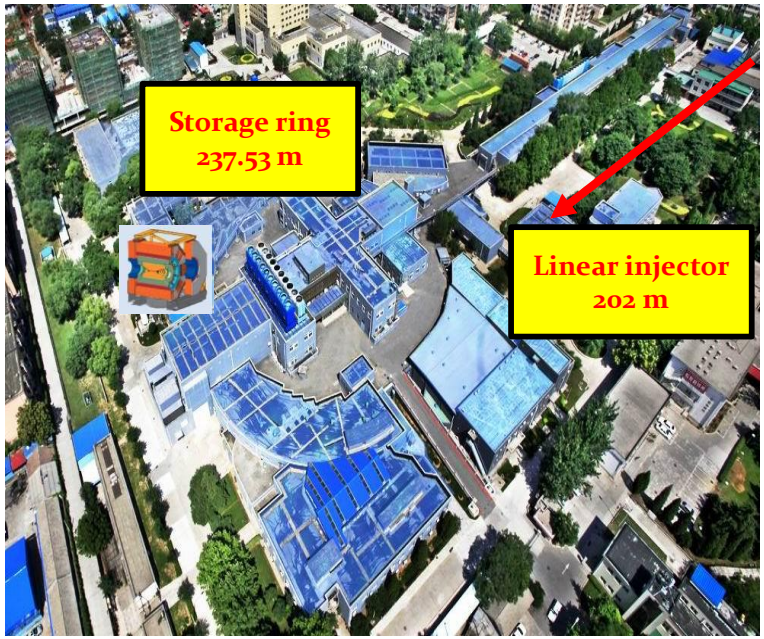
Hyperon physics at BESIII

***U**niversity of **S**cience and **T**echnology of **C**hina*
State Key Laboratory of Particle Detection and Electronics
He Li(lihe2013@mail.ustc.edu.cn)
On behalf of BESIII Collaboration

2022/08/10

BEPCII&BESIII



Electromagnetic Calorimeter

CsI(Tl): L=28 cm

Barrel σ_E=2.5%

Endcap σ_E=5.0%

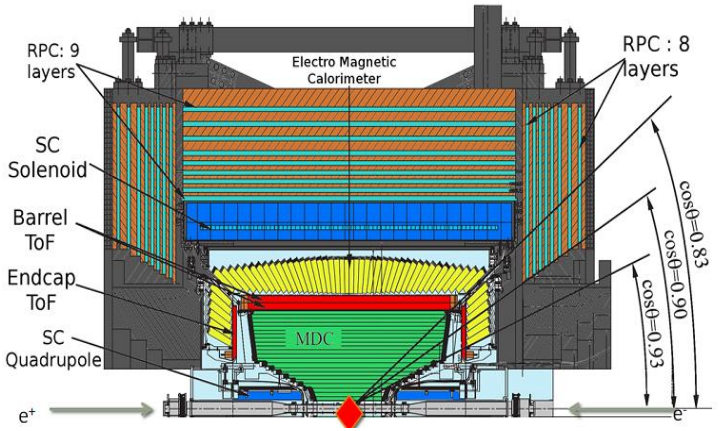
Muon Counter

RPC

Barrel: 9 layers

Endcap: 8 layers

$\sigma_{spatial}$=1.48 cm



E_{cm}= 2.0-4.6 GeV (2.0-4.95 GeV since 2019)

Peak luminosity in continuously operation

@ E_{cm} = 3.77 GeV: ~ 0.8×10^{33} $cm^{-2}s^{-1}$

Collision angle: 22 mrad

Main Drift Chamber

Small cell, 43 layer

σ_{xy}=130 μm

dE/dx~6%

σ_p/p= 0.5% at 1 GeV

Time Of Flight

Plastic scintillator

σ_T(barrel)=80 ps

σ_T(endcap)=110 ps

(update to 65 ps with MRPC)

Motivation

- Studies of two-body hyperon weak decays plays an important role in the study of the fundamental symmetries P and CP[1]
- Decay asymmetry is the probe of the mixing of Parity-conserving Amplitude(A^{PC}) and Parity-violating Amplitude(B^{PV}) in the transition matrix

