Search for CP violation with spin entangled hyperon-antihyperon pairs at BESIII

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(On behalf of the BESIII collaboration)

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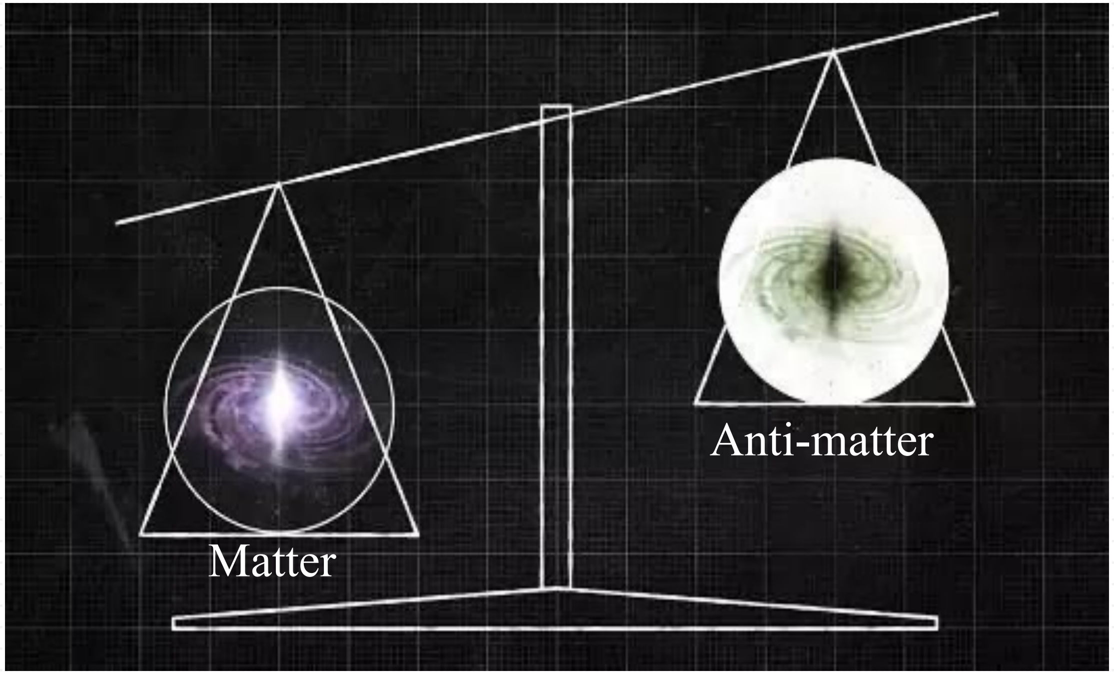
26th International Symposium on Spin Physics

A Century of Spin

Mystery of matter-antimatter asymmetry



- According to the Big Bang theory:
  - Matter and antimatter have the same amount
- The observed universe is matter dominant:

$$(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$$

Lect. Notes Phys. 591 (2002) 237-293

- The standard model predicted value：

$$(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-18}$$

- Why has the antimatter disappeared?

- Sakharov’s three conditions：
  - Baryon number violation
  - C and CP violation
  - Thermal non-equilibrium

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

Roadmap of CP violation in flavored hadrons

- **All of them are consistent with CKM theory in the Standard Model, but too small to explain the matter-dominant world.**
- **21 Mar 2025, first observation of CPV in Λ_b baryon decays.**

LHCb: 5.2σ CPV in Λ_b decay:

$$\Lambda_b \to p\pi^+\pi^-K^-$$

Nature volume 643, pages1223–1228 (2025)

K meson CPV — 1964

B meson CPV — 2001

D meson CPV — 2019

Baryon: Λ_b

What about hyperon?

James Watson Cronin

Val Logsdon Fitch

[1] Phys. Rev. 104 (1956) 254-258
[2] Phys. Rev. 105 (1957) 1413-1414
[3] Phys. Rev. Lett., 1964, 13: 138-140
[4] Phys. Rev. Lett., 2001, 87: 091801
[5] Phys. Rev. Lett., 2001, 87: 091802
[6] Phys. Rev. Lett., **122**, 211803 (2019)

Two conditions for a measurable CP violation

1) a $\mathcal{CP}$-violating phase:

ordinary phases in QM

matter — **antimatter**

δ — δ

same sign

$\mathcal{CP}$ violating phases

matter — **antimatter**

ξ — $-\xi$

opposite sign

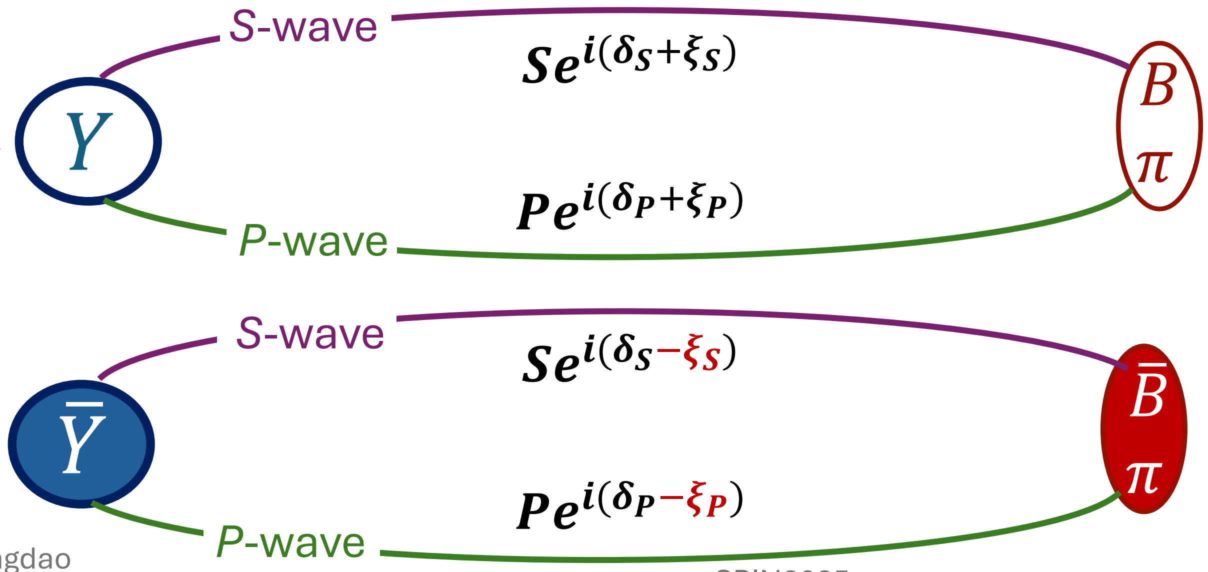
If only have one path:

$$\left|Ae^{i(\delta+\xi)}\right|^2 = A^2$$

The CPV phase vanishes in the probability density.

2) two or more interfering paths to the same final state

Spin-1/2 hyperon



Spin-1/2 baryon

Suitable for CPV searches!

Non-leptonic hyperon decays


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-1/2 hyperon B_i decay to a spin-1/2 baryon B_f and a π can be completely described by three decay parameters:

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

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

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

CP convervation: $\alpha_Y = -\bar{\alpha}_Y, \beta_Y = -\bar{\beta}_Y, \phi_Y = -\bar{\phi}_Y$

CP observables 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

strong phase — CPV phase

Not sensitive to CPV

Decay width difference $\Delta_{CP} = \frac{\Gamma-\bar{\Gamma}}{\Gamma+\bar{\Gamma}} \approx \sqrt{2}\frac{T_{\frac{3}{2}}}{T_{\frac{1}{2}}}\sin(\delta_P-\delta_S)\sin(\xi_P-\xi_S)$ — -5.4×10^{-7}

Easiest to measure

Decay parameter difference $A_{CP} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} \approx \tan(\delta_P-\delta_S)\,tan(\xi_P-\xi_S)$ — -0.5×10^{-4}

Polarization of the final-state baryon needs to be measured

Decay parameter difference $B_{CP} = \frac{\beta+\bar{\beta}}{\alpha-\bar{\alpha}} \approx tan(\xi_P-\xi_S)$ — 3.0×10^{-3}

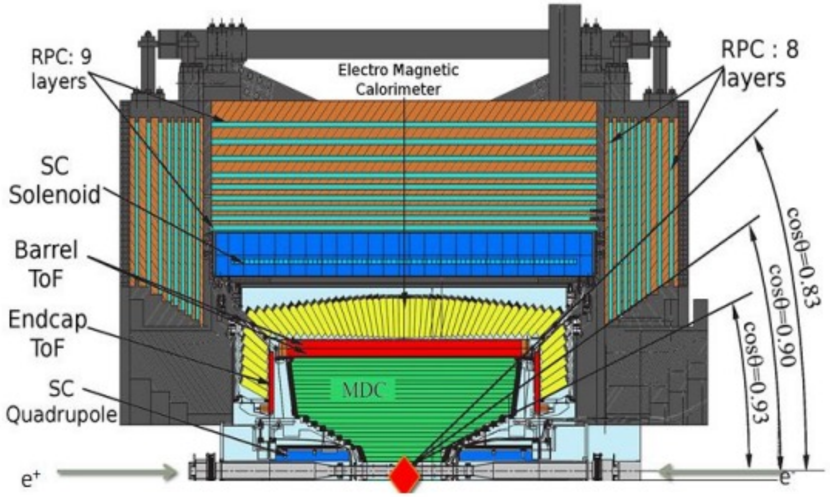
Ξ^-, Ξ^0, Ω^- cascade decay

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

Study hyperons at 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



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)

With 10 billion J/ψ and 2.7 billion $\psi(3686)$ collected at BESIII, $\sim 10^7$ spin-entangled hyperon pairs can be produced, which enables precise studies of the hyperon physics.

