

CP violation tests with quantum correlated hyperon-antihyperon pairs at BESIII

张剑宇

on behalf of the **BESIII** collaboration

中国科学院大学



中国科学院大学
UNIVERSITY OF CHINESE ACADEMY OF SCIENCES

第十九届重味物理和 CP 破坏研讨会



NNU · 南京师范大学
NANJING NORMAL UNIVERSITY



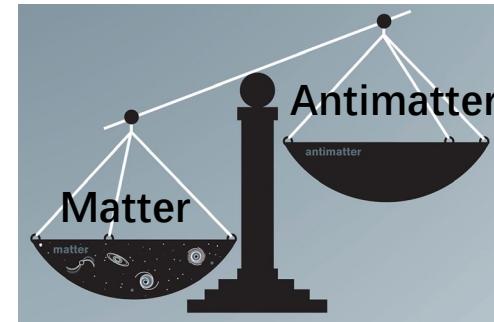
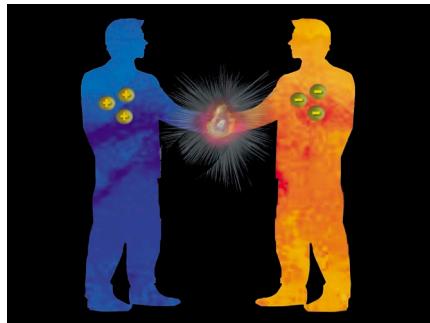
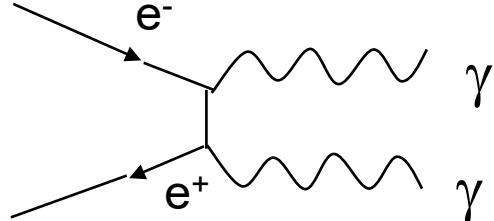
Outline

- Introduction
- CP tests in hyperon decays
- Recent results from BESIII
- Summary and outlooks

Matter-antimatter asymmetry in the universe

The Big Bang model predicts:

- Matter and antimatter are produced in equal amounts
- Matter and antimatter annihilated into energy



However the very fact that we exist in a matter-dominated universe.

Sakharov three conditions require C and CP violation processes exist.



Andrei Sakharov
(1921-1989)

Sakharov three conditions:

1. Baryon number B violation
2. C and CP symmetry violation
3. Interactions out of thermal equilibrium

Pisma Zh. Eksp. Teor. Fiz., 1967, 5: 32-35.

Illustrations of Charge conjugation and Parity (CP) symmetry



A brief history of Parity and CP violation



K meson *CP* violation [2]

1964

James Watson Cronin



Nobel Prize 1980

B meson *CP* violation [3,4]

2001



Val Logsdon Fitch

D meson *CP* violation [5]

2019



- [1] Phys. Rev. 104 (1956) 254-258
- [2] Phys. Rev. Lett., 1964, 13: 138-140
- [3] Phys. Rev. Lett., 2001, 87: 091801
- [4] Phys. Rev. Lett., 2001, 87: 091802
- [5] Phys. Rev. Lett., 2019, 122(21): 211803



CPV in Standard Model: CKM matrix



Dirac Medal 2010

Nobel Price 2008

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

CPV from phase δ

δ_s strong phase ϕ_w weak phase *CP*

For decay $A = A_1 e^{i\delta_s^1} e^{i\phi_w^1} + A_2 e^{i\delta_s^2} e^{i\phi_w^2}$ \rightarrow $\bar{A} = A_1 e^{i\delta_s^1} e^{-i\phi_w^1} + A_2 e^{i\delta_s^2} e^{-i\phi_w^2}$

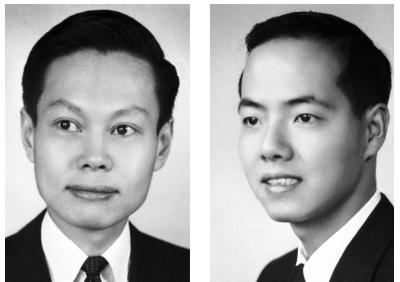
Make $r = A_2/A_1$, $\delta = \delta_s^2 - \delta_s^1$, $\phi = \phi_w^2 - \phi_w^1$

$$\begin{aligned} \text{Thus } A_{CP} &= \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = \frac{|A_1|^2 |1 + re^{i(\delta+\phi)}|^2 - |A_1|^2 |1 + re^{i(\delta-\phi)}|^2}{|A_1|^2 |1 + re^{i(\delta+\phi)}|^2 + |A_1|^2 |1 + re^{i(\delta-\phi)}|^2} \\ &= \frac{2r\cos(\delta+\phi) - 2r\cos(\delta-\phi)}{2(1+r^2 + r\cos(\delta+\phi) + r\cos(\delta-\phi))} = \frac{2r\sin\delta\sin\phi}{1+r^2+2r\cos\delta\cos\phi} \end{aligned}$$

- Strong and weak phase difference $\neq 0$
- At least two amplitudes, CPV arised from interference between amplitudes.

$\neq 0$, if $\delta \neq 0$ and $\phi \neq 0$

CPV in hyperon decay



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)

The amplitude of spin $\frac{1}{2}$ baryon B_i decay to a spin $\frac{1}{2}$ baryon B_f and π :

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

The decay parameters are defined as:

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

Two complex amplitudes: **ϕ weak phase, δ strong phase**

$$S = \sum_i S_i e^{i(\phi_i^S + \delta_i^S)}, \quad P = \sum_i P_i e^{i(\phi_i^P + \delta_i^P)}$$

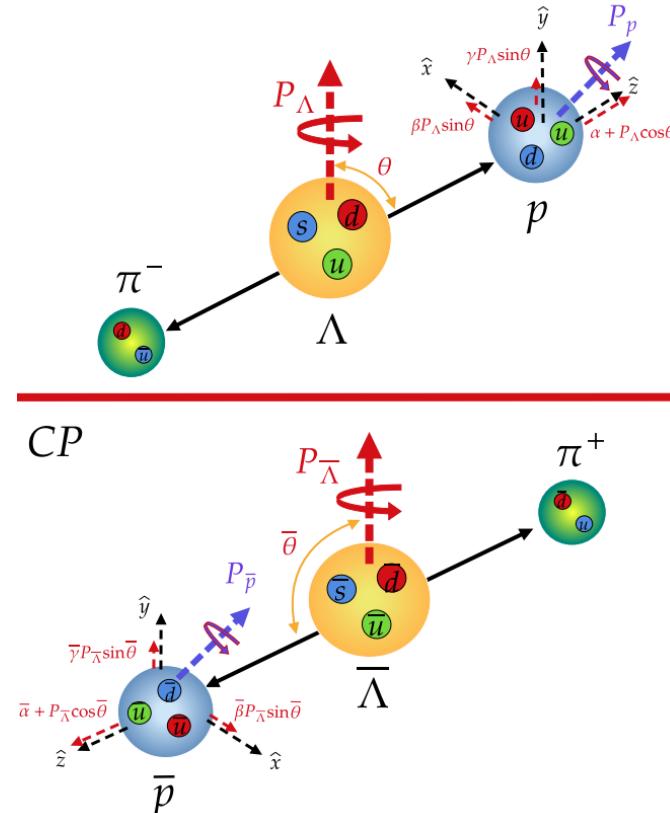
Under CP transformation:

$$\bar{S} = -\sum_i S_i e^{i(-\phi_i^S + \delta_i^S)}, \quad \bar{P} = \sum_i P_i e^{i(-\phi_i^P + \delta_i^P)}$$

If CP conserved: $S \xrightarrow{CP} -S$

$$P \xrightarrow{CP} P$$

$$\xrightarrow{CP} \begin{array}{l} \alpha \xrightarrow{CP} -\alpha \\ \beta \xrightarrow{CP} -\beta \end{array}$$



CPV observables

$$\left\{ \begin{array}{l} \Delta = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \\ A = \frac{\Gamma \alpha + \bar{\Gamma} \bar{\alpha}}{\Gamma \alpha - \bar{\Gamma} \bar{\alpha}} \approx \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} + \Delta \\ B = \frac{\Gamma \beta + \bar{\Gamma} \bar{\beta}}{\Gamma \beta - \bar{\Gamma} \bar{\beta}} \approx \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}} + \Delta \end{array} \right.$$

CP observable in hyperon decay



John F.
Donoghue

Xiao-Gang He

Sandip Pakvasa

PHYSICAL REVIEW D

VOLUME 34, NUMBER 3

1 AUGUST 1986

Hyperon decays and CP nonconservation

John F. Donoghue

Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003

Xiao-Gang He and Sandip Pakvasa

Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822

(Received 7 March 1986)

We study all modes of hyperon nonleptonic decay and consider the CP -odd observables which result. Explicit calculations are provided in the Kobayashi-Maskawa, Weinberg-Higgs, and left-right-symmetric models of CP nonconservation.