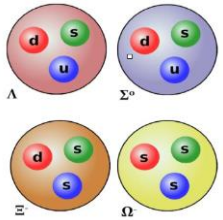
$$\frac{dN}{d\Omega} = \frac{N^0}{4\pi}(1 + \alpha_0 \mathbf{P}_i \cdot \hat{p}) \qquad \alpha_0 = \frac{2Re(A^{PC} * B^{PV})}{|A^{PC}|^2 + |A^{PV}|^2}$$

- CP violation confirmed in meson sector, not enough to explain the matter anti-matter asymmetry degree in the universe
  - In Kaon sector in 1964 (PRL 13, 138 (1964))
  - In B meson decay in 2001 (BaBar: PRL 87, 091801 (2001), Belle: PRL 87, 091802)
  - In neutral charm meson decays in 2019 (LHCb: PRL 122, 211803 (2019))
- The CP violation in baryon sector has never been observed, hyperon decays provide a good lab to test CP violation

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

Production of entangled hyperon-antihyperon pairs at BESIII

- Quasi-stable baryons composed of s quarks, discovered in 20th century in cosmic ray
- Hyperon decays falls into three categories:
  - Non-leptonic weak decays
  - Radiative decay decays
  - Beta decay or semi-leptonic decays



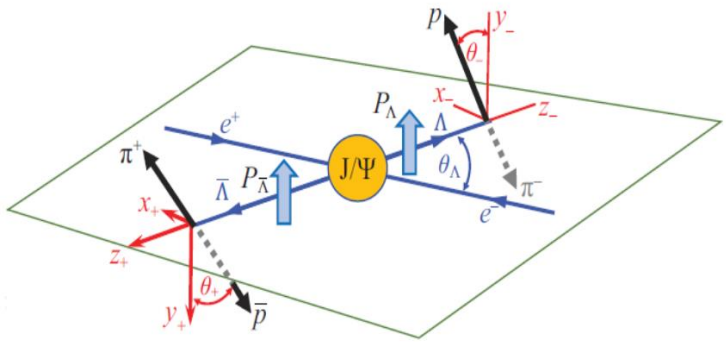
10 billion J/ψ		4 billion ψ'	
1.9×10^7	$\Lambda\bar{\Lambda}$	1.5×10^6	$\Lambda\bar{\Lambda}$
1.2×10^7	$\Sigma^0\bar{\Sigma}^0$	0.9×10^6	$\Sigma^0\bar{\Sigma}^0$
1.5×10^7	$\Sigma^+\bar{\Sigma}^-$	0.9×10^6	$\Sigma^+\bar{\Sigma}^-$
1.1×10^7	$\Xi^0\bar{\Xi}^0$	0.9×10^6	$\Xi^0\bar{\Xi}^0$
1.0×10^7	$\Xi^-\bar{\Xi}^+$	1.1×10^6	$\Xi^-\bar{\Xi}^+$
		0.2×10^6	$\Omega\bar{\Omega}$

- $e^+e^- \rightarrow J/\psi, \psi(3686) \rightarrow \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}, \Omega\bar{\Omega}$ at BESIII
- Parity conservation in charmonium decay guarantees that the $cos\theta$ dependent hyperon and anti-hyperon polarizations are equal and perpendicular to the production plane[2]

- If the relative phase between hadronic form factor of $e^+e^- \rightarrow \psi \rightarrow \bar{B}B$ is not zero(Polarized), the decay parameters could be simultaneously and directly measured, then test CP symmetry

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

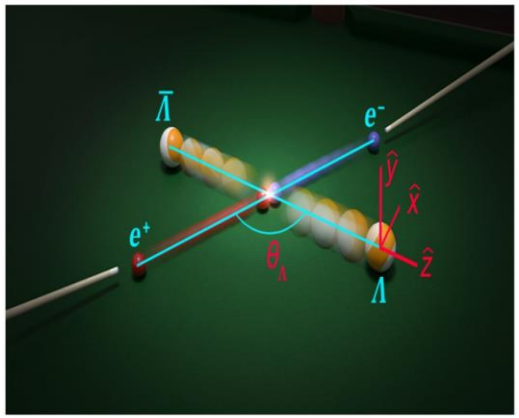
$$\frac{dN}{d\Omega} = \frac{N^0}{4\pi}(1+\alpha_\gamma \mathbf{P}_i \cdot \hat{p})$$



