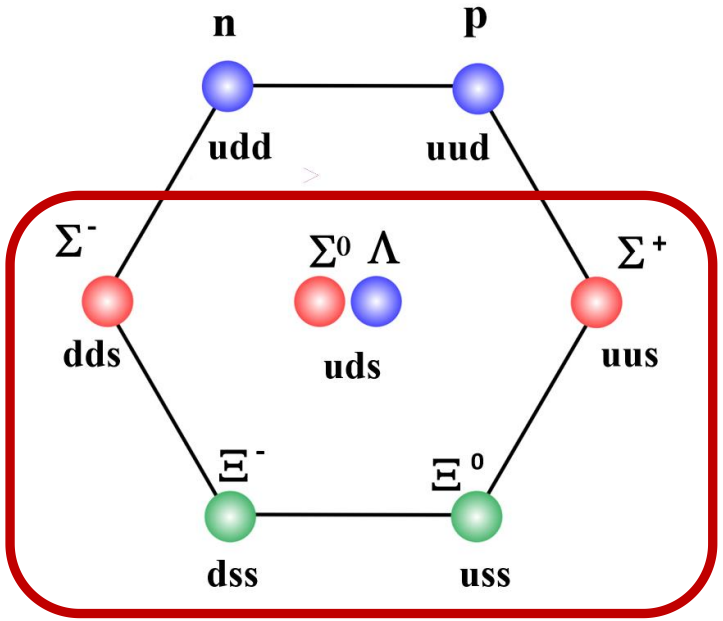
Prague, 18-24 July 2024

Outline

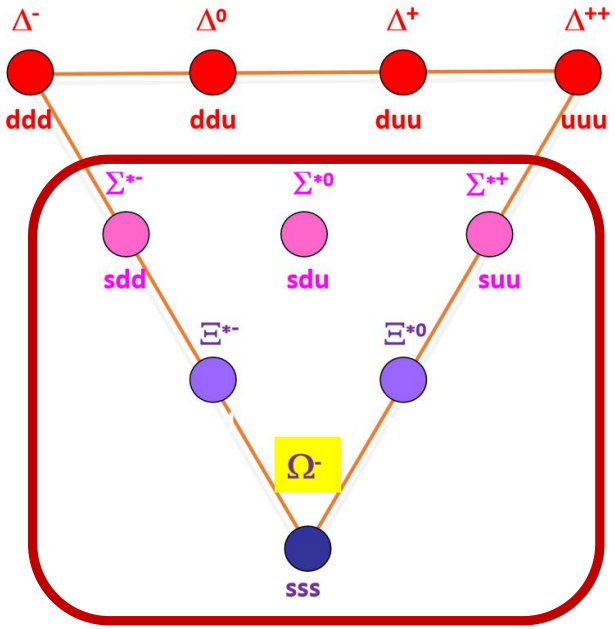
- Introduction
- Hyperon Physics at BESIII
  - Hyperon transverse polarization and CP tests
  - Hyperon weak radiative decays
  - Hyperon-nucleon interaction
- Summary

Introduction

- A unique tool for various unresolved puzzles
  - Matter-antimatter asymmetry
  - Confinement of quarks into hadrons

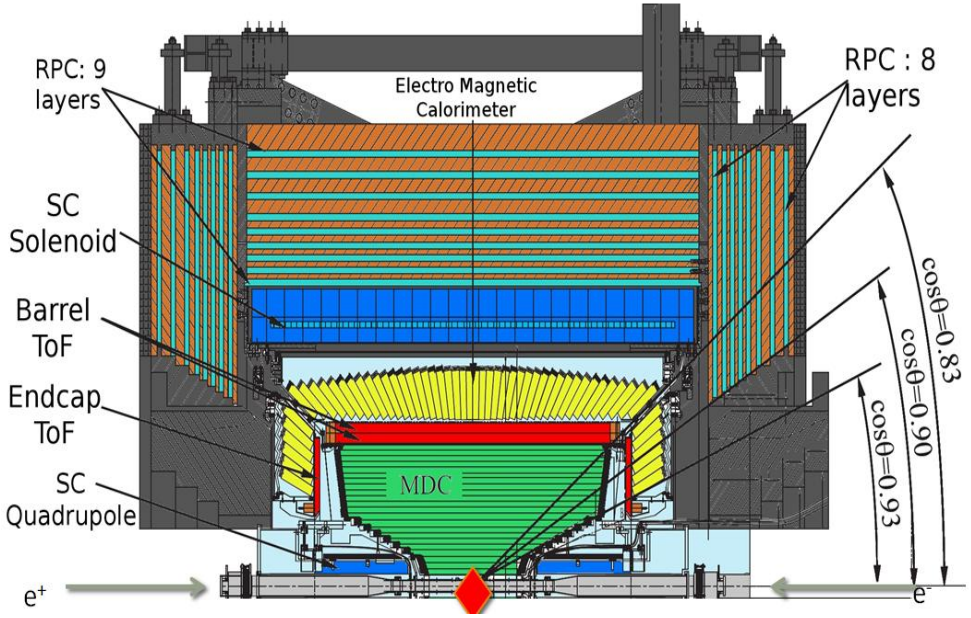


- Exploration of hyperon spin properties
  - Polarization and CP tests in final states of hyperon and antihyperon pairs
  - Electromagnetic properties in weak radiative decays
  - Inner structure of matter and fundamental interactions in scattering processes



BESIII: A hyperon factory

BESIII
- ✓ Cover 93% of full solid angle
- ✓ 1.0 T superconducting 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)

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

✓ Tests of CP symmetry in entangled $\Xi^0 - \overline{\Xi}^0$ pairs	PhysRevD.108.L031106 (2023)
✓ Strong and weak CP tests in sequential decays of polarized Σ^0 hyperons	arXiv:2406.06118
✓ Novel method to extract the femtometer structure of strange baryons using the vacuum polarization effect	arXiv:2309.04139
✓ Test of CP Symmetry in Hyperon to Neutron Decays	PhysRevLett.131.191802 (2023)
✓ Measurement of Λ transverse polarization in e^+e^- collisions at $\sqrt{s} = 3.68 - 3.71$ GeV	JHEP10(2023)081
✓ First simultaneous measurement of Ξ^0 and $\overline{\Xi}^0$ asymmetry parameters in $\psi(3683)$ decay	PhysRevD.108.L011101 (2023)
✓ Determination of the Σ^+ Timelike Electromagnetic Form Factors	PhysRevLett.132.081904 (2024)

New source for the CP asymmetry?