PRD 34,833 1986

**SM Prediction of
 Λ decay**

Not sensitive to CPV

Easiest to measure

Polarization of decayed baryon needs to be measured

→ Decay width difference

→ Decay parameter difference

→ Decay parameter difference

Ξ^-, Ξ^0, Ω^- cascade decay

$$\Delta = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \approx \sqrt{2} \frac{T_3}{T_1} \sin \Delta_s \sin \phi_{CP}$$

$$A = \frac{\Gamma \alpha + \bar{\Gamma} \bar{\alpha}}{\Gamma \alpha - \bar{\Gamma} \bar{\alpha}} \approx \tan \Delta_s \tan \phi_{CP}$$

$$B = \frac{\Gamma \beta + \bar{\Gamma} \bar{\beta}}{\Gamma \alpha - \bar{\Gamma} \bar{\alpha}} \approx \tan \phi_{CP}$$

-5.4×10^{-7}

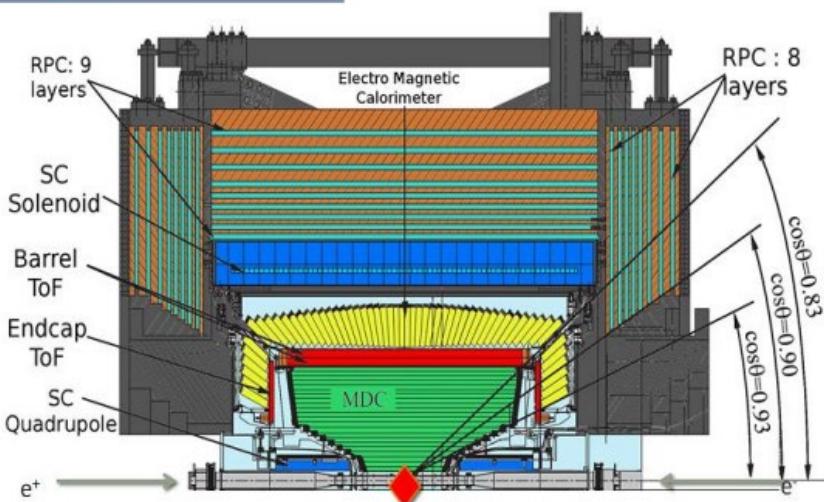
-0.5×10^{-4}

3.0×10^{-3}

Study hyperons at BESIII

Electromagnetic Calorimeter
 CsI(Tl): L=28 cm
 Barrel $\sigma_E = 2.5\%$
 Endcap $\sigma_E = 5.0\%$

Muon Counter
 RPC
 Barrel: 9 layers
 Endcap: 8 layers
 $\sigma_{\text{spatial}} = 1.48 \text{ cm}$

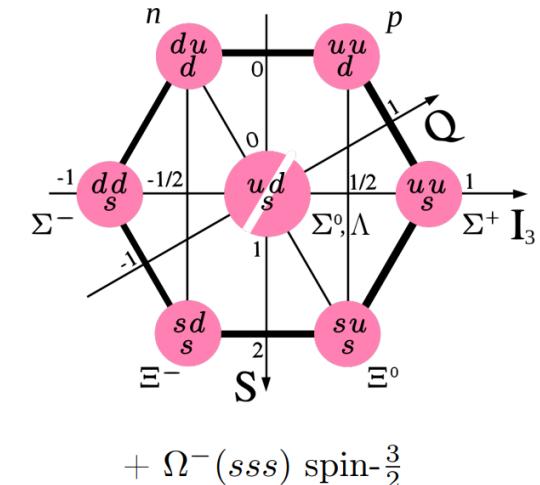


Main Drift Chamber
 Small cell, 43 layer
 $\sigma_{xy} = 130 \mu\text{m}$
 $dE/dx \sim 6\%$
 $\sigma_p/p = 0.5\% \text{ at } 1 \text{ GeV}$

Time Of Flight
 Plastic scintillator
 $\sigma_T(\text{barrel}) = 80 \text{ ps}$
 $\sigma_T(\text{endcap}) = 110 \text{ ps}$
 (update to 65 ps with MRPC)

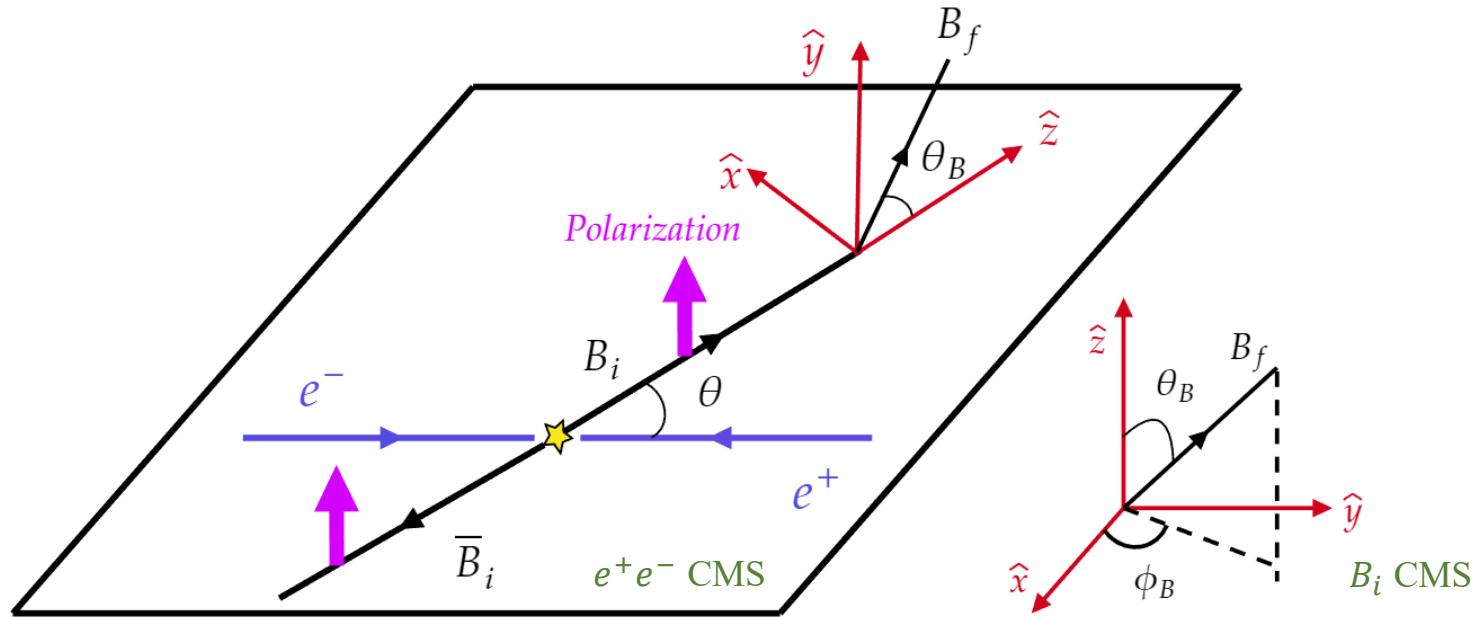
With 10 billion J/ψ and 3 billion $\psi(2S)$ collected at BESIII.

$\sim 10^7$ entangled hyperon pairs can be studied.