[2] IL NUOVO CIMENTO, 109A, 241 (1996))

Weak decay parameters and CP test in $J/\psi \to \bar{\Lambda}\Lambda$

- Helicity method [3] to describe the joint angular distribution of final state particles



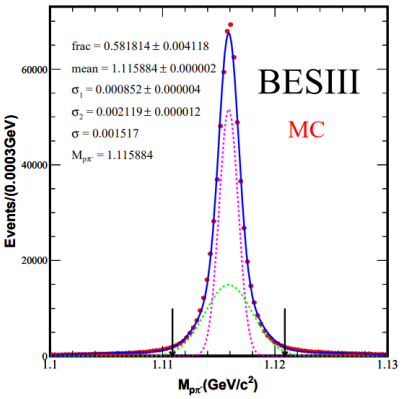
$$\omega(\xi, \Delta\Phi, \alpha_\psi, \alpha_+, \alpha_-) = 1 + \alpha_\psi \cos^2\theta_\Lambda \quad \textit{Unpolarized}$$

$$+\alpha_+\alpha_-\left[\sin^2\theta_\Lambda\left(n_{p,x}n_{\bar{p},x} - \alpha_\psi n_{p,y}n_{\bar{p},y}\right) + \left(\cos^2\theta_\Lambda + \alpha_\psi\right)n_{p,z}n_{\bar{p},z}\right]$$

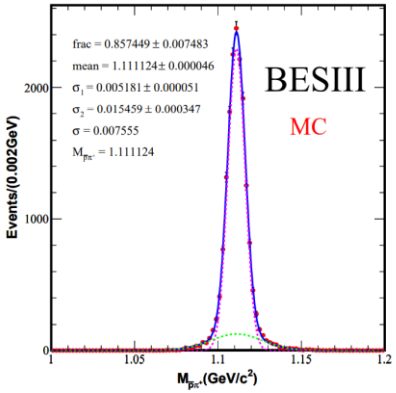
$$+ \alpha_+\alpha_-\sqrt{1-\alpha_\psi{}^2}\cos(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda\left(n_{p,x}n_{\bar{p},z} + n_{p,z}n_{\bar{p},x}\right) \quad \textit{Correlated}$$

$$+\sqrt{1-\alpha_\psi{}^2}\sin(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda\left(\alpha_+ n_{p,y} + \alpha_- n_{\bar{p},y}\right) \quad \textit{Polarized}$$