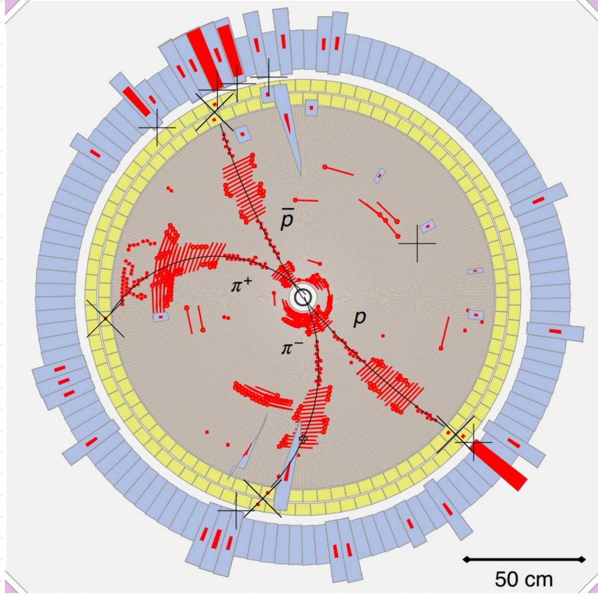
Front. Phys. 12(5), 121301 (2017)

Decay mode	$B(\times 10^{-3})$	$N_B(\times 10^6)$
$J/\psi \to \Lambda\bar{\Lambda}$	1.89 ± 0.09	~18.9
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.172 ± 0.032	~11.7
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.07 ± 0.04	~10.7
$J/\psi \to \Xi^0\bar{\Xi}^0$	1.17 ± 0.04	~11.7
$J/\psi \to \Xi^-\bar{\Xi}^+$	0.97 ± 0.08	~9.7
$\psi(2S) \to \Omega^-\bar{\Omega}^+$	0.057 ± 0.003	~0.17

More $\psi(3686)$ data will be taken after the upgrade of BEPCII and BESIII inner tracker.

A hyperon factory

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



Differential cross-section of this process:

$$\mathcal{W}(\xi) = \mathcal{F}_0(\xi) + \alpha_{J/\psi}\mathcal{F}_5(\xi) + \alpha_-\alpha_+ \times \left[\mathcal{F}_1(\xi) + \sqrt{1-\alpha_{J/\psi}^2}\cos(\Delta\Phi)\mathcal{F}_2(\xi) + \alpha_{J/\psi}\mathcal{F}_6(\xi)\right] + \sqrt{1-\alpha_{J/\psi}^2}\sin(\Delta\Phi)[\alpha_-\mathcal{F}_3(\xi) + \alpha_+\mathcal{F}_4(\xi)] \quad (1)$$

spin-correlation

polarization

$\alpha_-: \Lambda \to p\pi^-$
$\alpha_+: \bar{\Lambda} \to \bar{p}\pi^+$

If $\sin\Delta\Phi \neq 0$, Λ is transverse polarized.

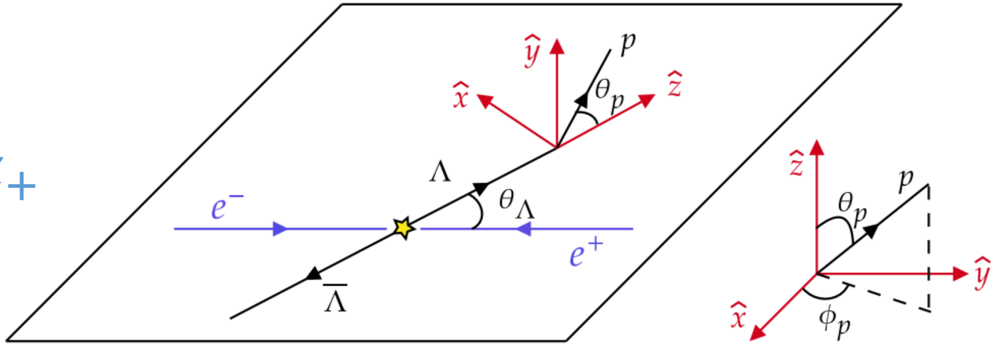
↓

Simultaneous measurement of α_-, α_+

↓

Test CP symmetry

Nuovo Cim. A 109, 241 (1996)
Phys. Rev.185 D 75, 074026 (2007)
Nucl. Phys. A190 771, 169 (2006)
Phys. Lett. B 772, 16(2017)



Search for CPV in Λ decay

Two BESIII papers have been published:

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

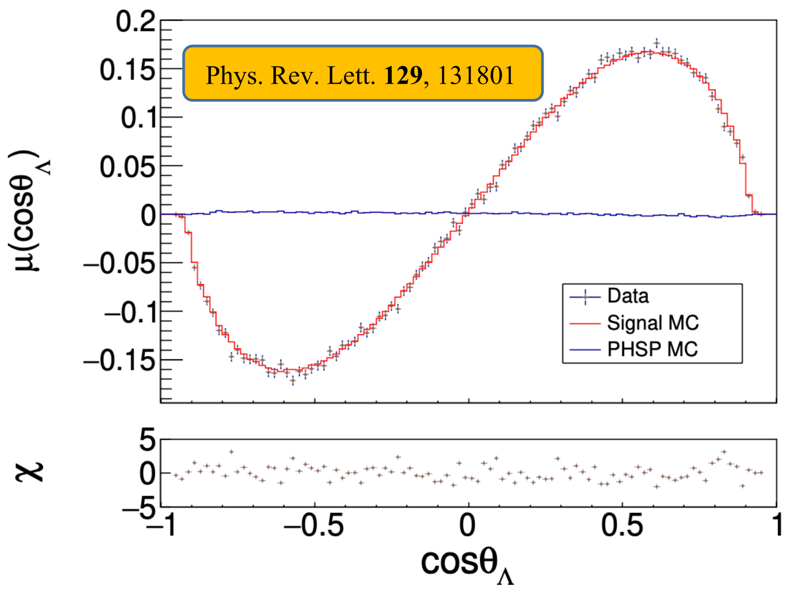
[2] 10 billion: Phys. Rev. Lett. 129 (2022) 13, 131801

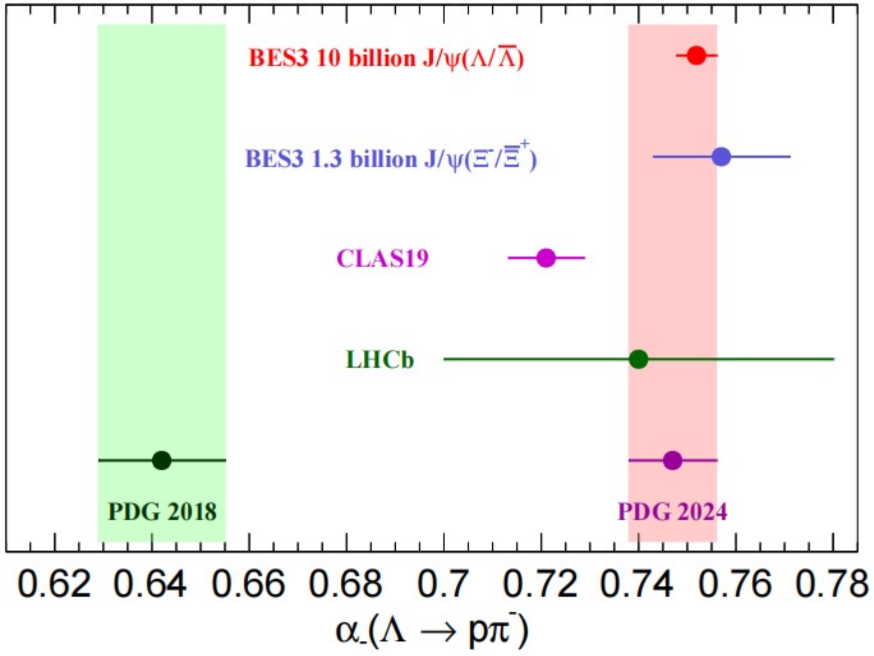
Par.	Newest BESIII results
$\alpha_{J/\psi}$	$0.4748 \pm 0.0022 \pm 0.0031$
$\Delta\Phi$	$0.7521 \pm 0.0042 \pm 0.0066$
α_-	$0.7519 \pm 0.0036 \pm 0.0024$
α_+	$-0.7559 \pm 0.0036 \pm 0.0030$
A_{CP}	$-0.0025 \pm 0.0046 \pm 0.0012$
α_{avg}	$0.7542 \pm 0.0010 \pm 0.0024$