Symmetry Magazine

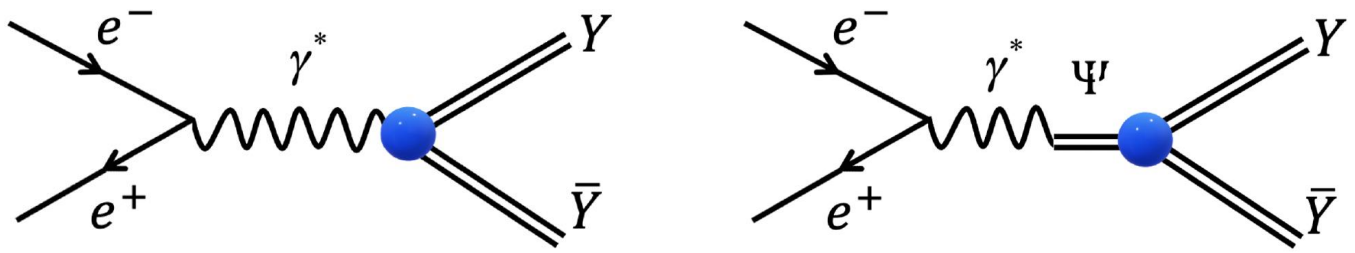
- Matter-antimatter asymmetry of the universe
  - Present universe: $\sim 10^{-10}$
  - Standard Model: $10^{-20} \sim 10^{-16} \ll 10^{-10}$

CPV in SM is small	Size	#Events	Experiments
B meson (2001)	O(1)	10^3	B factory
K meson (1964)	O(10^{-3})	10^6	Fix targets
D meson (2019)	O(10^{-4})	10^8	LHCb

- Not enough! Exploring new source for CP violation is necessary!
- BESIII provides the opportunity to investigate CP violation in hyperons.

Hyperon production at BESIII

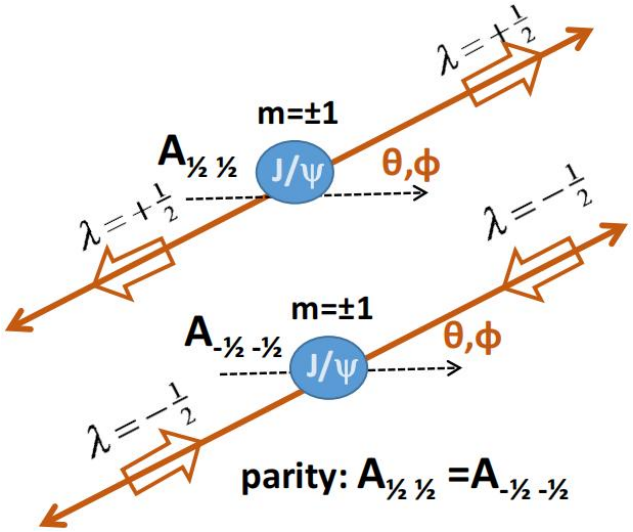
- High probability into a hyperon-antihyperon pair
  - Quantum spin correlation

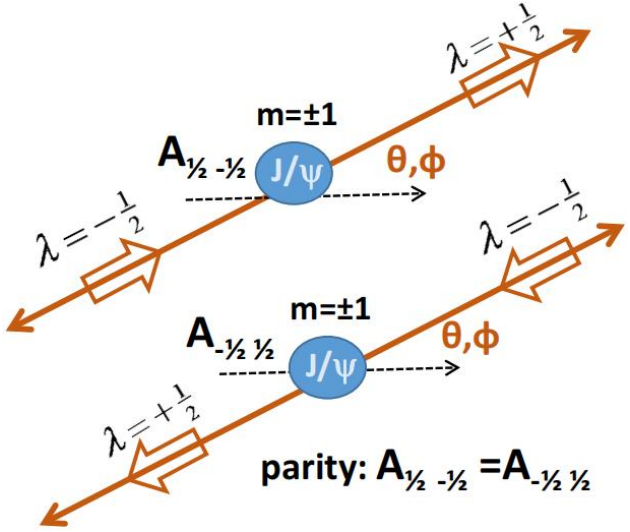


Phys. Rev. D 99, 056008 (2019)

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

- Same or opposite helicity states (for spin-1/2 hyperons): $A_{1/2\,1/2}$, $A_{1/2\,-1/2}$





ΔΦ: relative phase between $A_{1/2\,1/2}$ and $A_{1/2\,-1/2}$

Hyperon polarization

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

Nature Phys. 15, 631 (2019)

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

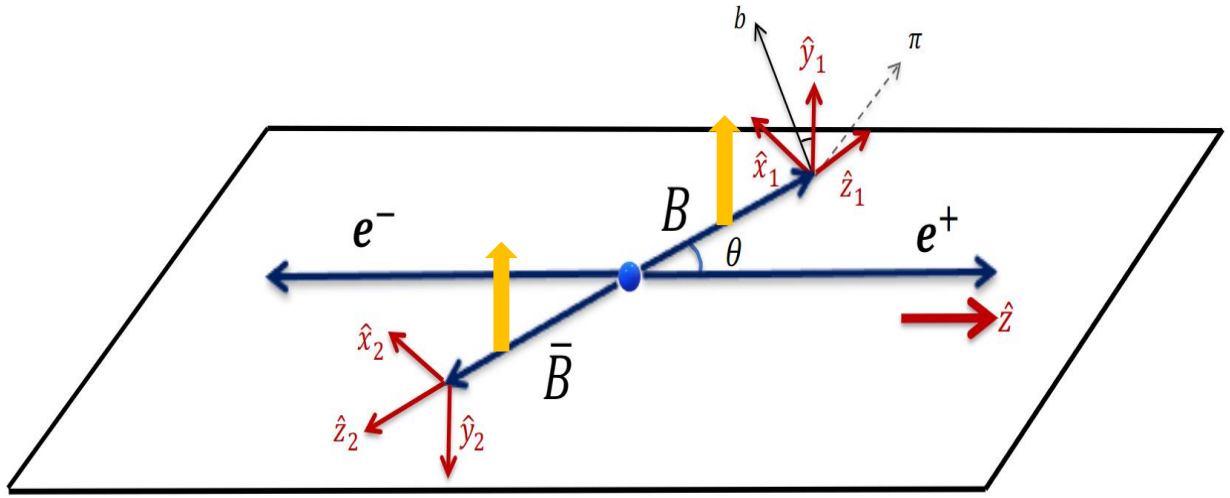
Relation with form factors G_E, G_M:

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

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

Physics Letters B 772 (2017)

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



Decay parameters & CP observables

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

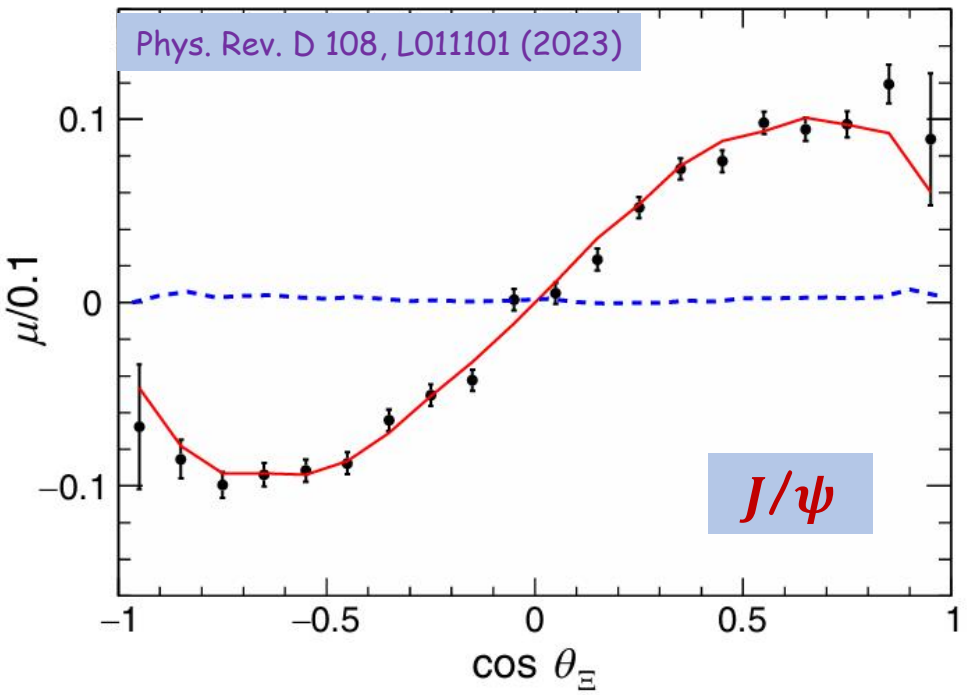
$$A_{CP} = \frac{\alpha_B + \alpha_{\bar{B}}}{\alpha_B - \alpha_{\bar{B}}}, \phi_{CP} = \frac{\phi_B - \phi_{\bar{B}}}{2}$$

Phys. Rev. 108, 1645 (1957)

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

- ✓ A clear transverse polarization of Ξ^0 from J/ψ decay is observed for the first time.
- ✓ Ξ^0 and $\bar{\Xi}^0$ decay parameters are determined with the most precise, which are improved by more than one order of magnitude over the previous measurements.
- ✓ The CP asymmetry observables are measured with the higher precision.

10 Billion J/ψ
#Signal: 327.3k



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]

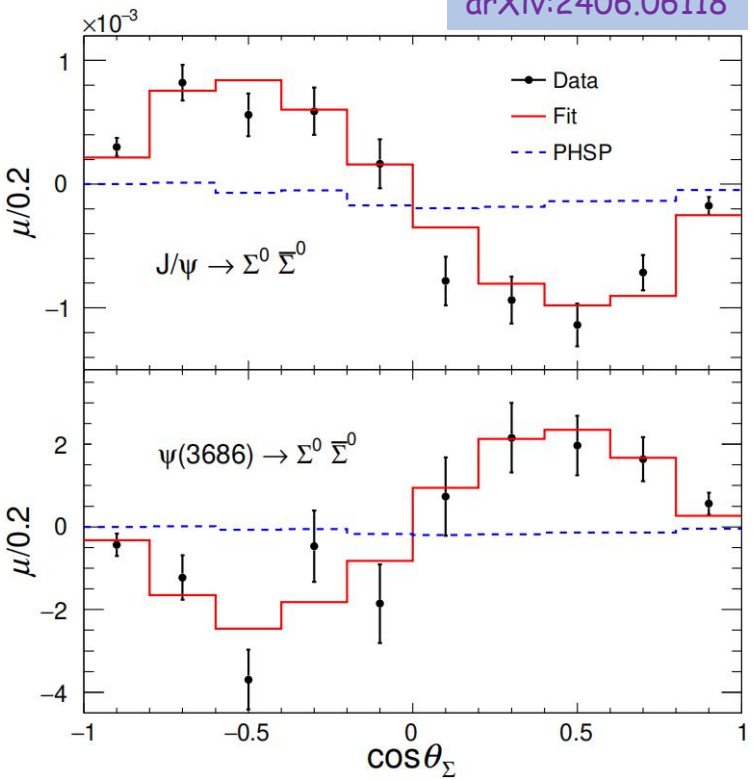
$e^+e^- \to J/\psi,\ \psi(2S) \to \Sigma^0\bar{\Sigma}^0, \Sigma^0(\bar{\Sigma}^0) \to \Lambda\gamma(\bar{\Lambda}\gamma)$

- ✓ For the first time, the transverse polarizations of Σ^0 in J/ψ and $\psi(2S)$ decays are observed with opposite directions.
- ✓ $\Sigma^0/\bar{\Sigma}^0$ decay parameter is determined in the decay of the Σ^0 hyperons.
- ✓ The CP test is performed in the subsequent decays of their daughter particles Λ and $\bar{\Lambda}$.