- The maximum likelihood fit to extract the decay parameters



(a) Invariant mass of Λ



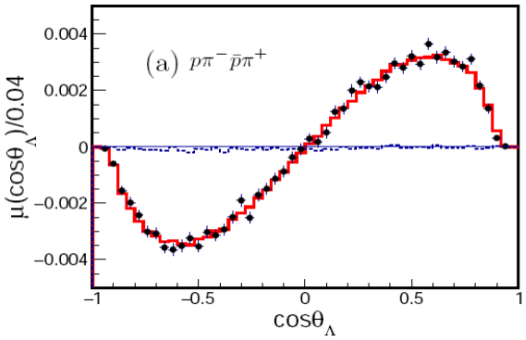
(b) Invariant mass of $\bar{n}\pi^0$

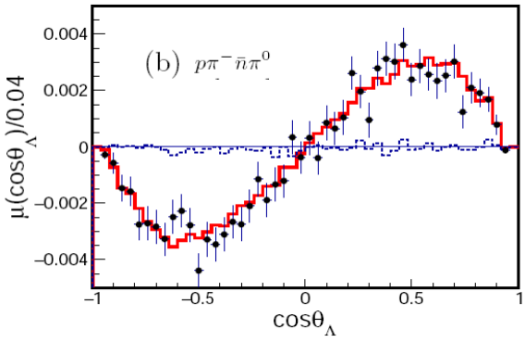
- Kinematic space $\xi(\theta_\Lambda, \hat{n}_p, \hat{n}_{\bar{p}})$:
  - $\hat{n}_p(\hat{n}_{\bar{p}})$: unit vector of $\bar{p}(p)$ momentum in the rest frame of $\bar{\Lambda}(\Lambda)$
- Parameter space:
  - α_ψ: angular distribution parameter
  - $\Delta\Phi$: helicity phase of two different amplitudes
  - α_-: decay asymmetry of $\Lambda \to p\pi^-$
  - α_+ : decay parameter of $\bar{\Lambda} \to \bar{p}\pi^+ / \bar{\Lambda} \to \bar{n}\pi^0$

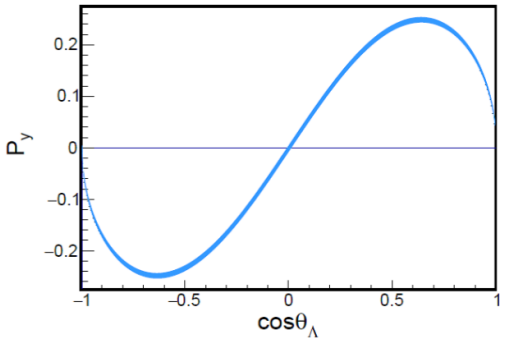
[3] Phys. Lett. B **772**, 16 (2017)

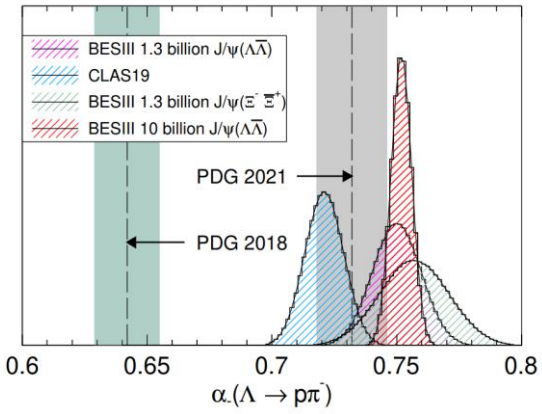
Weak decay parameters and CP test in $J/\psi \to \bar{\Lambda}\Lambda$

- First measurement of hyperon polarization in J/ψ decays, max polarization reaches 25% in longitudinal direction[4]
- Non-zero relative phase allows for individual determinations of Λ and $\bar{\Lambda}$ decay parameters, and thus allow for CP test
- The decay asymmetry of $\Lambda \to p\pi^-$: 7σ shift from PDG2018 average









10 billion J/ψ data is used to improve the accuracy[5]

Paras.	This work(10 billion)	Previous Results(1.3billion)
α_ψ	0.4748±0.0022±0.0024	0.461±0.006 ±0.007
$\Delta\Phi$	0.7521±0.0042±0.0080	0.740 ±0.009±0.004
α_-	0.7519±0.0036±0.0019	0.750±0.009 ±0.004
α_+	-0.7559±0.0036 ±0.0029	-0.758±0.010±0.007
A_{cp}	-0.0025±0.0046 ±0.0011	0.006±0.012±0.007
α_{avg}	0.7542±0.0010±0.0020	-

[4] Nat. Phys. 15, 631 (2019)
[5] arXiv:2204.11058

CP symmetry and weak phases with $J/\psi \to \Xi^- \bar{\Xi}^+$

- Lee-Yang parameters α, β and γ (decay parameters, govern the decay angular distribution and Only two are independent)

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

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

$$\boldsymbol{\tan\phi_Y = \beta_Y/\gamma_Y}$$

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

- The hyperon decay is completely described by two independent parameters α_{Ξ^-} and ϕ_{Ξ^-}
- CP violation can be quantified in terms of the observables

$$A_{CP} = \frac{\alpha_Y + \bar{\alpha}_Y}{\alpha_Y - \bar{\alpha}_Y} \qquad \Delta_{CP} = \frac{\phi_Y + \bar{\phi}_Y}{\phi_Y - \bar{\phi}_Y}$$