3.2 M $\Lambda\bar{\Lambda}$ pairs were reconstructed.

- Most precise measurement of Λ decay parameter
- Most precise A_{CP} measurement in hyperon decay:

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





Search for CPV in Σ^+ decay

$$e^+e^- \to J/\psi, \psi(3686) \to \Sigma^+\bar{\Sigma}^-,\ \Sigma^+ \to p\pi^0,\ \bar{\Sigma}^+ \to \bar{p}\pi^0$$

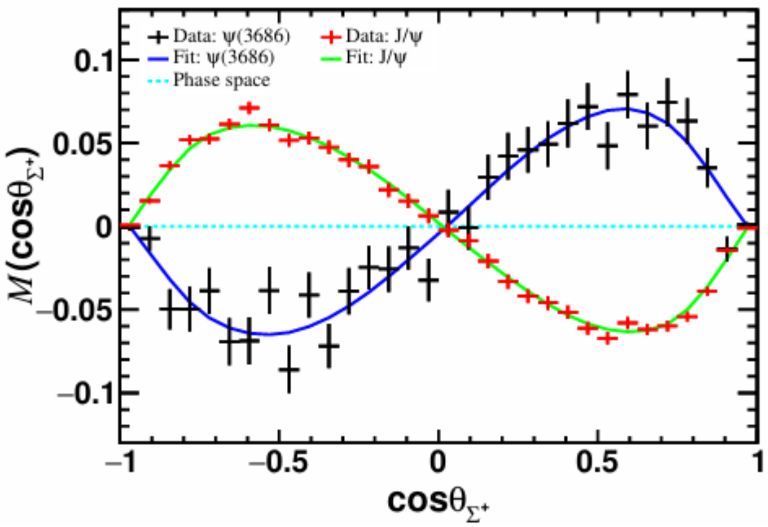
10B J/ψ and 2.7B $\psi(3686)$ ~1 M $\Sigma^+\bar{\Sigma}^-$ pairs reconstructed

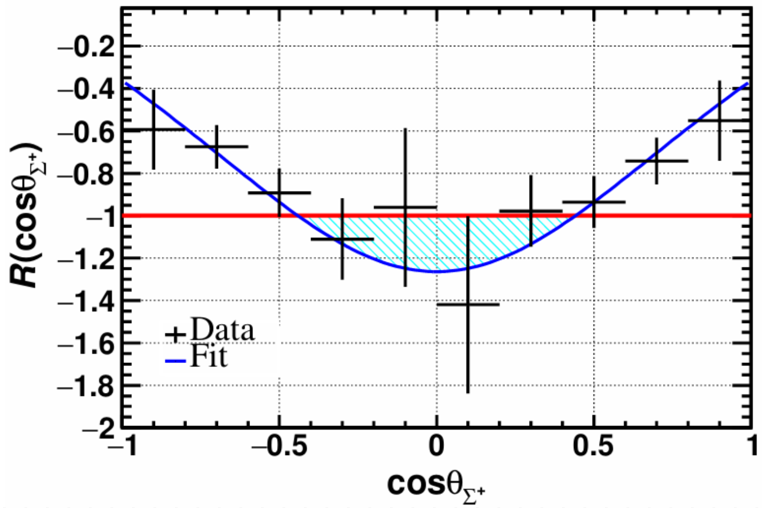
Parameter	This Letter	Phys. Rev. Lett. 131, 191802 (2023)
$\alpha_{J/\psi}$	$-0.5047 \pm 0.0018 \pm 0.0010$	$-0.508 \pm 0.006 \pm 0.004$
$\Delta\Phi_{J/\psi}$	$-0.2744 \pm 0.0033 \pm 0.0010$	$-0.270 \pm 0.012 \pm 0.009$
α_0	$-0.975 \pm 0.011 \pm 0.002$	$-0.998 \pm 0.037 \pm 0.009$
$\bar{\alpha}_0$	$0.999 \pm 0.011 \pm 0.004$	$0.990 \pm 0.037 \pm 0.011$
$\alpha_{\psi(3686)}$	$0.7133 \pm 0.0094 \pm 0.0065$	$0.682 \pm 0.030 \pm 0.011$
$\Delta\Phi_{\psi(3686)}$	$0.427 \pm 0.022 \pm 0.003$	$0.379 \pm 0.070 \pm 0.014$
$\langle\alpha_0\rangle$	$-0.9869 \pm 0.0011 \pm 0.0016$	$-0.994 \pm 0.004 \pm 0.002$
A_{CP}	$-0.0118 \pm 0.0083 \pm 0.0028$	$0.004 \pm 0.037 \pm 0.010$

arXiv:2503.17165, accepted by PRL

- Opposite directions of the Σ^+ polarization in J/ψ and $\psi(3686)$ decays
- Most precise measurements of the Σ^+ decay parameters
- Most precise CP test in the decays of Σ^+

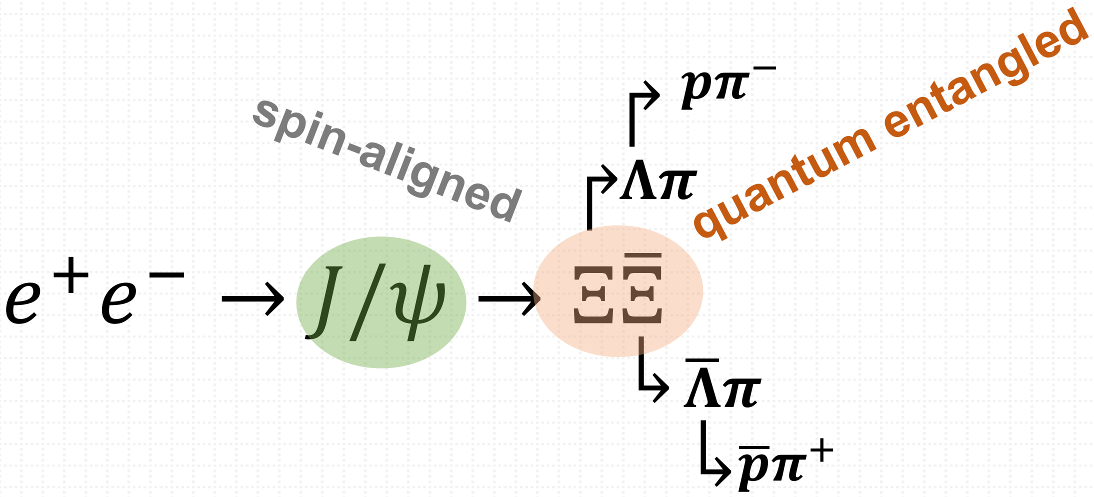
Polarizations of Σ^+

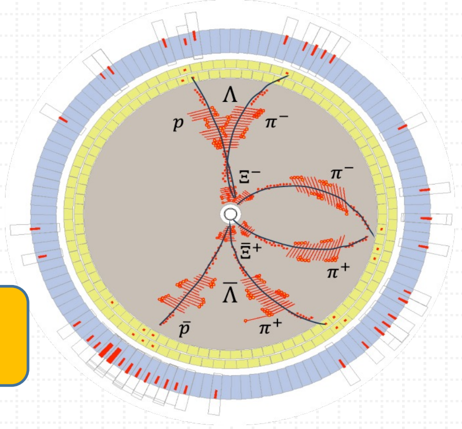




Polarization ratio of Σ^+ between J/ψ and $\psi(3686)$ decays

Search for CPV in Ξ decay





Phys. Rev. D 99, 056008 (2019)
Phys. Lett. B 772, 16 (2017)

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

Hyperon Production | Hyperon decays

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

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

Through the sequential decays of Ξ, the B_{CP} and $\Delta\phi_{CP}$ can be directly measured!