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

Polarized hyperon pairs produced in e^+e^- collisions



Polarization:

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

- Angular distribution of $\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_\psi \cos^2 \theta$, $\alpha_\psi \in [-1.0, 1.0]$
- Unpolarized e^+e^- beams \Rightarrow transverse polarized hyperon (if $\Delta\Phi \neq 0$):

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

- Joint amplitude:

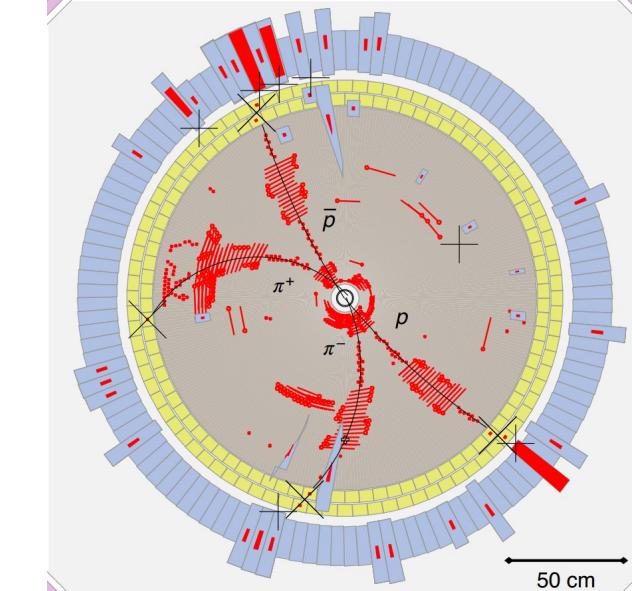
$$M = \frac{ie^2}{q^2} j_\mu \bar{u}(p_1) \left(F_1 \gamma_\mu + \frac{F_2}{2m} p_\nu \sigma^{\nu\mu} \gamma_5 \right) v(p_2)$$

- Differential cross section:

$$d\sigma \sim 1 + \alpha_\psi \cos^2 \theta_\Lambda + (\alpha_\psi + \cos^2 \theta_\Lambda) s_\Lambda^z s_{\bar{\Lambda}}^z +$$

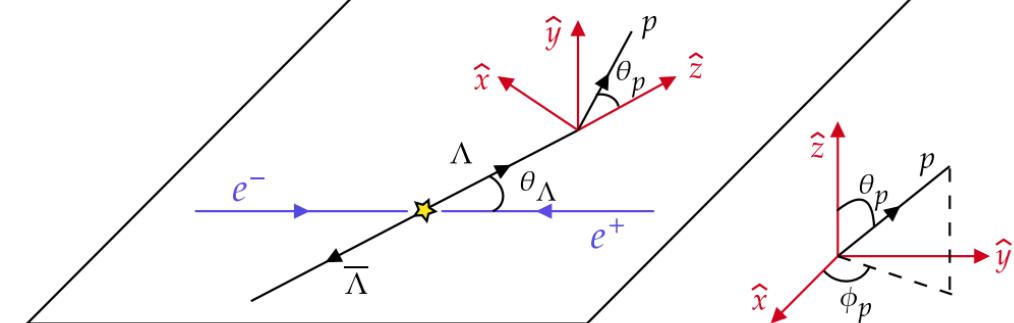
$$\sin^2 \theta_\Lambda s_\Lambda^x s_{\bar{\Lambda}}^x - \alpha_\psi \sin^2 \theta_\Lambda s_\Lambda^y s_{\bar{\Lambda}}^y + \sqrt{1 - \alpha_\psi^2} \cos \Delta\Phi \sin \theta_\Lambda \cos \theta_\Lambda (s_\Lambda^x s_{\bar{\Lambda}}^z +$$

$$s_\Lambda^z s_{\bar{\Lambda}}^x) + \sqrt{1 - \alpha_\psi^2} \sin \Delta\Phi \sin \theta_\Lambda \cos \theta_\Lambda (s_\Lambda^y + s_{\bar{\Lambda}}^y)$$



- The spin vector of Λ is denoted by s_Λ
- Only $\langle s^y \rangle$ could be non-zero, if $\sin \Delta\Phi \neq 0$

Nuovo Cim. A 109, 241 (1996)
 Phys. Rev. D 75, 074026 (2007)
 Nucl. Phys. A 190 771, 169 (2006)
 Phys. Lett. B 772, 16 (2017)



SPIN CORRELATIONS

POLARIZATIONS

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

BESIII has published 2 works based on 1.3 billion and 10 billion J/ψ data sample:

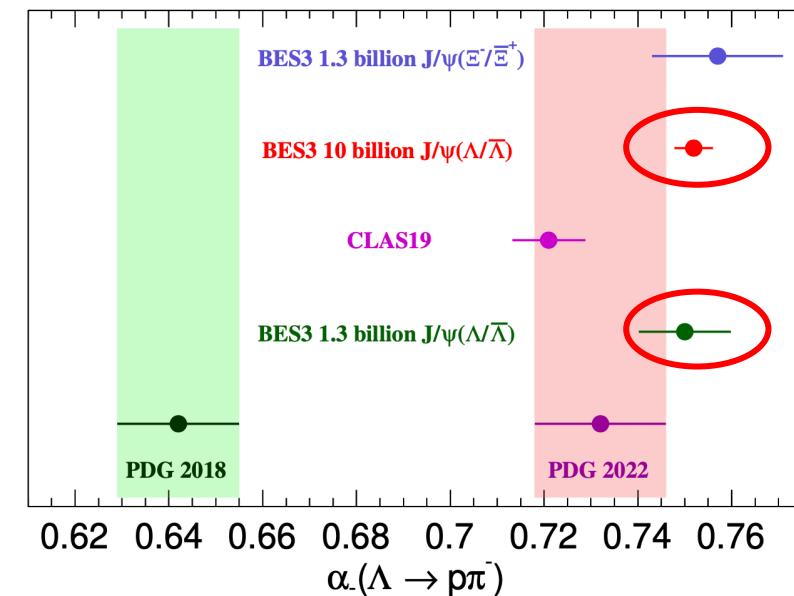
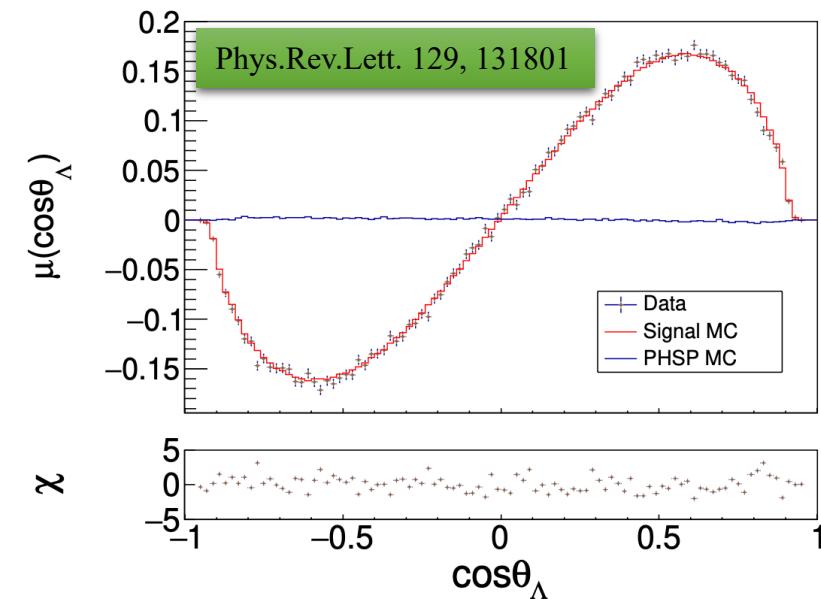
[1] 1.3 billion: Nature Phys. 15(2019)631

[2] 10 billion: Phys.Rev.Lett. 129 (2022) 13, 131801

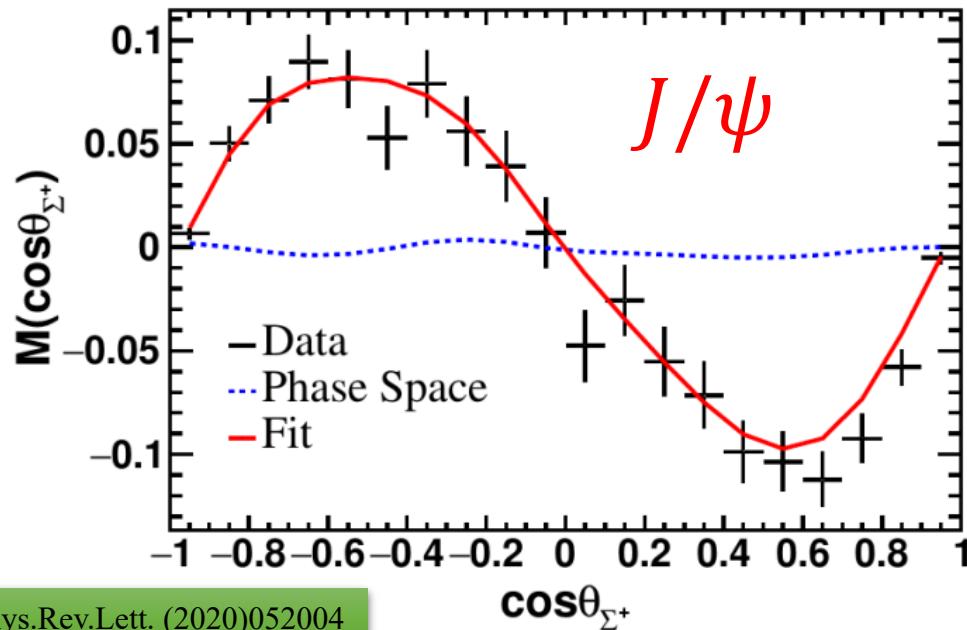
- Most precise values for Λ decay parameter
- One of the most precise CP test in the hyperon sector:

$$A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} = -0.0025 \pm 0.0046 \pm 0.0011$$