- Helicity method[3] to describe the joint angular distribution of final state particles

$$\mathcal{W}(\boldsymbol{\xi};\boldsymbol{\omega}) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu} \sum_{\mu'\nu'=0}^{3} a^{\Xi}_{\mu\mu'} a^{\bar{\Xi}}_{\nu\nu'} a^{\Lambda}_{\mu'0} a^{\bar{\Lambda}}_{\nu'0}$$

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

- Kinematic space $\xi\left(\theta_{\Xi^0}, \hat{n}_\Lambda, \hat{n}_{\bar{\Lambda}}, \hat{n}_p, \hat{n}_{\bar{p}}\right)$ in the rest frame of mother particle
- Parameter space:
  - $\alpha_\psi, \Delta\Phi$: production parameter and helicity phase
  - $\alpha_{\Xi^-}, \phi_{\Xi^-}, \alpha_{\bar{\Xi}^+}, \phi_{\bar{\Xi}^+}, \alpha_\Lambda, \bar{\alpha}_\Lambda$: decay parameter

[6]Nature volume 606, pages64–69 (2022))

CP symmetry and weak phases with $J/\psi \to \Xi^- \bar{\Xi}^+$

Results based on 1.3 billion J/ψ events at BESIII[6]

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		

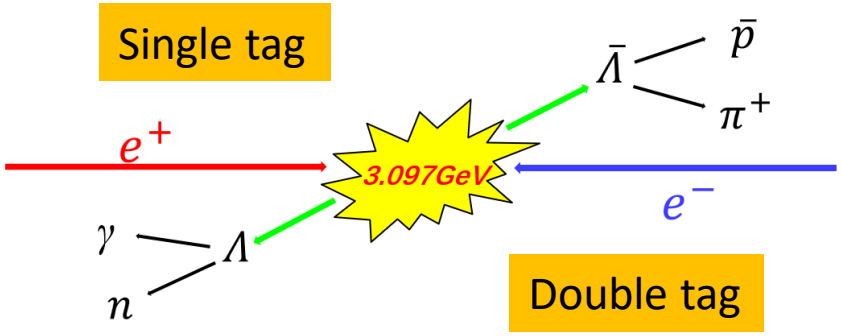
The $J/\psi \to \Xi^-\bar{\Xi}^+$ angular distribution parameter α_ψ, the hadronic form factor phase $\Delta\Phi$, the decay parameters for $\Xi^- \to \Lambda\pi^-$ (α_Ξ, ϕ_Ξ), $\bar{\Xi}^+ \to \bar{\Lambda}\pi^+$ ($\bar{\alpha}_\Xi, \bar{\phi}_\Xi$) $\Lambda \to p\pi^-$ (α_Λ) and $\bar{\Lambda} \to \bar{p}\pi^+$ ($\bar{\alpha}_\Lambda$); the CP asymmetries A_{CP}^{Ξ}, $\Delta\phi_{CP}^{\Xi}$ and A_{CP}^{Λ}, and the average $\langle\phi_\Xi\rangle$. The first and second uncertainties are statistical and systematic, respectively.

- First measurement of the polarization
- Direct measurement of all decay parameters
- Independent measurement of Λ decay parameters, good agreement with previous BESIII results
- First measurement of weak phase difference, one of the most precise tests of CP symmetry for strange baryons
- Three independent CP tests in single channel

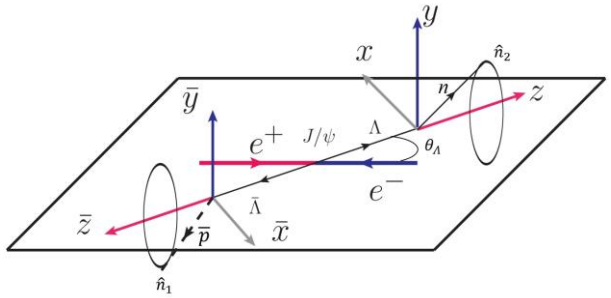
[6]Nature volume 606, pages64–69 (2022))

Hyperon radiative decay $\Lambda \to n\gamma (s \to d$ transition)