10 Billion J/ψ: #Signal: 1.1m
2.7 Billion $\psi(2S)$: #Signal: 51.8k

Parameter	This work	Previous results
$\alpha_{J/\psi}$	$-0.4133 \pm 0.0035 \pm 0.0077$	-0.449 ± 0.022 [51]
$\Delta\Phi_{J/\psi}$(rad)	$-0.0828 \pm 0.0068 \pm 0.0033$	...
$\alpha_{\psi(3686)}$	$0.814 \pm 0.028 \pm 0.028$	0.71 ± 0.12 [51]
$\Delta\Phi_{\psi(3686)}$(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	$0.730 \pm 0.051 \pm 0.011$	0.748 ± 0.007 [44]
$\bar{\alpha}_\Lambda$	$-0.776 \pm 0.054 \pm 0.010$	-0.757 ± 0.004 [44]
A_{CP}^Λ	$(-3.0 \pm 6.9 \pm 1.5) \times 10^{-2}$	$(-2.5 \pm 4.8) \times 10^{-3}$ [2]

arXiv:2406.06118

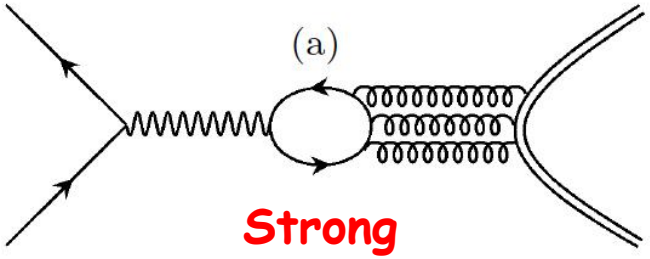


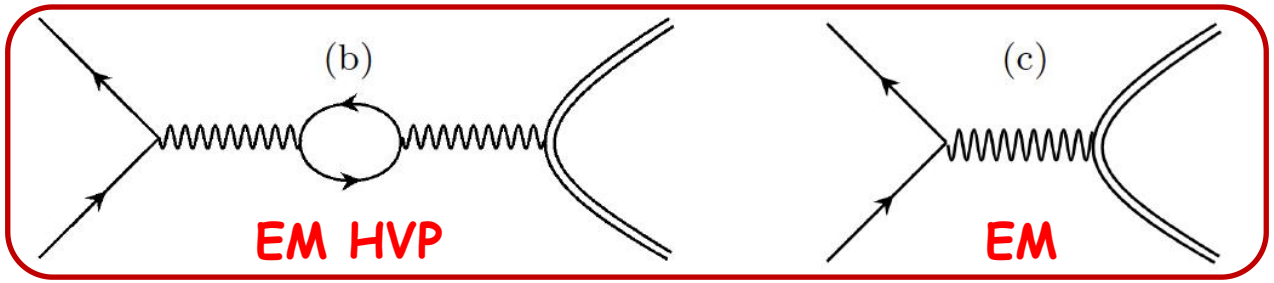
$e^+e^- \to J/\psi \to \bar{\Lambda}\Sigma^0, \Sigma^0 \to \gamma\Lambda$

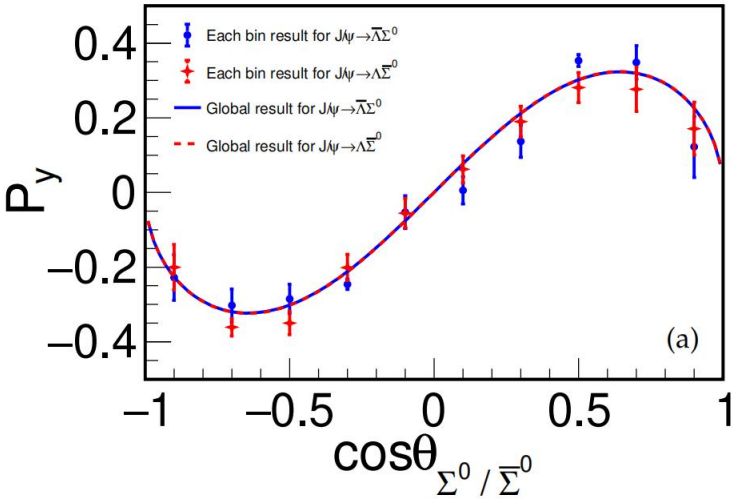
- ✓ $J/\psi \to \bar{\Lambda}\Sigma^0$ is a purely electromagnetic process.
- ✓ Hadronic vacuum polarization (HVP) at the J/ψ resonance results in a significantly enhanced signal.

10 Billion J/ψ, #Signal: 26k

arXiv:2309.04139







- $R = \left|\frac{G_E}{G_M}\right| = \frac{\sqrt{s}}{2M_Y}\sqrt{\frac{1-\alpha}{1+\alpha}} = 0.860 \pm 0.029(\text{stat.}) \pm 0.015(\text{syst.})$
- $\Delta\Phi_{\bar{\Lambda}\Sigma^0} = arg\left(\frac{G_E}{G_M}\right) = (1.011 \pm 0.094(\text{stat.}) \pm 0.010(\text{syst.}))\ \text{rad}$
- $\Delta\Phi_{\Lambda\bar{\Sigma}^0} = arg\left(\frac{G_E}{G_M}\right) = (2.128 \pm 0.094(\text{stat.}) \pm 0.010(\text{syst.}))\ \text{rad}$
- $\Delta\Phi_{CP} = (0.003 \pm 0.133(\text{stat.}) \pm 0.014(\text{syst.}))\ \text{rad}$