Par.	BESIII 10 billion [2]	BESIII 1.3 billion [1]
$\alpha_{J/\psi}$	$0.4748 \pm 0.0022 \pm 0.0031$	$0.461 \pm 0.006 \pm 0.007$
$\Delta\Phi$	$0.7521 \pm 0.0042 \pm 0.0066$	$0.740 \pm 0.010 \pm 0.009$
α_-	$0.7519 \pm 0.0036 \pm 0.0024$	$0.750 \pm 0.009 \pm 0.004$
α_+	$-0.7559 \pm 0.0036 \pm 0.0030$	$-0.758 \pm 0.010 \pm 0.007$
A_{CP}	$-0.0025 \pm 0.0046 \pm 0.0012$	$0.006 \pm 0.012 \pm 0.007$
α_{avg}	$0.7542 \pm 0.0010 \pm 0.0024$	-

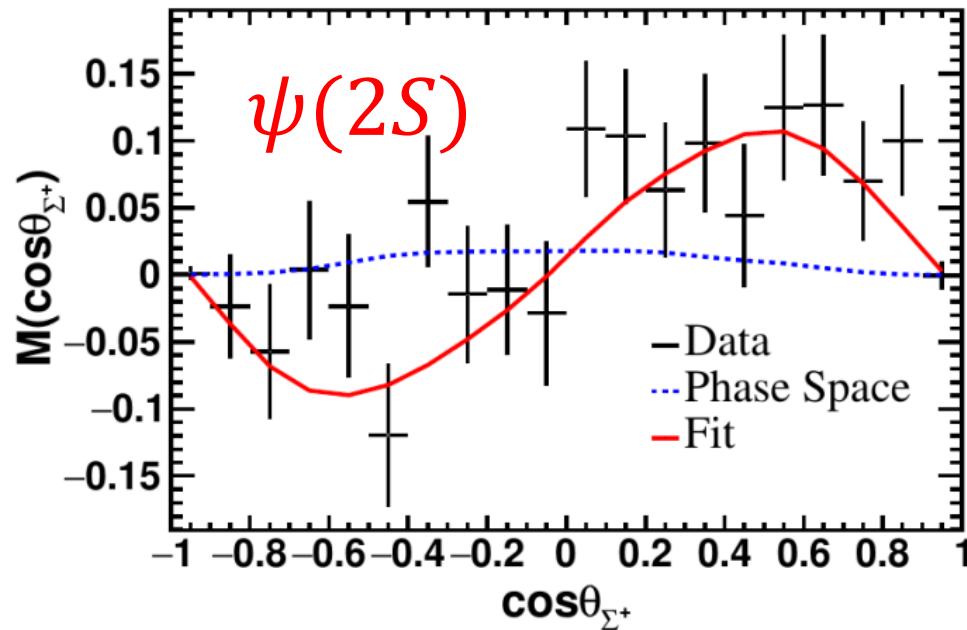


$$e^+ e^- \rightarrow J/\psi, \psi(2S) \rightarrow \Sigma^+ \bar{\Sigma}^-, \Sigma^+ \rightarrow p\pi^0 + c.c.$$



Phys.Rev.Lett. (2020)052004

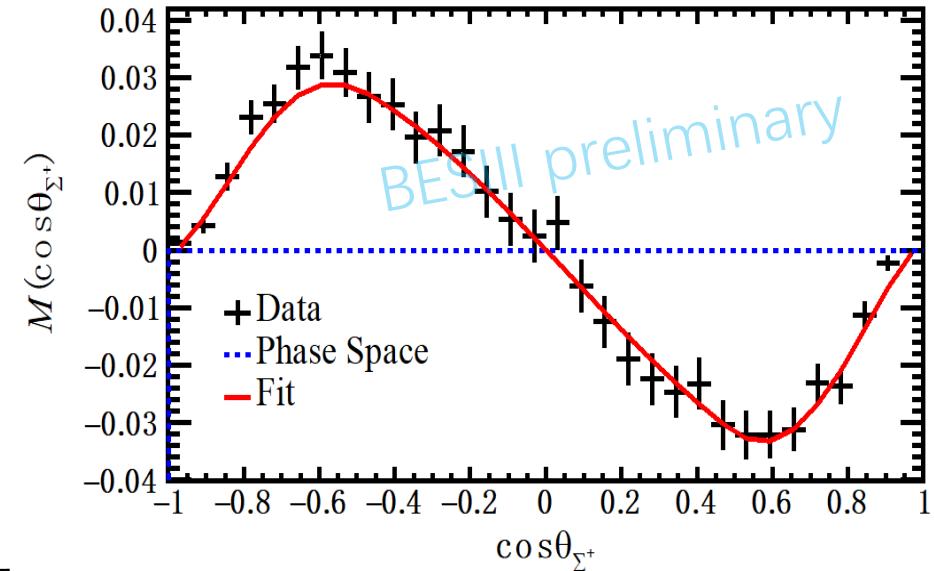
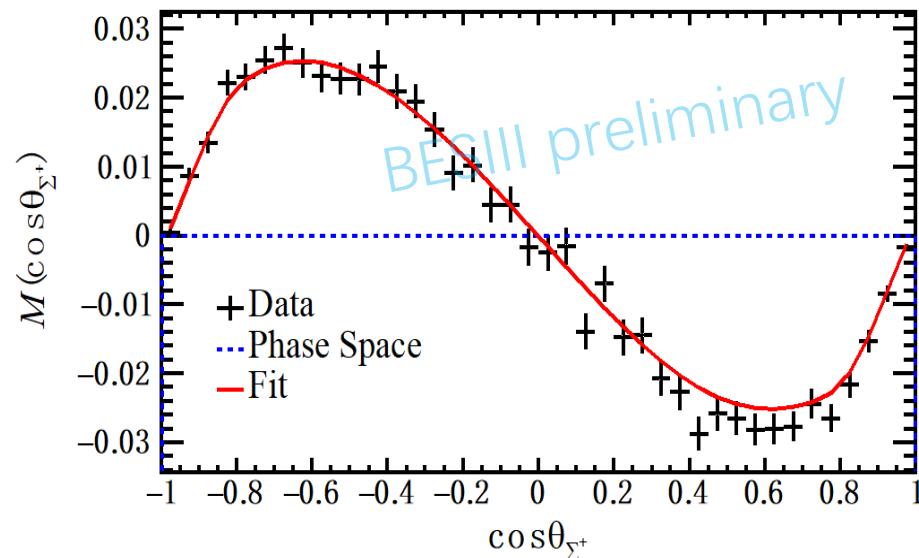
- Data sample: 1.3 billion J/ψ events.
- Final dataset: $87 \cdot 10^3$ events with 5% backgrounds.
- $\alpha_{J/\psi} = -0.508 \pm 0.006_{\text{stat}} \pm 0.004_{\text{syst}}$
- $\Delta\Phi(J/\psi) = (-15.5 \pm 0.7_{\text{stat}} \pm 0.5_{\text{syst}})^\circ$
- $\langle \alpha_\Sigma \rangle = -0.994 \pm 0.004_{\text{stat}} \pm 0.002_{\text{syst}}$
- $A_{CP}^\Sigma = -0.004 \pm 0.037_{\text{stat}} \pm 0.010_{\text{syst}}$



- Data sample: 0.5 billion $\psi(2S)$ events.
- Final dataset: $5 \cdot 10^3$ events with 1% backgrounds.
- $\alpha_{\psi(2S)} = 0.682 \pm 0.030_{\text{stat}} \pm 0.011_{\text{syst}}$
- $\Delta\Phi(\psi(2S)) = (21.7 \pm 4.0_{\text{stat}} \pm 0.8_{\text{syst}})^\circ$

The analysis based on 10 billion J/ψ and 3 billion $\psi(2S)$ are undergoing.