- The radiative decay provides a unique probe for strong/weak/EM interactions [7]
- A long standing puzzle is "Hara's theorem" that parity violating amplitude should vanish[8] while experiments find large negative α_γ in $\Sigma^+ \to \gamma p$ and $\Xi^0 \to \gamma\Lambda/\Sigma^0$[9]
- It is proposed that $\Lambda \to n\gamma$ could resolve the ambiguities of various theoretical models[10]
- Branching fraction(BF) of $\Lambda \to n\gamma$ measured based on fixed target, differ by 2σ
- No information of decay asymmetry α_γ obtained experimentally
- DT method to determine the branching fraction and helicity method to extract the asymmetry



Double tag method

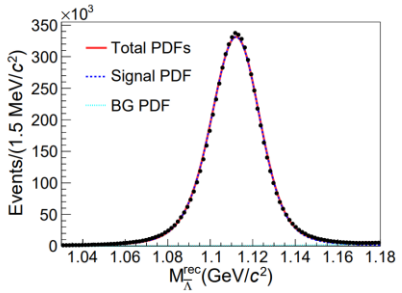


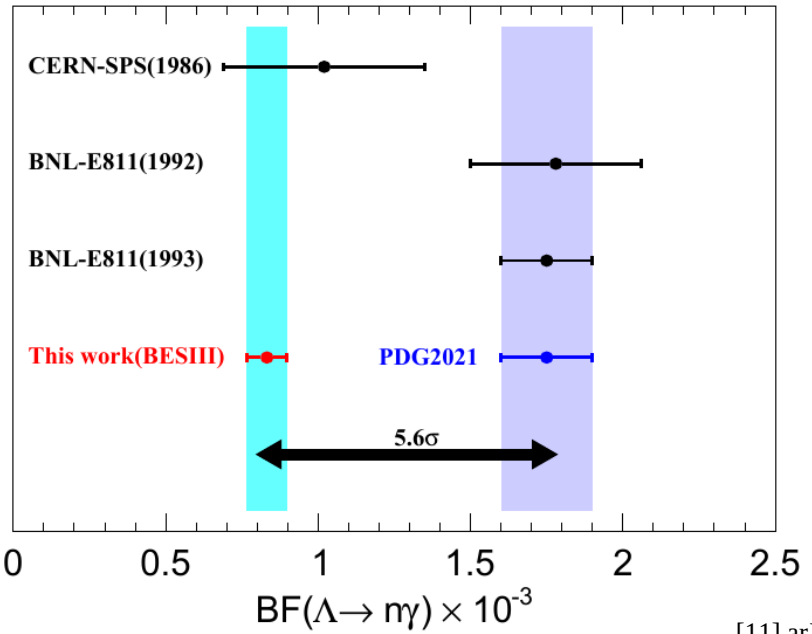
Helicity frame

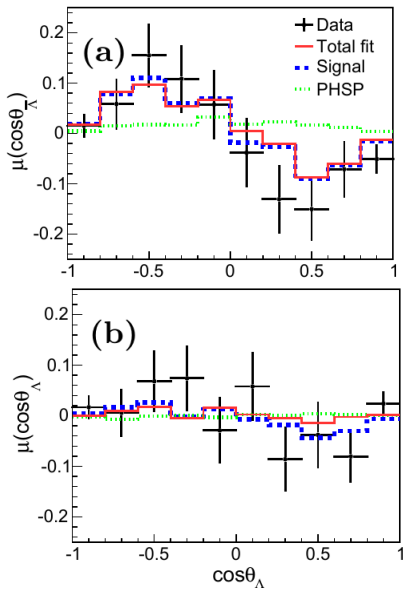
[7] Front. Phys, 12(5), 121301 (2017)
[8] Phys. Rev. Lett. 12, 378 (1964)
[9] (Particle Data Group), PTEP 2020, 083C01 (2020)
[10] Acta Phys. Polon. B 51, 2111 (2020)

Hyperon radiative decay $\Lambda \to n\gamma (s \to d$ transition)