The ***perfect*** reaction for hyperon CPV searches!

Search for CPV in Ξ decay

Ξ^- 1.3 billion J/ψ 73K $\Xi^-\bar{\Xi}^+$ pairs

Parameter	Nature **606** (2022) 64-69	Previous result
α_ψ	0.586±0.012±0.010	0.58±0.04±0.08
$\Delta\Phi$	1.213±0.046±0.016 rad	–
α_Ξ	−0.376±0.007±0.003	−0.401±0.010
ϕ_Ξ	0.011±0.019±0.009 rad	−0.042 ± 0.011 ± 0.011
$\bar{\alpha}_\Xi$	0.371±0.007±0.002	HyperCP: PRL 93(2004) 011802
$\bar{\phi}_\Xi$	−0.021±0.019±0.007 rad	–
α_Λ	0.757±0.011±0.008	0.750±0.009±0.004
$\bar{\alpha}_\Lambda$	−0.763±0.011±0.007	−0.758±0.010±0.007
$\xi_P-\xi_S$	(1.2±3.4±0.8)×10^{-2} rad	–
$\delta_P-\delta_S$	(−4.0±3.3±1.7)×10^{-2} rad	(10.2±3.9)×10^{-2} rad
A_{CP}^{Ξ}	(6±13±6)×10^{-3}	–
$\Delta\phi_{CP}^{\Xi}$	(−5±14±3)×10^{-3} rad	–
A_{CP}^{Λ}	(−4±12±9)×10^{-3}	(−6±12±7)×10^{-3}
$\langle\phi_\Xi\rangle$	0.016±0.014±0.007 rad	

The results of 10B J/ψ is on the way!

First measurements of the weak (CPV) phase difference in Ξ^-/Ξ^0 decays

Three CP tests in Ξ^-/Ξ^0 decays

320K $\Xi^0\bar{\Xi}^0$ pairs

10 billion J/ψ Ξ^0

Parameter	Phys. Rev. D 108, L031106 (2023)
$\alpha_{J/\psi}$	$0.514 \pm 0.006 \pm 0.015$
$\Delta\Phi$(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)	$0.0052 \pm 0.0069 \pm 0.0016$
$\langle\alpha_\Lambda\rangle$	$0.7499 \pm 0.0029 \pm 0.0013$

PRD(L) Editor's Suggestion

Search for CPV in Ξ decay

New Measurement of $\Xi^- \to \Lambda\pi^-$ Decay Parameters

M. Huang,[10] R. A. Burnstein,[5] A. Chakravorty,[5] Y. C. Chen,[1] W. S. Choong,[2,7] K. Clark,[9] E. C. Dukes,[10] C. Durandet,[10] J. Felix,[4] G. Gidal,[7] H. R. Gustafson,[8] T. Holmstrom,[10] C. James,[3] C. M. Jenkins,[9] T. Jones,[7] D. M. Kaplan,[5] L. M. Lederman,[5] N. Leros,[6] M. J. Longo,[8] Fred Lopez,[8] L. Lu,[10] W. Luebke,[5] K. B. Luk,[2,7] K. S. Nelson,[10] H. K. Park,[8] J. P. Perroud,[6] D. Rajaram,[5,8] H. A. Rubin,[5] J. Volk,[3] C. White,[5] S. White,[5] and P. Zyla[7]

(HyperCP Collaboration)

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(Received 13 February 2004; published 30 June 2004)

Based on a sample of 144×10^6 polarized $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ decays collected by the HyperCP experiment (E871) at Fermilab, we report a new measurement of the Ξ^- decay-parameter angle $\phi_\Xi = (-2.39 \pm 0.64 \pm 0.64)^\circ$ from which we deduce the decay parameters $\beta_\Xi = -0.037 \pm 0.011 \pm 0.010$ and $\gamma_\Xi = 0.888 \pm 0.0004 \pm 0.006$. Assuming that the *CP*-violating phase difference between *s* and *p* waves is negligible, the strong phase-shift difference, $\delta_p - \delta_s$, for $\Lambda\pi$ scattering is determined to be $(4.6 \pm 1.4 \pm 1.2)^\circ$.

HyperCP: Phys. Rev. Lett. 93 (2004) 011802

144 M Ξ^-: $\phi_\Xi = -0.032 \pm 0.011 \pm 0.011$ rad

Probing CP symmetry and weak phases with entangled double-strange baryons

events. The final-state particles are measured in the main drift chamber, where a superconducting solenoid provides a magnetic field allowing momentum determination with an accuracy of 0.5% at 1.0 GeV/*c*. The Λ ($\bar{\Lambda}$) candidates are identified by combining $p\pi^-$ ($\bar{p}\pi^+$) pairs and the Ξ^- ($\bar{\Xi}^+$) candidates by subsequently combining $\Lambda\pi^-$ ($\bar{\Lambda}\pi^+$) pairs. Because it was found that the long-lived Ξ^- and $\bar{\Xi}^+$ can only be reconstructed with sufficient quality if they fulfil $|\cos\theta| < 0.84$, only Ξ^- and $\bar{\Xi}^+$ reconstructed within this range were considered. After applying all selection criteria, 73,244 $\Xi^-\bar{\Xi}^+$ event candidates remain in the sample. The number of background events in the signal is estimated to be 199 ± 17. More details of the analysis are given in Methods.

BESIII: Nature 606 (2022) 64-69

73K $\Xi^-\bar{\Xi}^+$ pairs : $\langle\phi_\Xi\rangle = 0.016 \pm 0.014 \pm 0.007$ rad

With 73 K reconstructed $\Xi^-\bar{\Xi}^+$ pairs from 1.3 billion J/ψ events at BESIII, we achieved a precision for ϕ parameter comparable to that in the HyperCP experiment in which 144 million Ξ^- are reconstructed.

The spin correlation between the Ξ^- and $\bar{\Xi}^+$ significantly improved the precision of the decay parameter measurements; the single-event sensitivity of BESIII is 1000 times that of HyperCP.

Search for CPV in Ξ decay and test of the $\Delta I = 1/2$ rule

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

10 billion J/ψ

Parameters	PRL **132** (2024) 101801
A_{CP}^{Ξ}	$-0.009 \pm 0.008^{+0.007}_{-0.002}$
$\Delta\phi_{CP}^{\Xi}$ (rad)	$-0.003 \pm 0.008^{+0.003}_{-0.007}$
$\xi_P - \xi_S$ (rad)	$0.007 \pm 0.020^{+0.018}_{-0.005}$
α_Ξ	$-0.367 \pm 0.004^{+0.003}_{-0.004}$
$\bar{\alpha}_\Xi$	$0.374 \pm 0.004^{+0.003}_{-0.004}$

The results are consistent with the previous BESIII results, Nature 606 (2022) 64-69, but with higher precision.

The most precise CP test in Ξ^- decays

$\Delta I = 1/2$ rule: total isospin change in weak interaction $\Delta I = 1/2$, it gives $\frac{\alpha_0}{\alpha_-} = 1$.

Parameters	This work	Previous result
α_0/α_-	$0.877 \pm 0.015^{+0.014}_{-0.010}$	1.01 ± 0.07 [1]
$\bar{\alpha}_0/\alpha_+$	$0.863 \pm 0.014^{+0.012}_{-0.008}$	$0.913 \pm 0.028 \pm 0.012$ [2]

[1] [PTEP2022(2022)083C01] [2] [Nature Phys.15(2019)631] [3] [PRL129(2022)131801]

$\alpha_0: \Lambda \to n\pi^0$ $\quad$ $\alpha_-: \Lambda \to p\pi^-$

$\bar{\alpha}_0: \bar{\Lambda} \to \bar{n}\pi^0$ $\quad$ $\alpha_+: \bar{\Lambda} \to \bar{p}\pi^+$

The ratio deviates from 1, indicating that the $\Delta I = 3/2$ component is not negligible!