$$e^+ e^- \rightarrow J/\psi \rightarrow \Sigma^+ \bar{\Sigma}^-, \Sigma^+ \rightarrow n\pi^+, \bar{\Sigma}^- \rightarrow \bar{p}\pi^0 + c.c.$$



parameters	This work	Previous result
$\alpha_{J/\psi}$	$-0.516 \pm 0.003 \pm 0.ooo$	$-0.508 \pm 0.006 \pm 0.004$ [1]
$\Delta\Phi_{J/\psi}(\text{rad})$	$-0.277 \pm 0.004 \pm 0.ooo$	$-0.270 \pm 0.012 \pm 0.009$ [1]
$\bar{\alpha}_+$	$-0.057 \pm 0.005 \pm 0.ooo$	-
α_+	$0.048 \pm 0.003 \pm 0.ooo$	0.068 ± 0.013 (PDG)
$\bar{\alpha}_+/\bar{\alpha}_0$	$-0.057 \pm 0.005 \pm 0.ooo$	-
α_+/α_0	$-0.049 \pm 0.003 \pm 0.ooo$	-0.069 ± 0.021 [2]
A_{CP}	$-0.080 \pm 0.052 \pm 0.ooo$	-

Asymmetrical parameter α : $\alpha_+ = \alpha(\Sigma^+ \rightarrow n\pi^+)$, $\alpha_0 = \alpha(\Sigma^+ \rightarrow p\pi^0)$
 Asymmetrical parameter $\bar{\alpha}$: $\bar{\alpha}_+ = \alpha(\bar{\Sigma}^- \rightarrow \bar{n}\pi^-)$, $\bar{\alpha}_0 = \alpha(\bar{\Sigma}^- \rightarrow \bar{p}\pi^0)$

With 10 billion J/ψ data sample:

- First measurement of the decay parameter of $\bar{\Sigma}^- \rightarrow \bar{n}\pi^-$
- **First time to probe CP violation in the final neutron state for all hyperon decays**

The value of systematic uncertainties (display in xxx form) are under internal review, but they are comparable with statistical uncertainties.

[1] Phys. Rev. Lett. 125, 052004(2020)

[2] Phys. Rev. D 21, 2501 (1980)

$$e^+ e^- \rightarrow J/\psi \rightarrow \Xi^- \bar{\Xi}^+, \Xi^- \rightarrow \Lambda(\rightarrow p\pi^-)\pi^- + c.c.$$

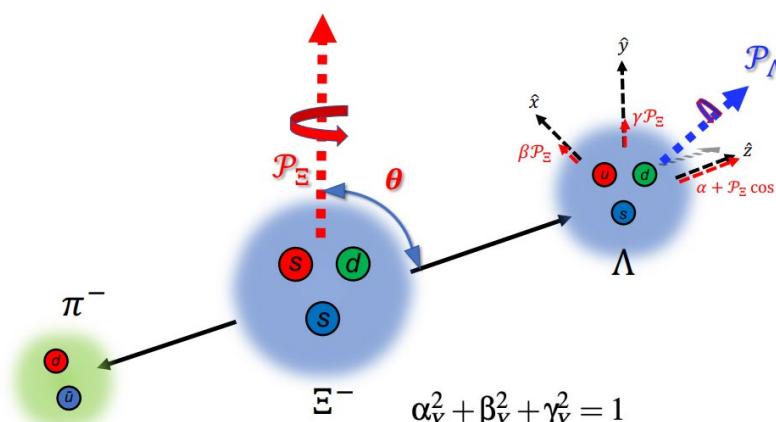
- For the sequential weak decays, the formula of sequential decays is:

$$\mathcal{W}(\xi, \omega) = \sum_{\mu, \bar{\nu}=0}^3 C_{\mu \bar{\nu}} \sum_{\mu', \bar{\nu}'=0}^3 a_{\mu \mu'}^{B_1} a_{\bar{\nu} \bar{\nu}'}^{\bar{B}_1} a_{\mu' 0}^{B_2} a_{\bar{\nu}' 0}^{\bar{B}_2}$$

PRD99(2019)056008
PRD100(2019)114005

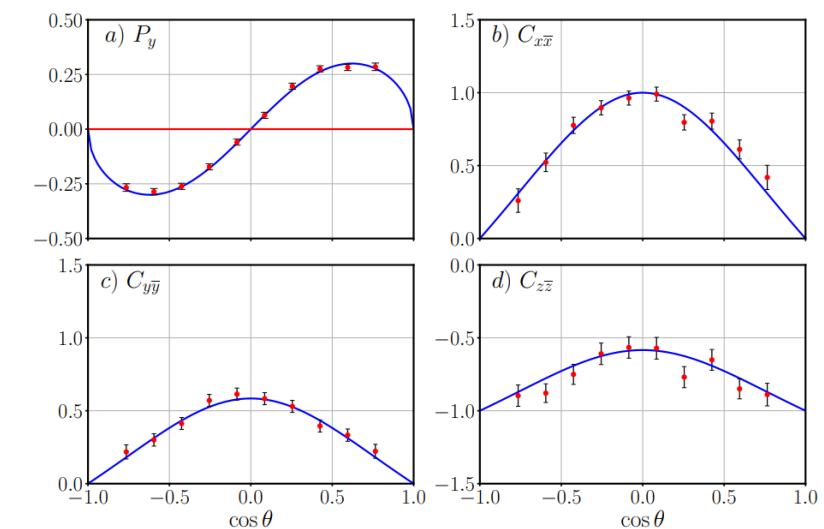
- Angular distribution $d\Gamma \propto W(\xi, \omega)$

- ξ : 9 kinematic variables, denoted by 9 helicity angles
- $\omega = (\alpha_\psi, \Delta\Phi, \alpha_\Xi, \alpha_{\bar{\Xi}}, \phi_\Xi, \phi_{\bar{\Xi}}, \alpha_\Lambda, \alpha_{\bar{\Lambda}})$: 8 free parameters
first measurement



2022/12/1 $\beta_Y = \sqrt{1 - \alpha_Y^2} \sin \phi_Y, \quad \gamma_Y = \sqrt{1 - \alpha_Y^2} \cos \phi_Y$

More parameters in sequential decay!



- Data sample: 1.3 billion J/ψ events.
- Final dataset: $73.2 \cdot 10^3$ events with 199 backgrounds.

$$e^+ e^- \rightarrow J/\psi \rightarrow \Xi^- \bar{\Xi}^+, \Xi^- \rightarrow \Lambda(\rightarrow p\pi^-)\pi^- + c.c.$$

Nature 606 (2022) 7912, 64-69

Parameter	This work	Previous result
a_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016 \text{ rad}$	-
a_{Ξ}	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010
ϕ_{Ξ}	$0.011 \pm 0.019 \pm 0.009 \text{ rad}$	$-0.037 \pm 0.014 \text{ rad}$
\bar{a}_{Ξ}	$0.371 \pm 0.007 \pm 0.002$	-
$\bar{\phi}_{\Xi}$	$-0.021 \pm 0.019 \pm 0.007 \text{ rad}$	-
a_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$
\bar{a}_Λ	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$
$\xi_p - \xi_s$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2} \text{ rad}$	-
$\delta_p - \delta_s$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2} \text{ rad}$	$(10.2 \pm 3.9) \times 10^{-2} \text{ rad}$
A_{CP}^Ξ	$(6 \pm 13 \pm 6) \times 10^{-3}$	-
$\Delta\phi_{CP}^\Xi$	$(-5 \pm 14 \pm 3) \times 10^{-3} \text{ rad}$	-
A_{CP}^Λ	$(-4 \pm 12 \pm 9) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007 \text{ rad}$	