Hyperon weak radiative decays

- ✓ Measurement of the Absolute Branching Fraction and Decay Asymmetry of $\Lambda \to n\gamma$ PhysRevLett.129.212002 (2022)
- ✓ Precision Measurement of the Decay $\Sigma^+ \to p\gamma$ in the Process $J\psi \to \Sigma^+\bar{\Sigma}^-$ PhysRevLett.130.211901 (2023)

Hyperon weak radiative decays

- Interplay of the electromagnetic, weak, and strong interactions
- Parity conserving (P wave) amplitude
- Parity violating (S wave) amplitude (if $\neq 0$)
- Asymmetric angular distribution of the daughter baryon in the hyperon rest frame

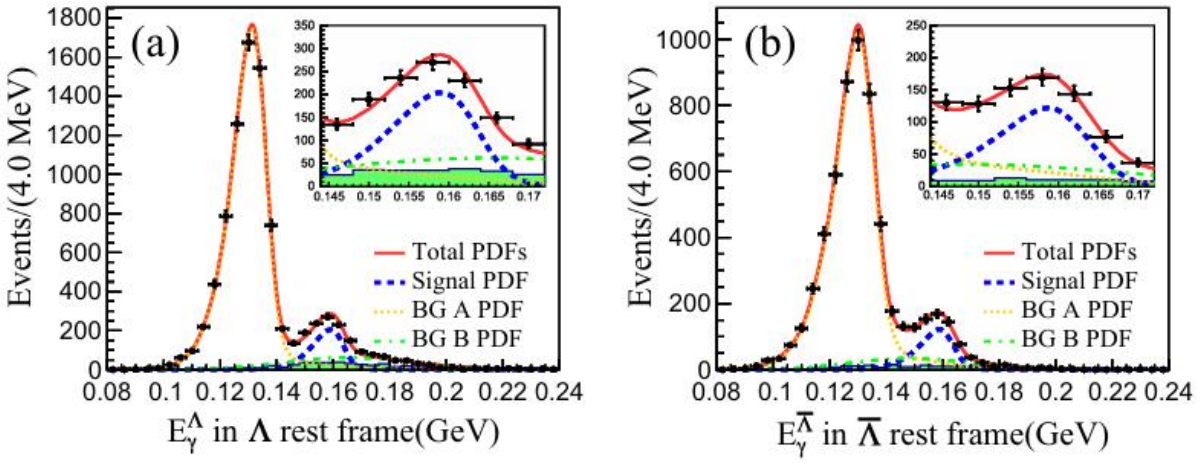
$$\frac{dN}{d\Omega} \propto \frac{N}{4\pi}(1 + \alpha_\gamma \boldsymbol{P}_i \cdot \hat{\boldsymbol{p}})$$

- In unitary symmetry, $\alpha_\gamma = 0$
- Experimentally, α_γ is large

- ✓ Various phenomenological models?
- ✓ ChPT !!!
- ✓ Check in more precise measurements

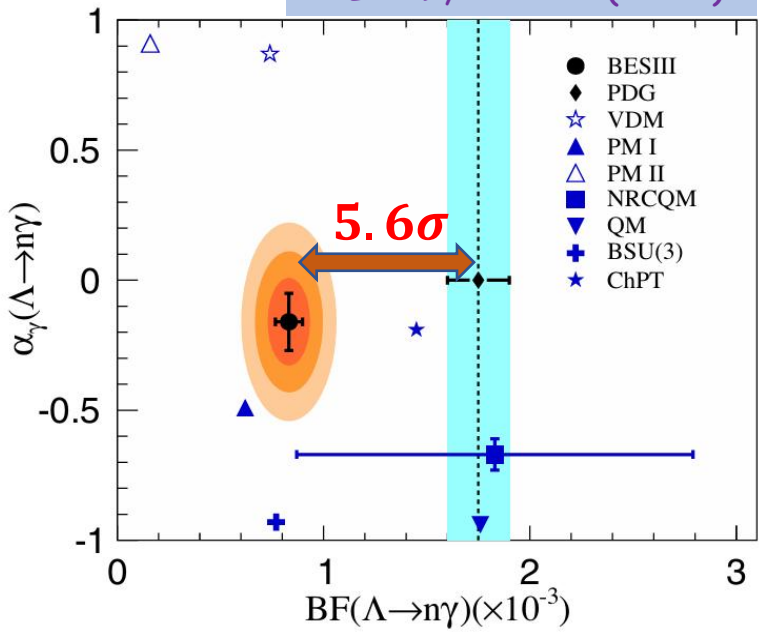
$\Lambda \to n\gamma$

- ✓ The absolute branching fraction of the decay $\Lambda \to n\gamma$ is determined for the first time
- ✓ First determination of the decay asymmetry α_γ is reported



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	$-0.13 \pm 0.13 \pm 0.03$	$0.21 \pm 0.15 \pm 0.06$
	$\mathbf{-0.16 \pm 0.10 \pm 0.05}$	

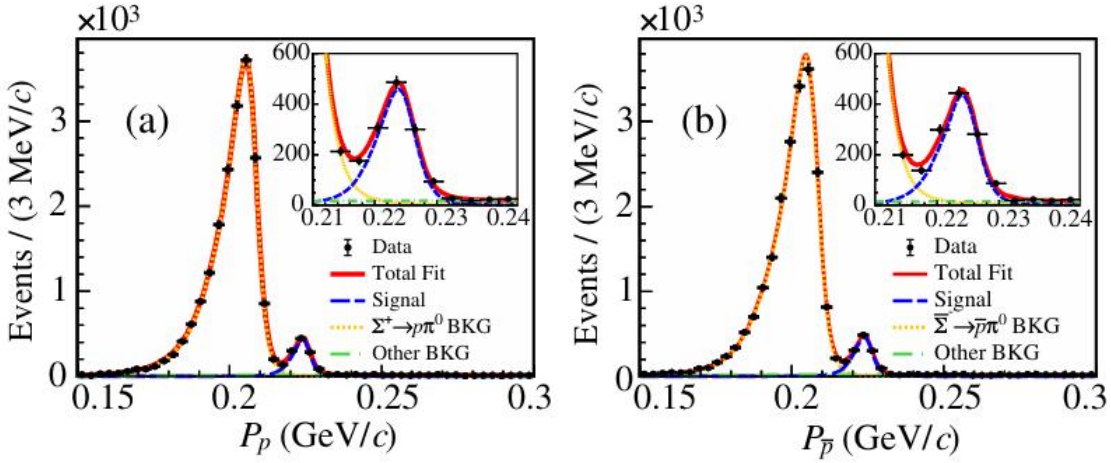
PRL 129, 212002 (2022)