Search for Strong CPV in $\Sigma^0 \to \Lambda\gamma$ decay

The CPV sources in SM:

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

10 B J/ψ and 2.7 B $\psi(3686)$

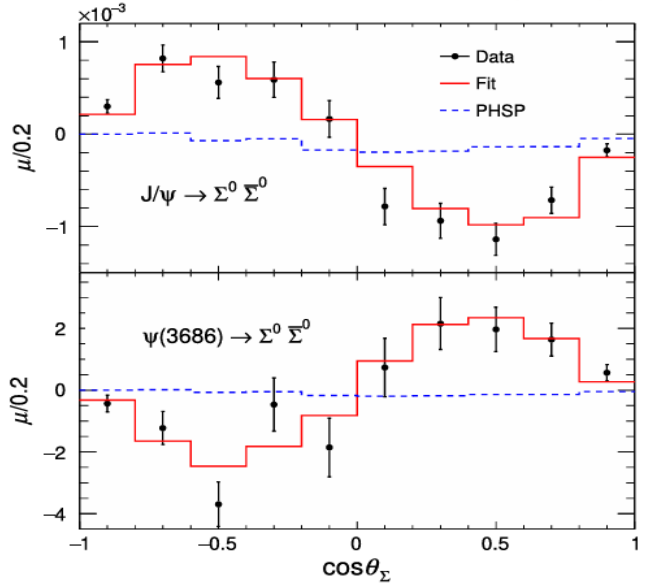
$e^+e^- \to J/\psi, \psi(3686) \to \Sigma^0(\to \Lambda\gamma)\bar{\Sigma}^0(\to \bar{\Lambda}\gamma), \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$

Parameter	Phys. Rev. Lett. 133 (2024) 10, 101902
$\alpha_{J/\psi}$	$-0.4133 \pm 0.0035 \pm 0.0077$
$\Delta\Phi_{J/\psi}$ (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}	$(-3.0 \pm 6.9 \pm 1.5) \times 10^{-2}$

Phys. Lett. B **788**, 535 (2019)

The Transition EDM of $\Sigma^0 \to \Lambda\gamma$ —SU(3) symmetry→ Neutron EDM

$$\frac{d_{\Sigma\Lambda}}{d_n} = \frac{d_{\Sigma\Lambda}^{\text{tree}} + d_{\Sigma\Lambda}^{\text{loop}}}{d_n^{\text{tree}} + d_n^{\text{loop}}} \approx -0.88$$



Polarizations of Σ^0

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

Opposite directions of the Σ^0 polarization

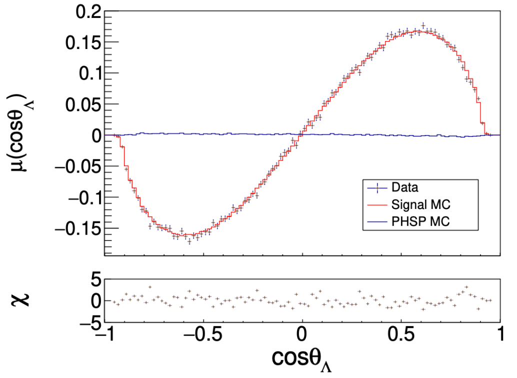
The first attempt to measure the P-violating decay parameter of $\Sigma^0 \to \Lambda\gamma$.

The first strong-CP test in hyperon decays.

Spin polarizations of different hyperons

$J/\psi \to \Lambda\bar{\Lambda}$

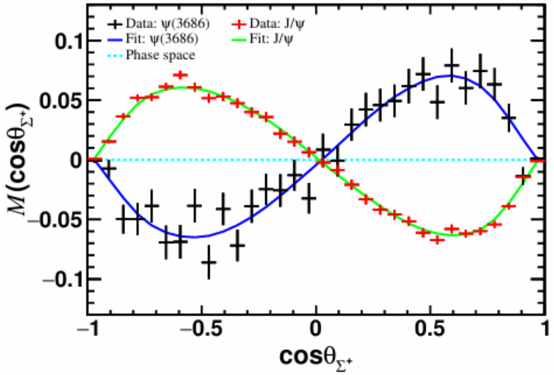
PRL129, 131801(2022)



$\Delta\Phi = (0.7521 \pm 0.0042 \pm 0.0066)$ rad

$\psi \to \Sigma^+\bar{\Sigma}^-$

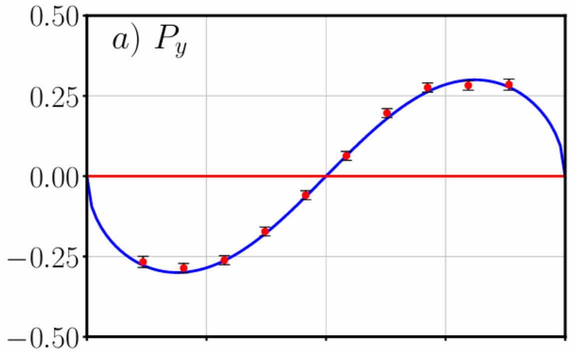
arXiv:2503.17165



$\Delta\Phi(J/\psi) = (-0.2744 \pm 0.0033 \pm 0.0010)$rad
$\Delta\Phi(\psi(2S)) = (0.427 \pm 0.022 \pm 0.003)$rad

$J/\psi \to \Xi^-\bar{\Xi}^+$

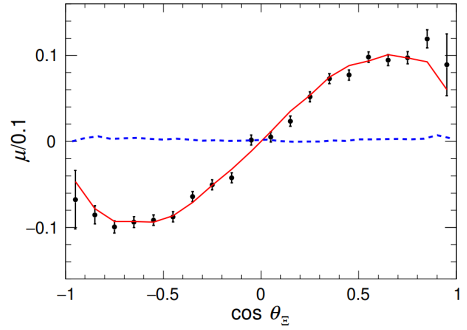
Nature 606, 64 (2022)



$\Delta\Phi = (1.213 \pm 0.046 \pm 0.016)$ rad

$J/\psi \to \Xi^0\bar{\Xi}^0$

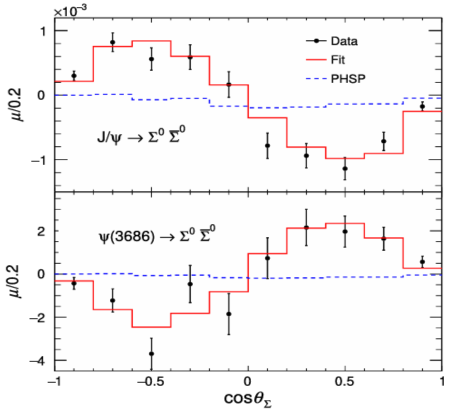
Phys. Rev. D 108, L031106 (2023)



$\Delta\Phi = (1.168 \pm 0.019 \pm 0.018)$ rad

$\psi \to \Sigma^0\bar{\Sigma}^0$

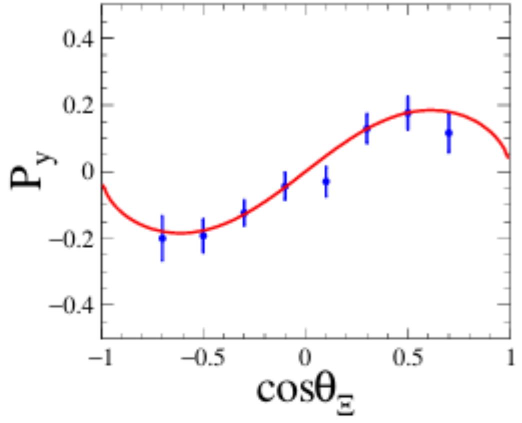
Phys. Rev. Lett. 133 (2024) 10, 101902



$\Delta\Phi(J/\psi) = (-0.0828 \pm 0.0068 \pm 0.0033)$rad
$\Delta\Phi(\psi(2S)) = (0.512 \pm 0.085 \pm 0.034)$rad

$\psi(2S) \to \Xi^-\bar{\Xi}^+$

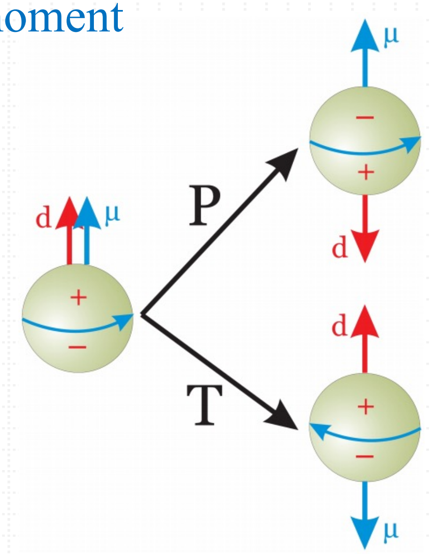
Phys. Rev. D 106, L091101 (2022)