First measurement of the Ξ^- polarization in J/ψ decay

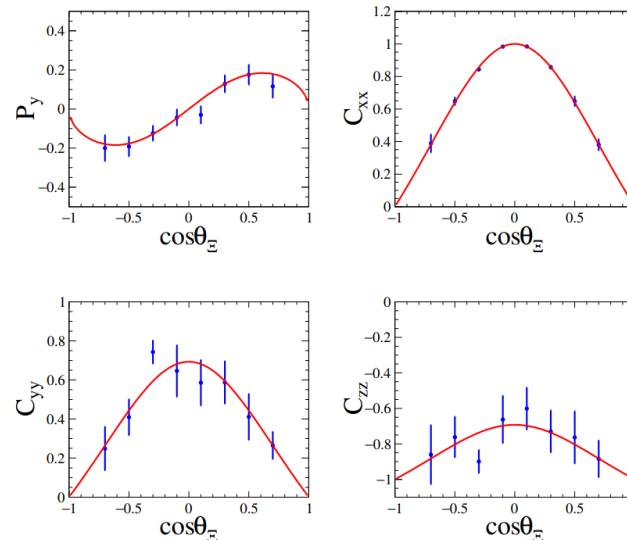
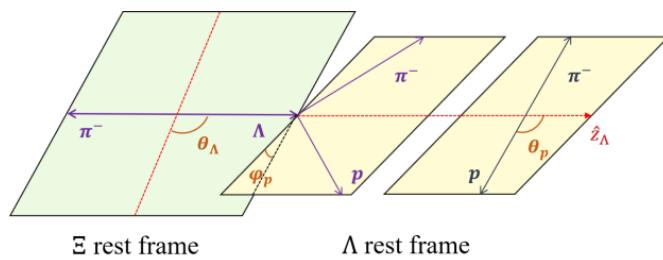
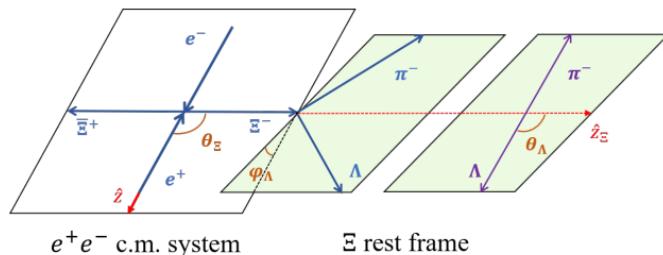
First direct and simultaneously measurement of the charged Ξ decay parameters

Independent measurement of Λ decay parameters

First measurement of weak phase difference in Ξ decay

Three independent CP tests

$$e^+ e^- \rightarrow \psi(2S) \rightarrow \Xi^- \bar{\Xi}^+, \Xi^- \rightarrow \Lambda(\rightarrow p\pi^-)\pi^- + c.c.$$



An independent measurement

arXiv:2206.10900
Accepted by Phy. Rev. D (Letter)

Parameter	$\psi(3686) \rightarrow \Xi^- \bar{\Xi}^+$	$J/\psi \rightarrow \Xi^- \bar{\Xi}^+$
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)	$-0.123 \pm 0.073 \pm 0.004$	$-0.021 \pm 0.019 \pm 0.007$
$\delta_p - \delta_s$ (10^{-2} rad)	$-19.5 \pm 13.4 \pm 0.7$	$-4.0 \pm 3.3 \pm 1.7$
$A_{CP,\Xi}$ (10^{-3})	$-14.7 \pm 50.8 \pm 10.3$	$6.0 \pm 13.4 \pm 5.6$
$\Delta\phi_{CP}$ (10^{-3} rad)	$-49.9 \pm 52.1 \pm 2.6$	$-4.8 \pm 13.7 \pm 2.9$

- Data sample: 0.5 billion $\psi(2S)$ events.
- Final dataset: $5 \cdot 10^3$ events with 15 backgrounds.

The results are consistent with that from J/ψ decay

Hyperon physics at Super Tau-Charm Facility (STCF)