- ✓ More precise in branch fraction $\Lambda \to n\gamma$
- ✓ 5.6σ deviate from the previous measurement
- ✓ α_γ is in good agreement with the prediction in covariant baryon ChPT

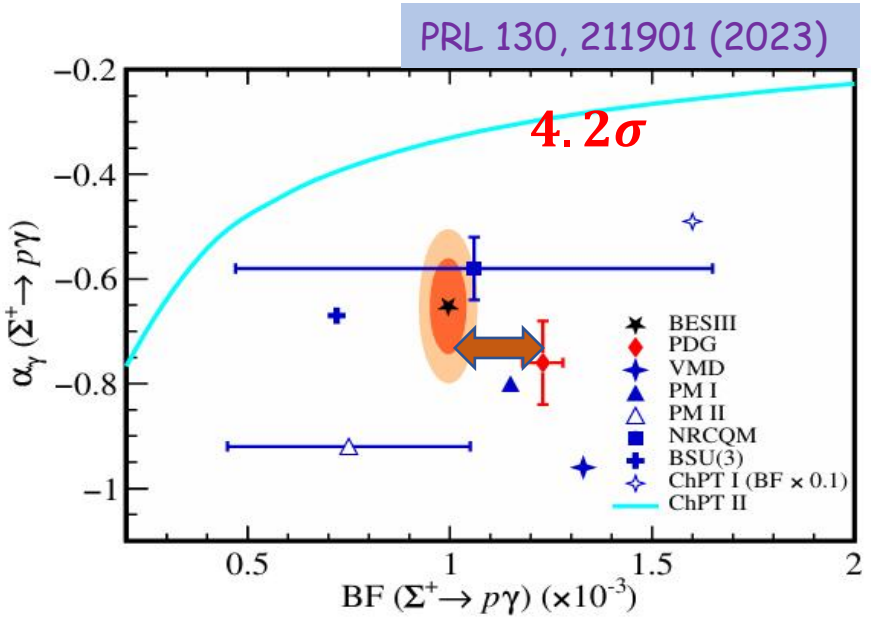
$\Sigma^+ \to p\gamma$

- ✓ The absolute branching fraction of the decay $\Sigma^+ \to p\gamma$ is determined with more precise
- ✓ The decay asymmetry parameter α_γ is determined with the most precise



Mode	$\Sigma^+ \to p\gamma$	$\bar{\Sigma}^- \to \bar{p}\gamma$
$N_{\rm ST}^{\rm obs}$	$2\,177\,771 \pm 2285$	$2\,509\,380 \pm 2301$
$\varepsilon_{\rm ST}$ (%)	39.00 ± 0.04	44.31 ± 0.04
$N_{\rm DT}^{\rm obs}$	1189 ± 38	1306 ± 39
$\varepsilon_{\rm DT}$ (%)	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	$-0.651 \pm 0.056 \pm 0.020$	

PRL 130, 211901 (2023)



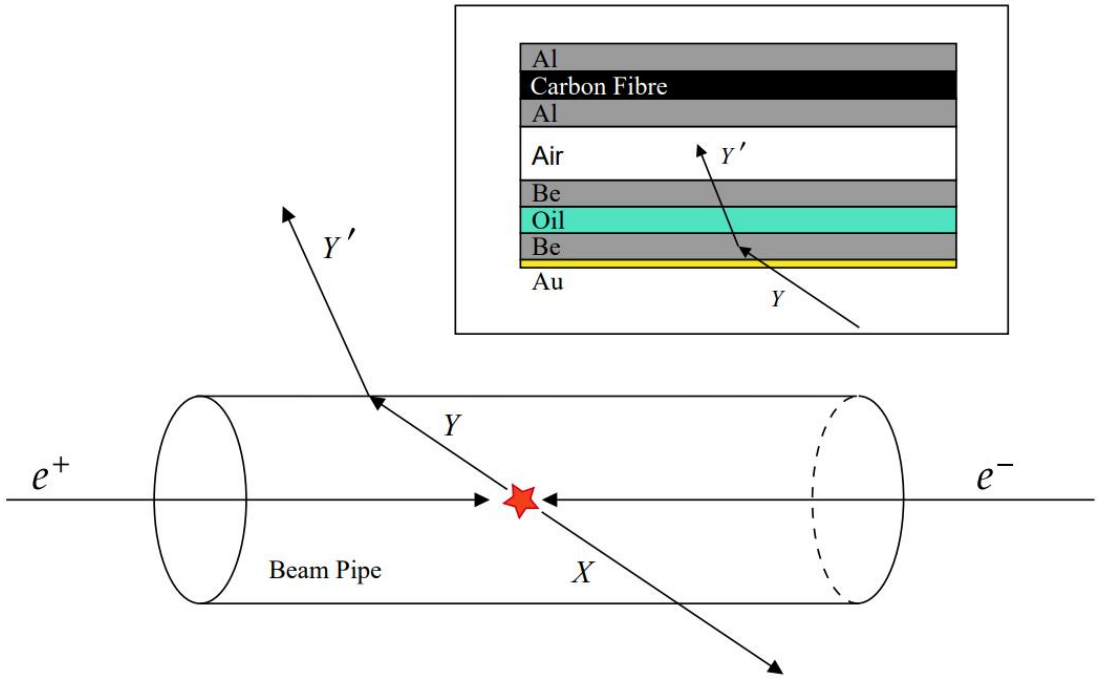
- ✓ Precisions are improved by 78% and 34%
- ✓ BF is lower than PDG value by 4.2σ
- ✓ α_γ is consistent with the world average value