$\Delta\Phi = (0.667 \pm 0.111 \pm 0.058)$ rad

Search for Hyperon Electric Dipole Moments at BESIII

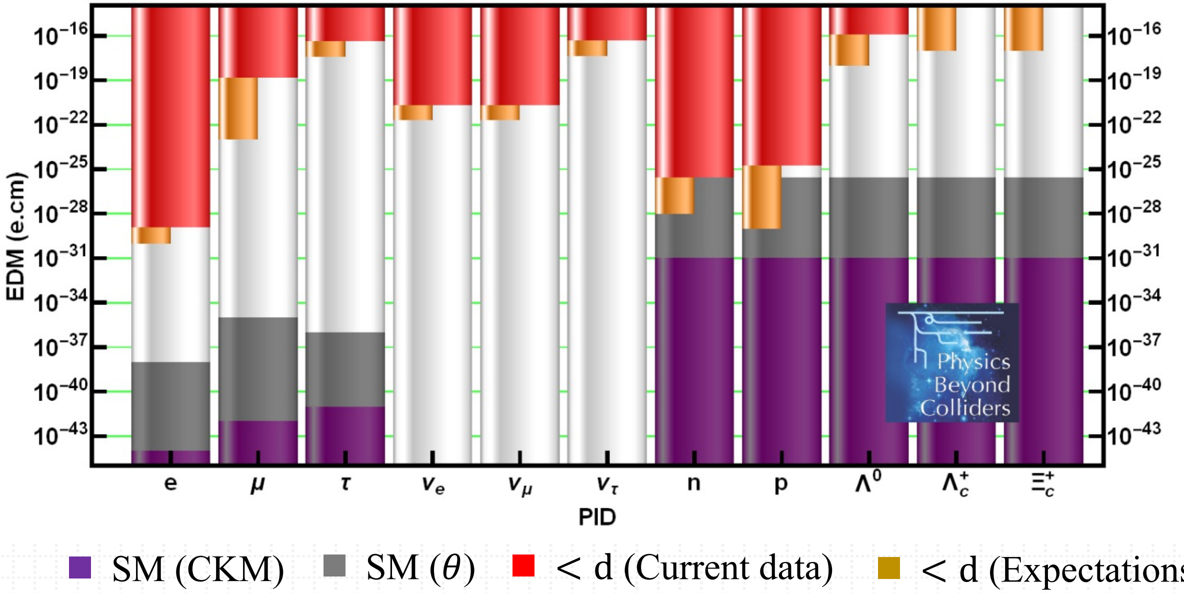
μ: magnetic moment
d: EDM



A non-zero intrinsic EDM would violate both parity (P) and time-reversal (T) symmetries.

- When CPT symmetry is conserved, T violation is equivalent to CP violation.

The EDM of the hyperons can be systematically measured at BESIII!
Among the hyperon family, only the EDM of Λ has been measured (with relatively low precision). Utilizing a vast amount of quantum-correlated hyperon-antihyperon pairs, BESIII is expected to improve the precision of the Λ EDM measurement by a factor of 1000 and, for the first time, provide measurements of the EDM for Σ, Ξ, and Ω hyperons.

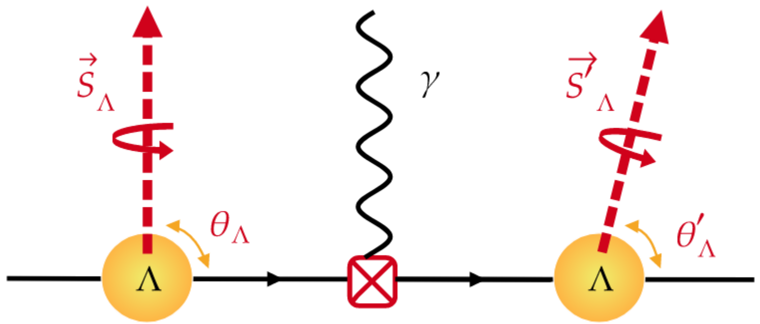


J. Phys. G 47 (2020) 1, 010501

World's Most Precise Λ EDM Measurement

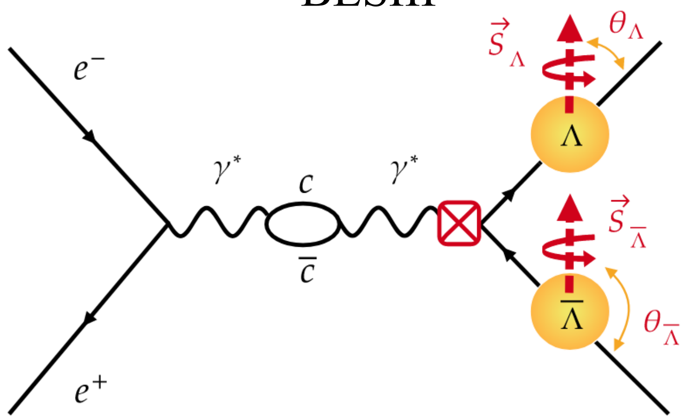
Phys. Rev. D 108 (9), L091301 (2023)

Traditional experiments



Spin procession method

BESIII



Extract EDM through CP-violating FF

Prior direct Λ EDM limit (Fermilab, 1981): $|d_\Lambda| < \ 1.5 \times 10^{-16} e \cdot cm.$

- EDM extracted via **full angular analysis** of entangled decays:

$$\mathrm{Re}(d_\Lambda) = (-3.1 \pm 3.2 \pm 0.5)\times 10^{-19}\ e\cdot \mathrm{cm}$$
$$\mathrm{Im}(d_\Lambda) = (2.9 \pm 2.6 \pm 0.6)\times 10^{-19}\ e\cdot \mathrm{cm}$$

which corresponds to an upper bound of:

BESIII: arXiv:2506.19180

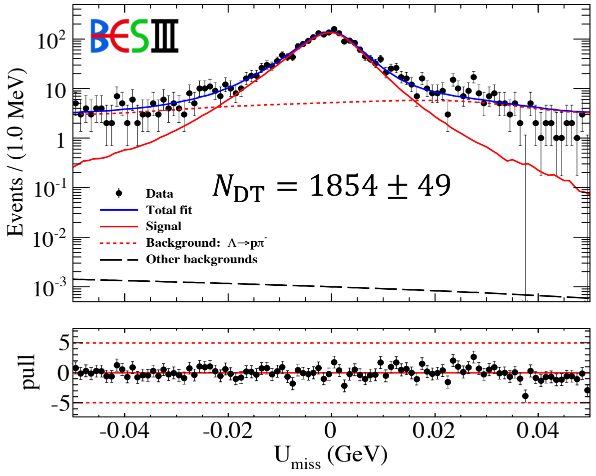
$$|d_\Lambda| < \ 6.5\times 10^{-19}\ e\cdot cm \quad (95\%\ CL)$$

- Improves sensitivity by more than **2 orders of magnitude** over previous best.

Measurements of the $\Sigma^{+,0}, \Xi^{-,0}$ EDMs are currently underway, with an expected precision comparable to that of the Λ EDM can be achieved.

Study of $\Lambda \to p e^- \bar{\nu}_e$ in spin-entangled $\Lambda\bar{\Lambda}$

$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p e^- \nu_e, \bar{\Lambda} \to \bar{p}\pi^+$



First absolute BF measurement

$\mathcal{B}(\Lambda \to p e^- \bar{\nu}_e) = (8.16 \pm 0.22 \pm 0.15) \times 10^{-4}$

arXiv:2509.09266

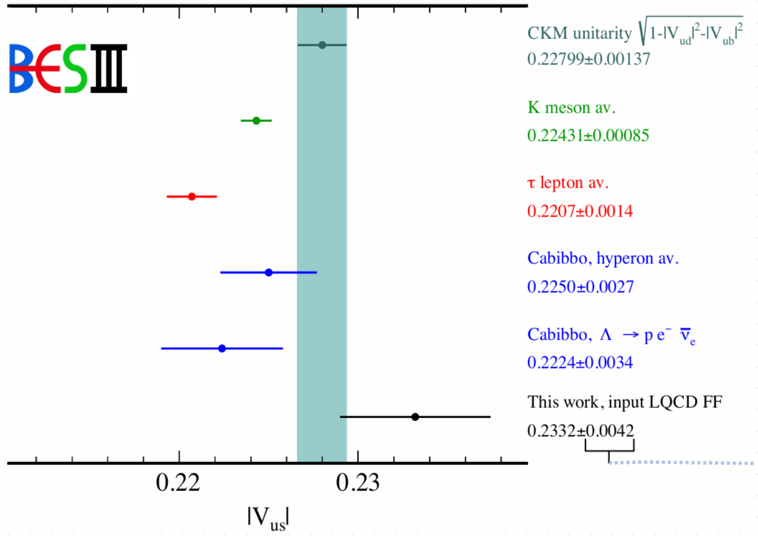
Observable	This work	Previous result
g_{av}^-	$0.742^{+0.075}_{-0.057} \pm 0.009$	0.718 ± 0.015 [PDG2024]
g_{av}^+	$-0.706^{+0.069}_{-0.073} \pm 0.014$	-
$\langle g_{av} \rangle$	$0.729^{+0.048}_{-0.047} \pm 0.007$	-
g_w^-	$0.93 \pm 0.51 \pm 0.17$	0.15 ± 0.30 [PRD41(1990)780]
g_w^+	$0.89 \pm 0.49 \pm 0.20$	-
$\langle g_w \rangle$	$0.89 \pm 0.35 \pm 0.14$	-
$\langle g_{av} \rangle$	$0.706^{+0.089}_{-0.086}$	-
$\langle g_w \rangle$	$0.77^{+0.53}_{-0.49}$	-
$\langle g_{av2} \rangle$	$-0.19^{+0.65}_{-0.63}$	-