BESII: 58 million



BESIII collected 10 billion J/ψ



$10^{12} J/\psi$ per year at a super J/ψ factory

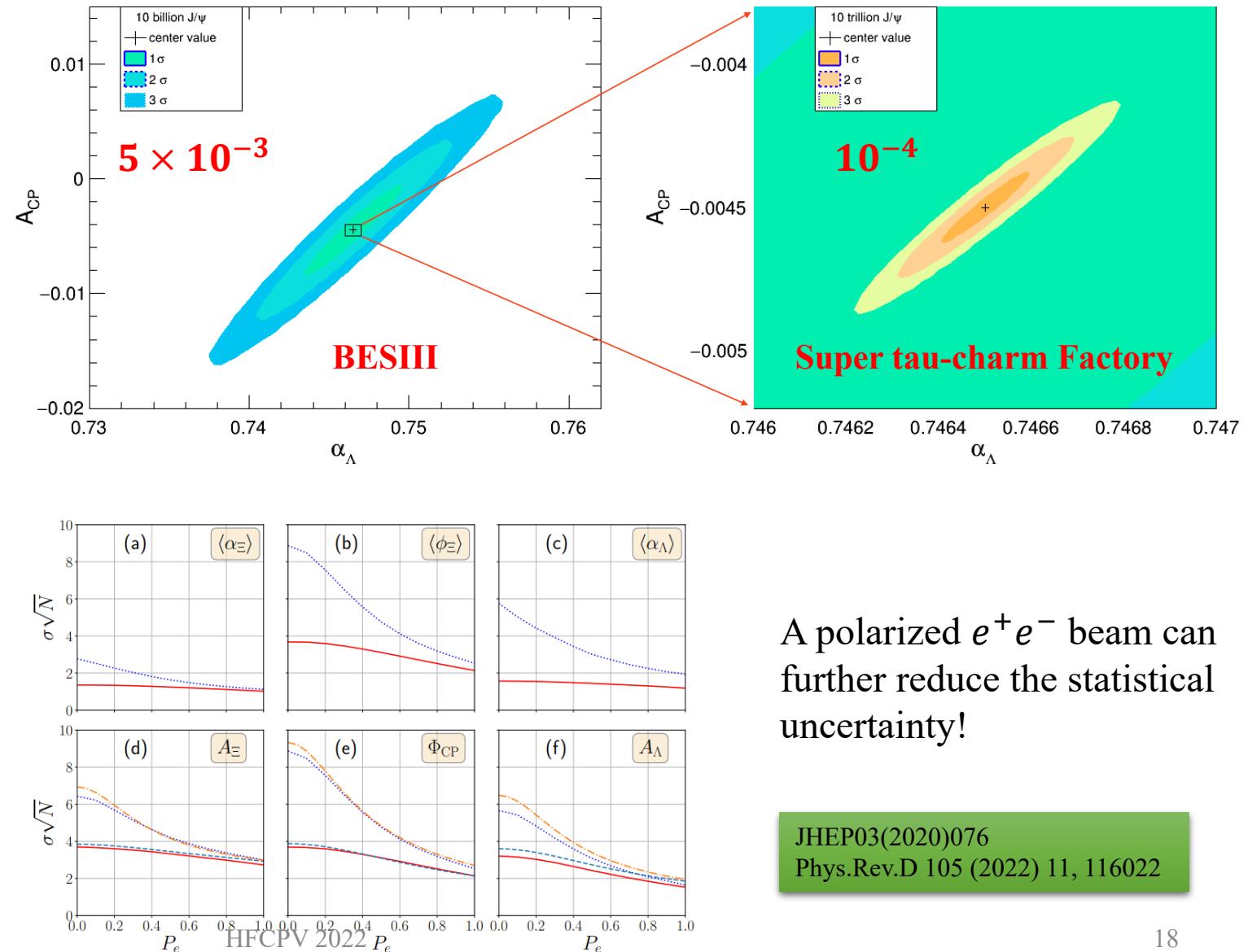


10 Billions of hyperon pairs produced

Billion of hyperon pairs reconstructed

CPV: $10^{-4} - 10^{-5}$

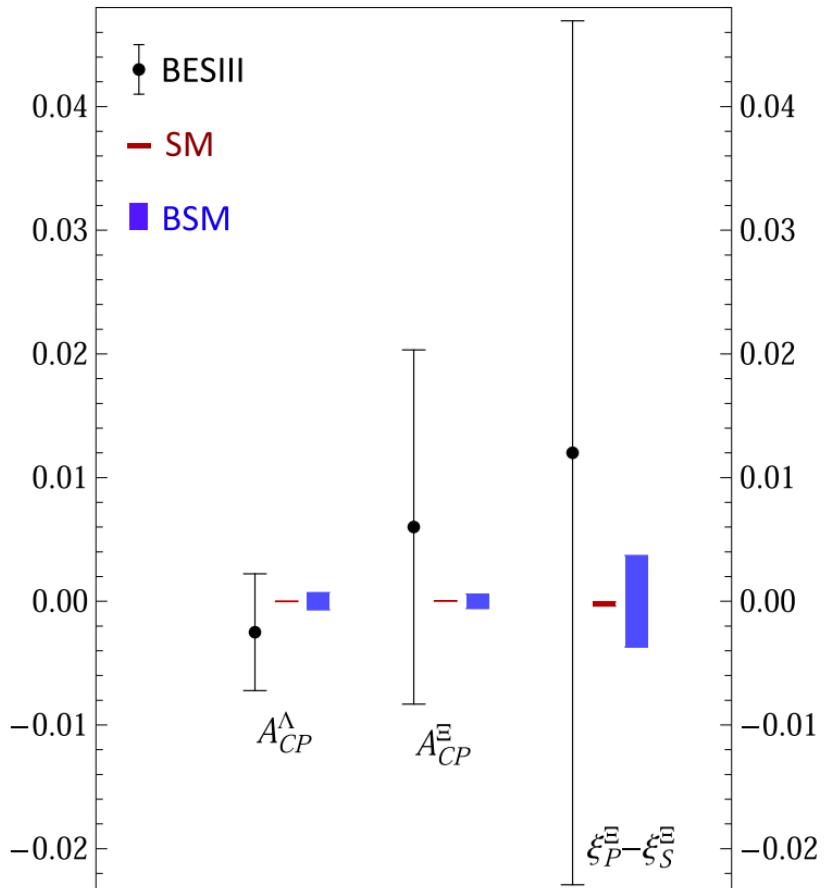
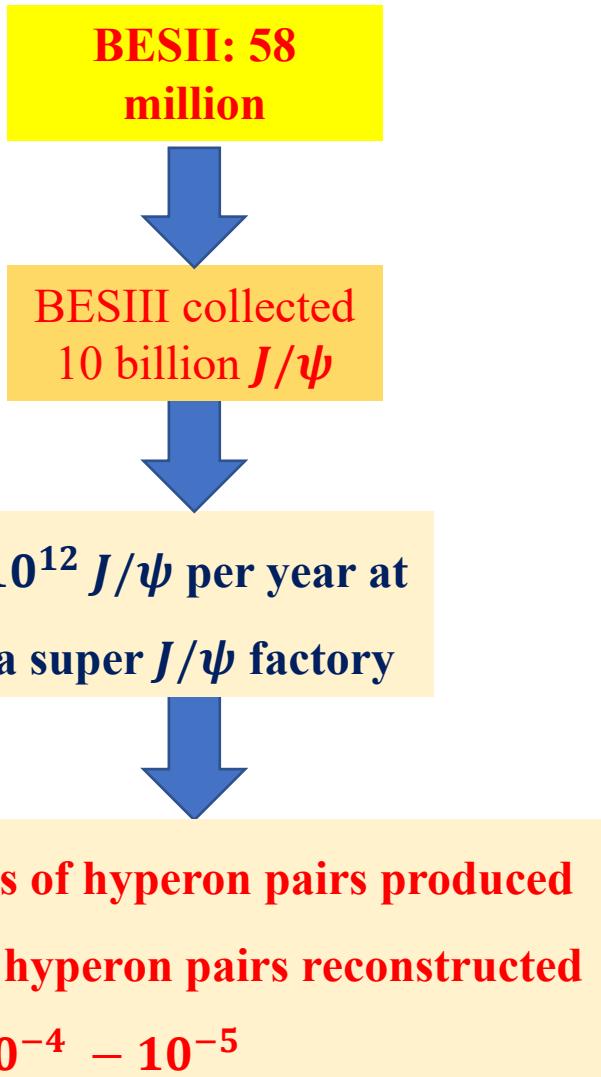
Challenge the SM



A polarized $e^+ e^-$ beam can further reduce the statistical uncertainty!

JHEP03(2020)076
Phys.Rev.D 105 (2022) 11, 116022

Hyperon physics at Super Tau-Charm Facility (STCF)



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

Prob new physics
Constrain BSM

Summary and Outlooks

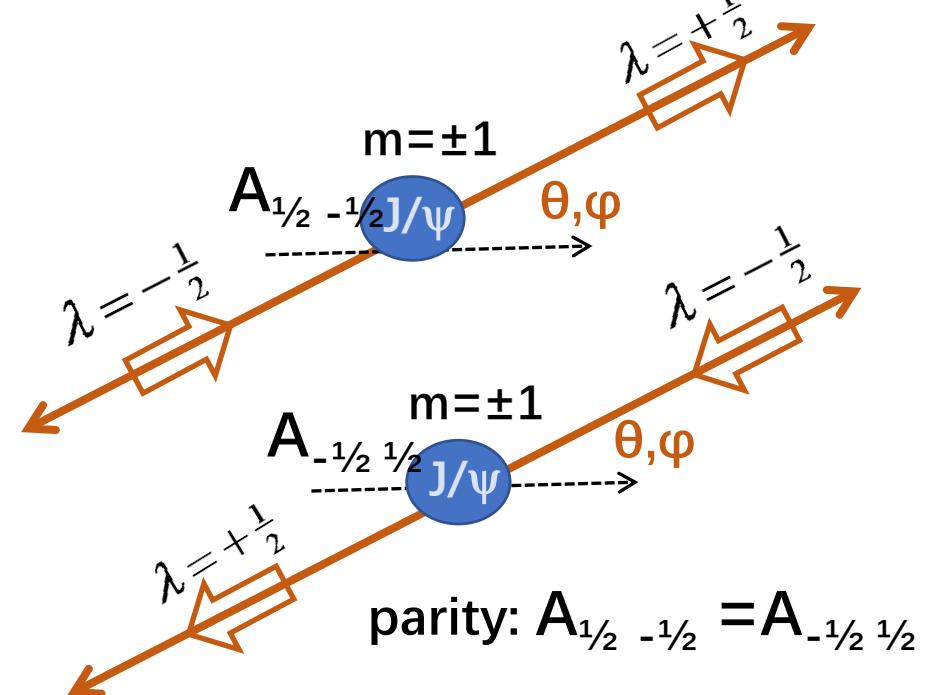
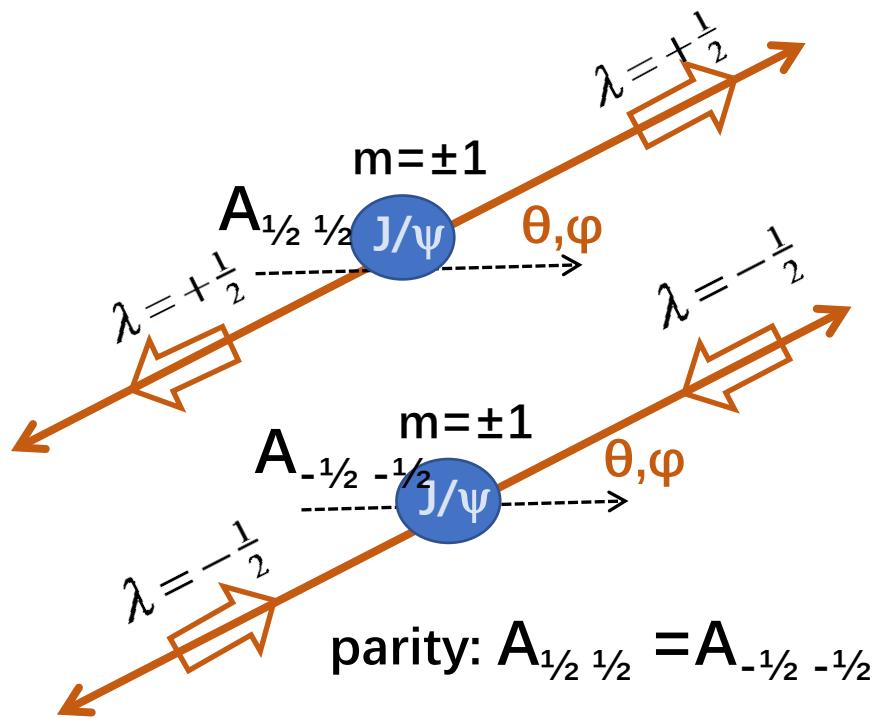
- Hyperon polarization in J/ψ , $\psi(2S)$ decays → new way to study *CPV*
 - complementary to CPV studies with Kaons
 - BESIII has already rewritten the PDG book for Λ and Ξ decays
 - Results of Σ^\pm, Ξ with 10 billion J/ψ will be coming soon
- Hyperon physics at STCF: next new frontier for CPV studies!
 - At least **10^{12}** J/ψ per year at a super J/ψ factory
 - **Polarized** electron beam can be used
 - Statistical uncertainty of CPV will be comparable to the SM predictions

Thank you!

Backup

$$e^+e^- \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}$$

Production: 2 independent helicity amplitudes: $A_{1/2 \ 1/2}, A_{1/2 \ -1/2}$



$\Delta\Phi = \text{complex phase between } A_{1/2 \ 1/2} \text{ and }$

$A_{1/2 \ -1/2}$

$$\frac{d|\mathcal{M}|^2}{d \cos \theta} \propto (1 + \alpha_{J/\psi} \cos^2 \theta), \quad \text{with} \quad \alpha_{J/\psi} = \frac{|A_{1/2,-1/2}|^2 - 2|A_{1/2,1/2}|^2}{|A_{1/2,-1/2}|^2 + 2|A_{1/2,1/2}|^2}$$

EM form-factors and Helicity Amplitudes

Phys.Rev.D99,056008

$$h_2 \equiv A_{1/2,-1/2} = A_{-1/2,1/2} = \sqrt{1 + \alpha_\psi} e^{-i\Delta\Phi}$$

$$h_1 \equiv A_{1/2,1/2} = A_{-1/2,-1/2} = \sqrt{1 - \alpha_\psi} / \sqrt{2}$$

Phys.Lett.B772,16

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

$$\frac{G_E}{G_M} = e^{i\Delta\Phi} \left| \frac{G_E}{G_M} \right|$$

where s is the square of $p_B + p_{\bar{B}}$ and M is the mass of $B(\bar{B})$.