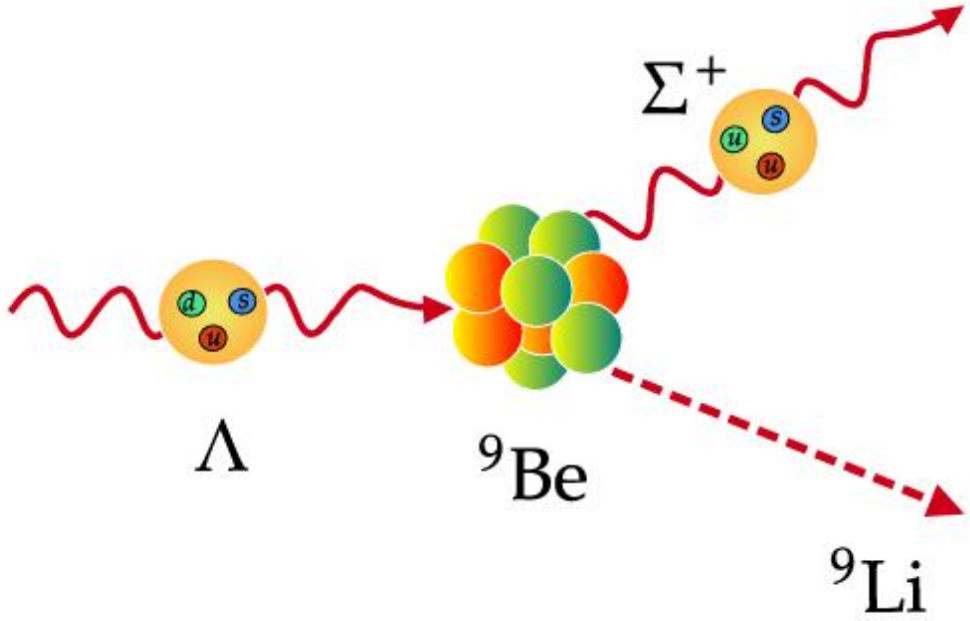
Hyperon-nucleon interaction

- ✓ First Study of Reaction $\Xi^0 n \to \Xi^- p$ Using Ξ^0-Nucleus Scattering at an Electron-Positron Collider — PhysRevLett.130.251902 (2023)
- ✓ First Study of Antihyperon-Nucleon Scattering $\overline{\Lambda} p \to \overline{\Lambda} p$ and Measurement of $\Lambda p \to \Lambda p$ Cross Section — PhysRevLett.132.231902 (2024)
- ✓ First measurement of ΛN inelastic scattering with Λ from $e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$ — PhysRevC.109.L052201 (2024)

Hyperon-nucleon interaction

- Well-established models exist for nucleon-nucleon interactions
- There are difficulties in modeling hyperon-nucleon scattering
- The lack of experimental measurements