Rows g_{av}^-, g_{av}^+, $\langle g_{av} \rangle$: axial vector coupling constant

Rows g_w^-, g_w^+, $\langle g_w \rangle$: weak magnetism coupling constant

Row $\langle g_{av2} \rangle$: weak electricity coupling constant

First six rows: Assuming $g_{av2} = 0$

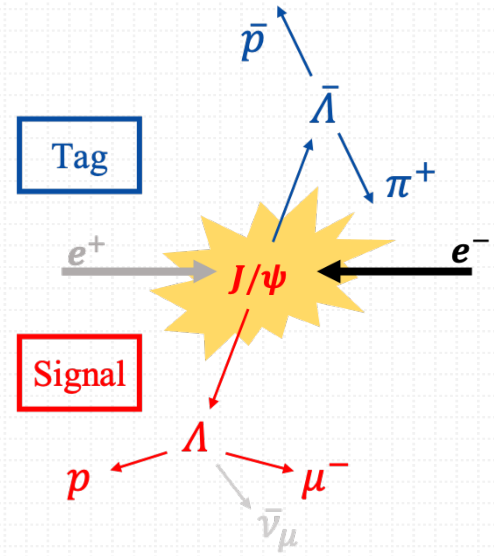


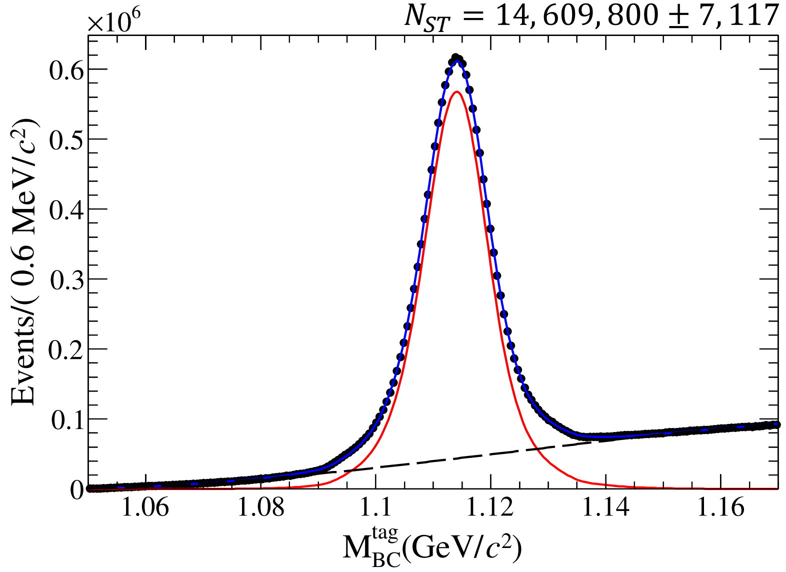
Determiantion of $|V_{us}|$

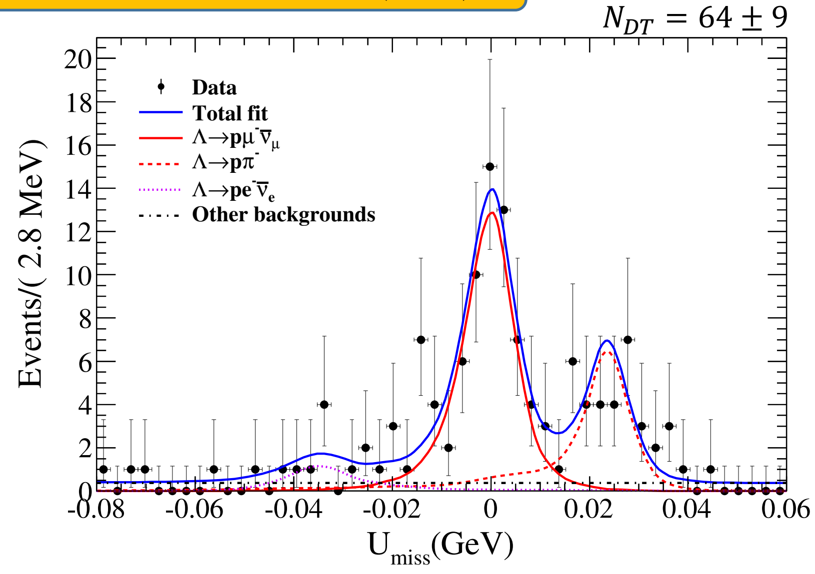
- Assume SU(3) is conserved, $f_1 = \sqrt{3/2}$ [PRL92(2004)251803]
  $|V_{us}|_{SU(3)} = 0.2199 \pm 0.0036_{\text{BESIII BF}} \pm 0.0087_{\text{BESIII FF}} \pm 0.0004_{\tau_\Lambda} \pm 0.0005_{\text{RC}}$
- Using LQCD FF prediction [arXiv:2507.09970]
  $|V_{us}|_{\text{LQCD}} = 0.2332 \pm 0.0039_{\text{BESIII BF}} \pm 0.0004_{\tau_\Lambda} \pm 0.0006_{\text{RC}} \pm 0.0014_{\text{LQCD}}$

Absolute BF measurement of $\Lambda \to p\mu^-\bar{\nu}_\mu$

Phys. Rev. Lett. 127, 121802 (2021)







First absolute BF measurement

$$\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu) = (1.48 \pm 0.21 \pm 0.08)\times 10^{-4}$$

- ✓ The first study of its absolute BF
- ✓ The most precise result to date

Test lepton flavor universality

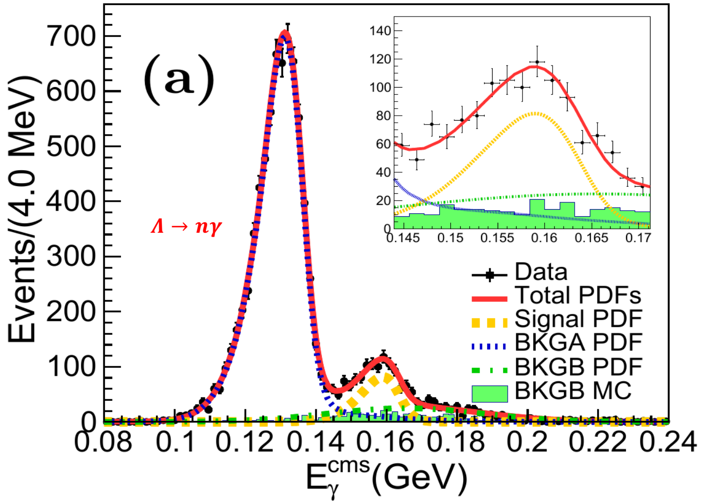
$$R^{\mu e} = \frac{\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda \to pe^-\bar{\nu}_e)_{PDG}} = 0.178 \pm 0.028$$