- The first study of hyperon radiative decays at electron-positron collider[11]
- Absolute BF of $\Lambda \to n\gamma$ with improved precision $(0.832 \pm 0.038 \pm 0.054) \times 10^{-3}$, smaller than PDG value $(1.75 \pm 0.15) \times 10^{-3}$ by 5.6σ
- First determination of decay asymmetry α_γ= -0.16±0.10±0.05
- The results provide essential input for Hara's theorem validation and constraining the effective models





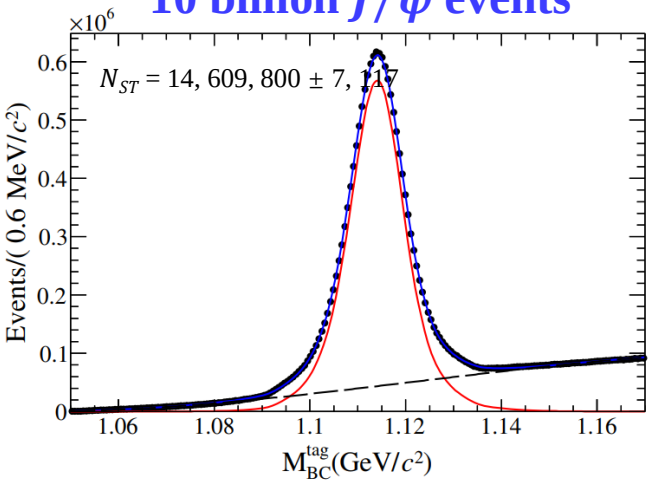


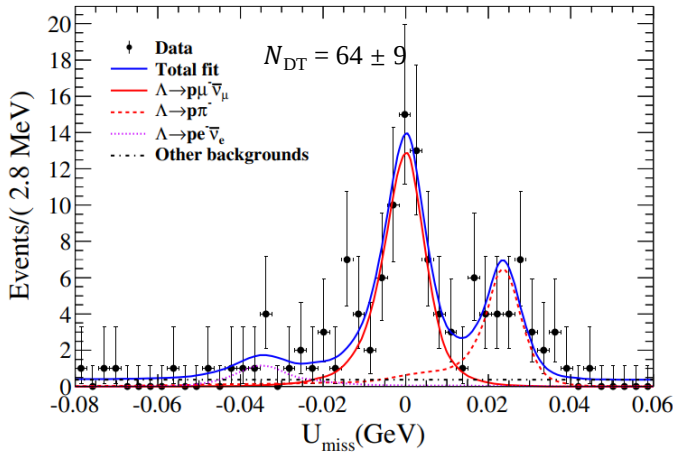
[11] arXiv:2206.10791 [hep-ex]

Hyperon semi-leptonic decay $\Lambda \to p\mu^-\bar{\nu}_\mu$

- Absolute BF measurement[12] of the branching fraction of $\Lambda \to p\mu^-\bar{\nu}_\mu$ with DT method

10 billion J/ψ events





- First study at a collider experiment; most precise result to date; Update measurement after ~50 years
- Test lepton flavor universality
- Search for CP violation

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

Consistent with SM

$R^{\mu e}_{SM} = 0.153 \pm 0.008$ (PRL 114, 161802 (2015))

$$\mathcal{A}_{CP} = \frac{\mathcal{B}_{\Lambda\to p\mu^-\bar{\nu}_\mu} - \mathcal{B}_{\bar{\Lambda}\to\bar{p}\mu^+\nu_\mu}}{\mathcal{B}_{\Lambda\to p\mu^-\bar{\nu}_\mu} + \mathcal{B}_{\bar{\Lambda}\to\bar{p}\mu^+\nu_\mu}} = 0.02 \pm 0.14 \pm 0.02$$

Consistent with CP symmetry

[12] PRL 127, 121802 (2021)

Summary

- Entangled and polarized hyperon-antihyperon pairs produced from charmonium decays open a new era to search for CP violation
- Studies of hyperon non-leptonic weak decays, radiative decays and semi-leptonic decays are performed at BESIII
- 10 Billion J/ψ data and 4 Billion $\psi(3686)$ data collected will bring more exciting results in the future

Thanks for your attention!