Relation:

$$h_2 = \frac{\sqrt{2s}}{\sqrt{s|G_M|^2 + 4M^2|G_E|^2}} G_M$$

$$h_1 = \frac{2M}{\sqrt{s|G_M|^2 + 4M^2|G_E|^2}} G_E$$

CPV observables in $\Xi^- \rightarrow \Lambda\pi$ decay

decay rate difference

$$\frac{\Gamma_{\bar{\Lambda}\pi^+} - \Gamma_{\Lambda\pi^-}}{\Gamma} \equiv 0$$

← $\Lambda\pi$ final states are purely Ispin=1, only $\Delta l=1/2$ transitions
allowed, no $\Delta l=3/2$ transition possible

decay asymmetry difference

$$\alpha_0 = \pm \frac{2 \operatorname{Re}(S * P)}{|S|^2 + |P|^2} = \pm \frac{2|S||P|\cos(\Delta_s \pm \phi_{CP})}{|S|^2 + |P|^2}$$

$$\frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+} = \frac{\sin \Delta_s \sin \phi_{CP}}{\cos \Delta_s \cos \phi_{CP}} = \tan \Delta_s \tan \phi_{CP}$$

← in this case, the strong phase ($\Delta_s = \delta_S - \delta_P$) is measureable (see below)

final-state polarization difference

$$\beta_0 = \pm \frac{2 \operatorname{Im}(S * P)}{|S|^2 + |P|^2} = \pm \frac{2|S||P|\sin(\Delta_s \pm \phi_{CP})}{|S|^2 + |P|^2}$$

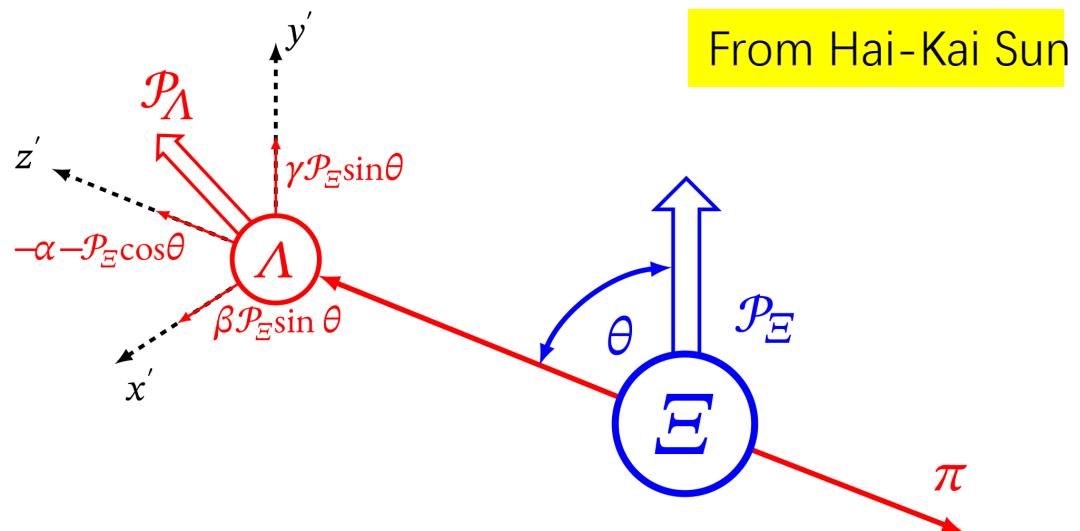
$$\frac{\beta_- + \beta_+}{\alpha_- - \alpha_+} = \frac{\cos \Delta_s \sin \phi_{CP}}{\cos \Delta_s \cos \phi_{CP}} = \tan \phi_{CP}$$

$$\frac{\beta_- - \beta_+}{\alpha_- - \alpha_+} = \frac{\sin \Delta_s \cos \phi_{CP}}{\cos \Delta_s \cos \phi_{CP}} = \tan \Delta_s$$

← Strong phase cancels out

← measures the strong phase

big advantage for Ξ over Λ



From Hai-Kai Sun

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

$$\beta = \sqrt{1 - \alpha^2} \sin \phi_{\Xi}$$

$$\gamma = \sqrt{1 - \alpha^2} \cos \phi_{\Xi}$$

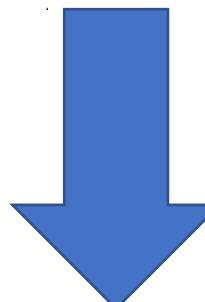
$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

$$\tan \phi_{\Xi} = \frac{\beta}{\gamma}$$

Both α and ϕ_{Ξ} of $\Xi(\bar{\Xi})$ can be measured via $J/\psi \rightarrow \Xi\bar{\Xi}$ at BESIII!

$$\alpha_{\mp} = \pm \frac{2\text{Re}(S^* \cdot P)}{|S|^2 + |P|^2} = \pm \frac{|S||P| \cos(\Delta_s \pm \Delta_w)}{|S|^2 + |P|^2}$$

$$\beta_{\mp} = \pm \frac{2\text{Im}(S^* \cdot P)}{|S|^2 + |P|^2} = \pm \frac{|S||P| \sin(\Delta_s \pm \Delta_w)}{|S|^2 + |P|^2}$$



Sandip PAKVASA



X.G. He

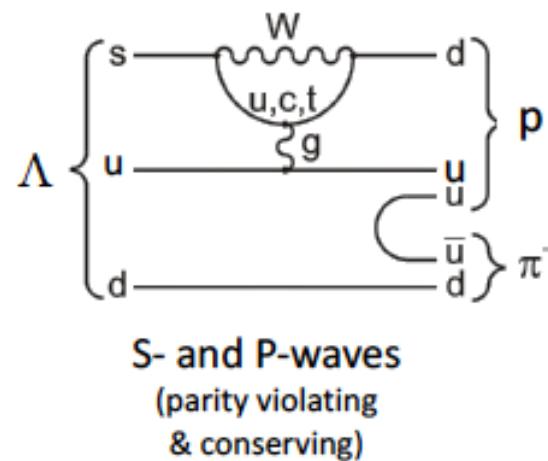


John Donoghue

$$\frac{\beta_- - \beta_+}{\alpha_- - \alpha_+} = \frac{\sin \Delta_s \cos \Delta_w}{\cos \Delta_s \cos \Delta_w} = \tan \Delta_s$$

$$\frac{\beta_- + \beta_+}{\alpha_- - \alpha_+} = \frac{\cos \Delta_s \sin \Delta_w}{\cos \Delta_s \cos \Delta_w} = \tan \Delta_w$$

Constraints from Kaon decays

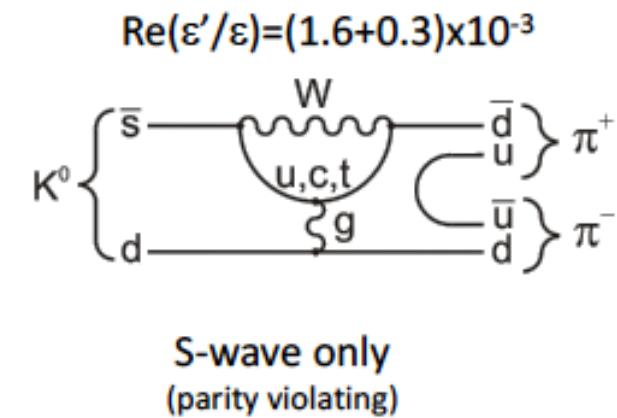


He & Valencia PRD 52, 5257

$\Lambda \rightarrow p\pi^-$	A_{NP}
S-wave	$< 6 \times 10^{-5}$
P-wave	$< 3 \times 10^{-4}$

parity violating
parity conserving

$$A_{SM} \sim 10^{-5}$$



CPV measurement in Kaon system strongly constrains NP in S-waves, but no P-waves.

Thus, searches of CPV in hyperon are complementary to those with Kaons.