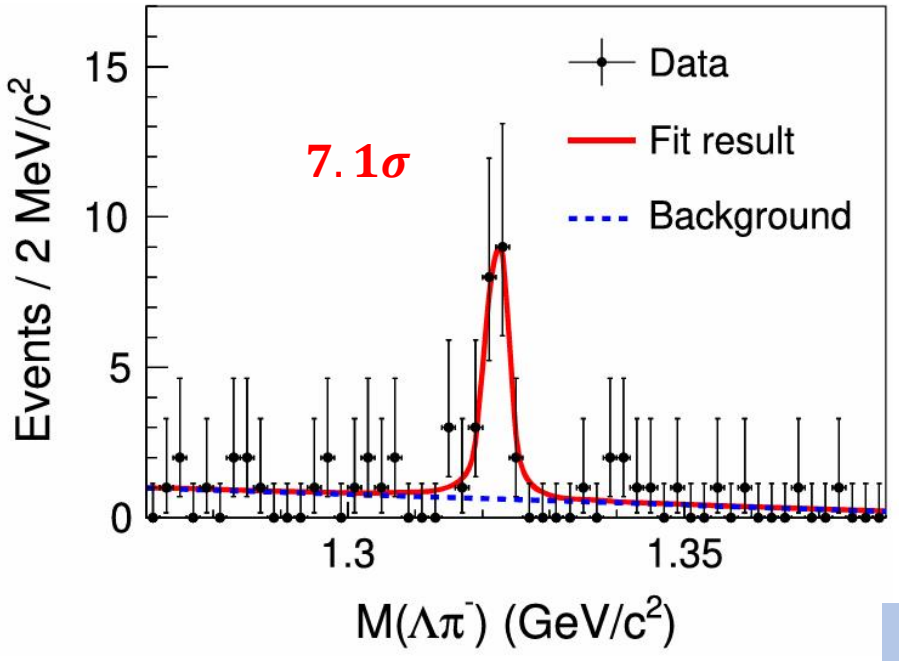




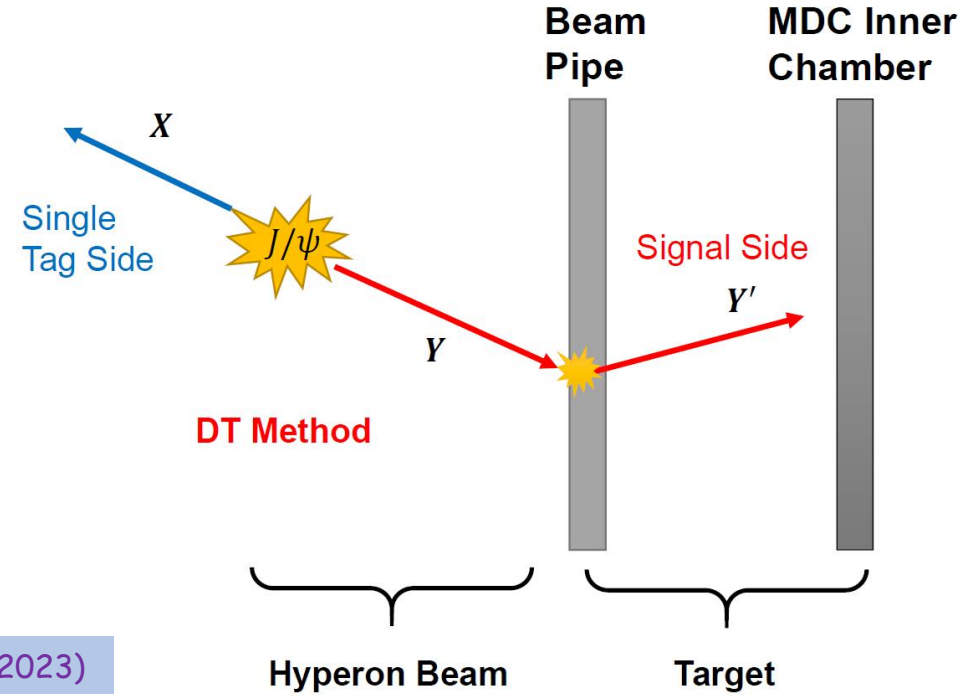
Chin. Phys. C 48 (2024) 7, 073003

$\Xi^0 n \to \Xi^- p$

- ✓ First study of hyperon-nucleon interactions in electron-positron collisions
- ✓ $\Xi^0 n \to \Xi^- p$ is observed for the first time
- ✓ $\sigma(\Xi^0 n \to \Xi^- p) = (7.4 \pm 1.8(\text{stat.}) \pm 1.5(\text{syst.}))$ mb
- ✓ $\sigma(\Xi^0 + {}^9\text{Be} \to \Xi^- + p + {}^8\text{Be}) = (22.1 \pm 5.3(\text{stat.}) \pm 4.5(\text{syst.}))$ mb



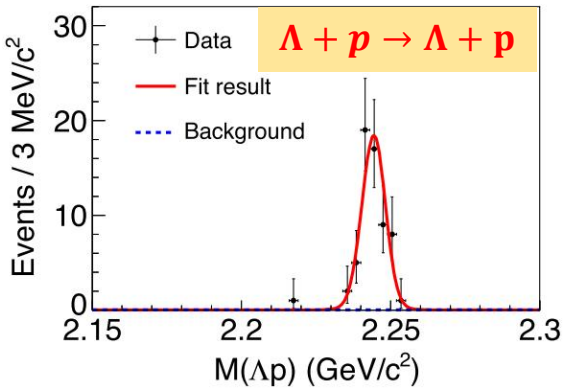
PRL 130, 251902 (2023)

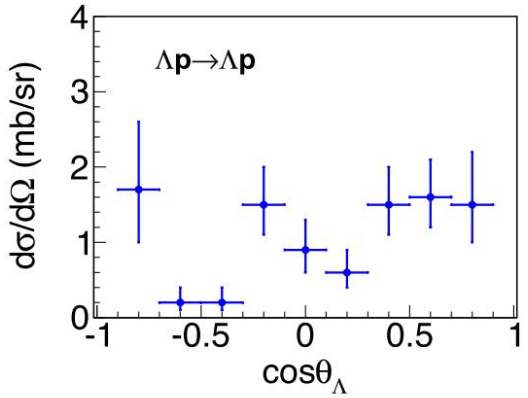


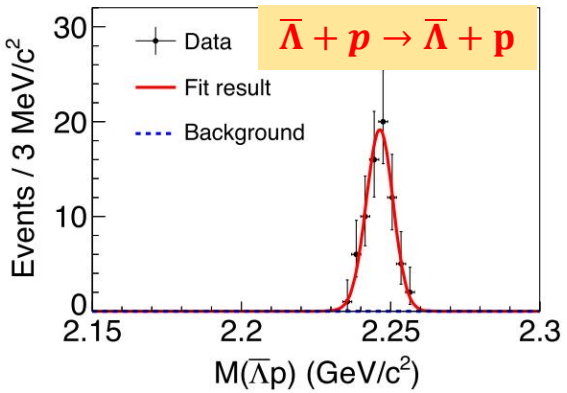
$\Lambda p \to \Lambda p$ & $\bar{\Lambda} p \to \bar{\Lambda} p$

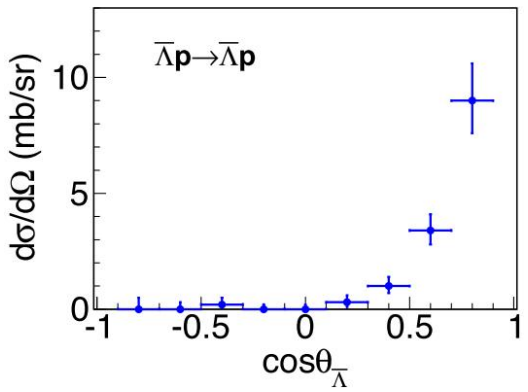
- ✓ First study of antihyperon-nucleon scattering
- ✓ $\sigma(\Lambda p \to \Lambda p) = (12.2 \pm 1.6(\text{stat.}) \pm 1.1(\text{syst.}))$ mb
- ✓ $\sigma(\bar{\Lambda} p \to \bar{\Lambda} p) = (17.5 \pm 2.1(\text{stat.}) \pm 1.6(\text{syst.}))$ mb
- ✓ Differential cross sections of the two reactions are also measured

Phys. Rev. Lett. 132, 231902 (2024)









- ✓ Slight tendency of forward scattering for $\Lambda p \to \Lambda p$
- ✓ Strong forward peak for $\bar{\Lambda} p \to \bar{\Lambda} p$

Summary

- BESIII has collected a large number of J/ψ and $\psi(2S)$ data events
  - Large hyperon pair productions ($\Lambda\overline{\Lambda}, \Sigma\overline{\Sigma}, \Xi\overline{\Xi}$)
  - Hyperon polarization measurement and CP violation searches
  - Hyperon weak radiative decays
  - Hyperon-Nucleus interaction studies
- More interesting results expected in the future!
  - Hyperon rare decays, electric dipole moment (EDM) searches ……

Thank you!