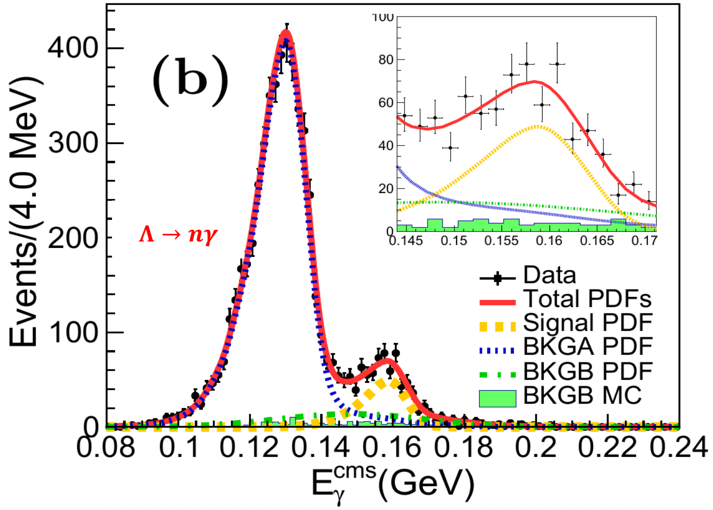
Consistent with LFU

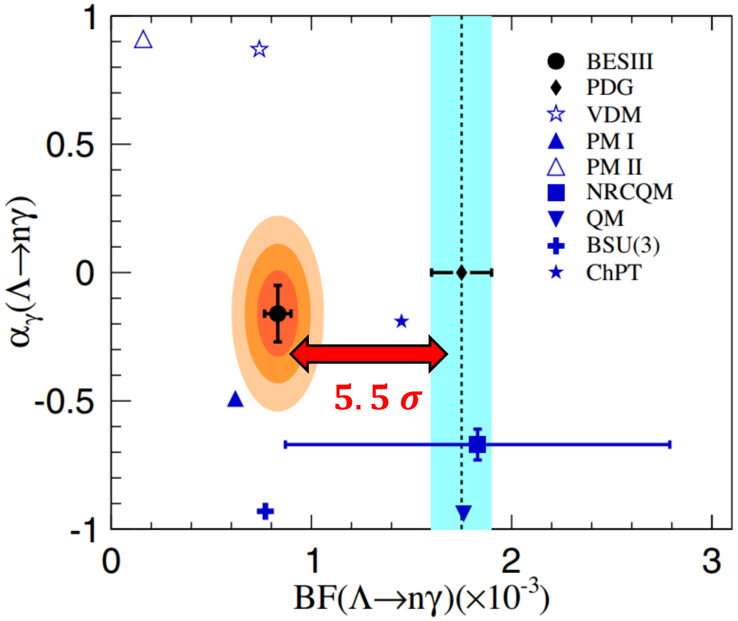
0.153 ± 0.008

Radiative decay: $\Lambda \to n\gamma$ in $J/\psi \to \Lambda\bar{\Lambda}$

Phys. Rev. Lett. 129, 212002 (2022)





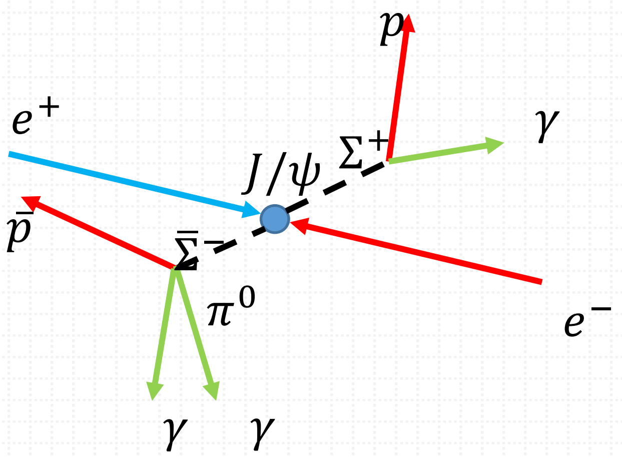


Variables	$\Lambda \to \gamma n (\times 10^{-3})$	$\bar{\Lambda} \to \gamma \bar{n} (\times 10^{-3})$	Combined$(\times 10^{-3})$
BF	$0.834 \pm 0.046 \pm 0.064$	$0.876 \pm 0.071 \pm 0.082$	$0.832 \pm 0.038 \pm 0.054$
α_γ	$-0.13 \pm 0.13 \pm 0.02$	$0.21 \pm 0.15 \pm 0.06$	$-0.16 \pm 0.10 \pm 0.05$

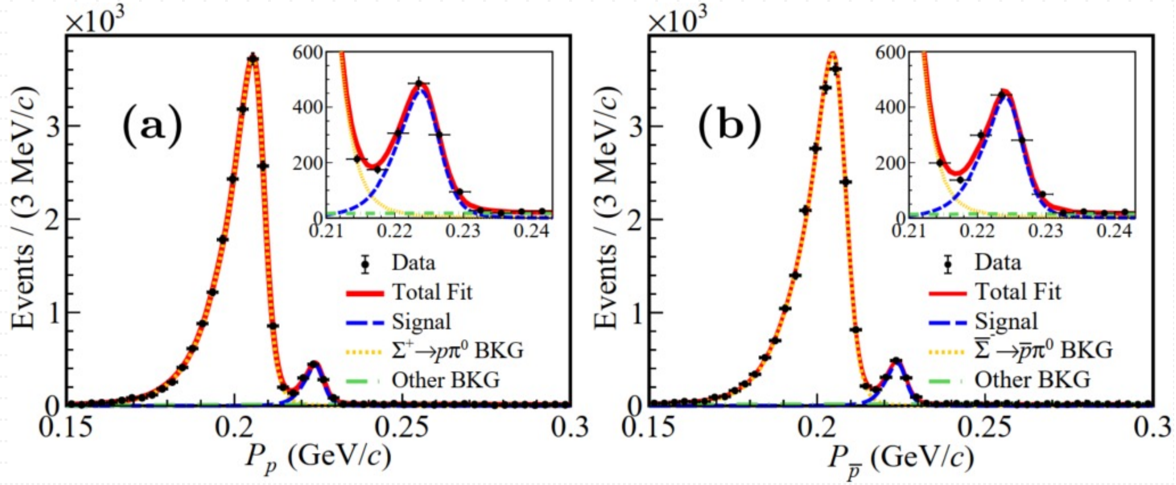
BF of $\Lambda \to n\gamma$, with improved precision, smaller than PDG value by 5.5σ

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

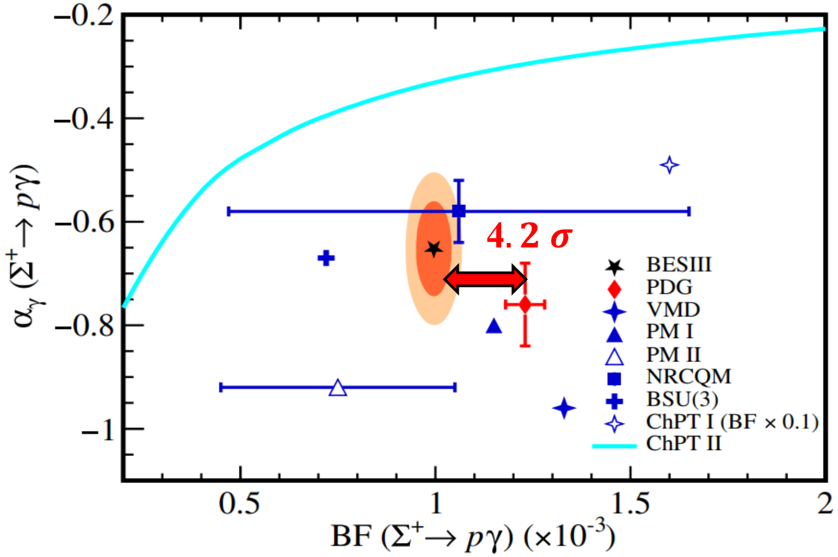
Phys. Rev. Lett. 130, 211901(2023)



Signal side: momentum distributions of proton in the rest frame of Σ :



The decay rate deviates from previous PDG value by 4.2σ



The decay BF $(0.996 \pm 0.022_{stat} \pm 0.017_{syst}) \times 10^{-3}$

The decay parameter: $-0.651 \pm 0.056_{stat} \pm 0.020_{syst}$

Summary

- BESIII has made fruitful achievements in hyperon physics!
  - CPV searches in hyperon decays
  - Measurements of the hyperon EDM
  - Semi-leptonic decays of hyperons
  - Weak radiative decays of hyperons
  - …

- More exciting hyperon results are expected in the near future.

Thank you!

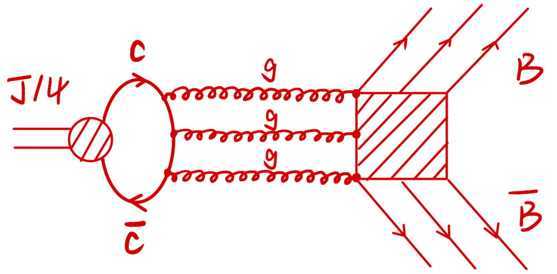
Backup

Searching for hyperon EDM at BESIII

Phys.Lett.B 839(2023)137834

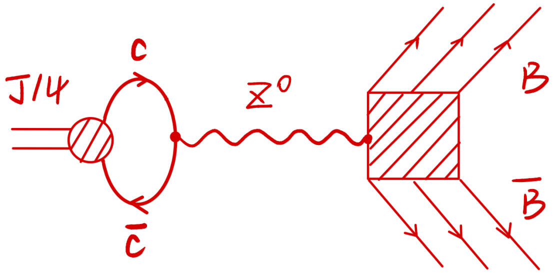
Detailed dynamics in J/ψ decay to hyperon pair, have been studied:

$$\mathcal{A} = \epsilon_\mu(\lambda)\bar{u}(\lambda_1)\left(F_V\gamma^\mu + \frac{i}{2M_\Lambda}\sigma^{\mu\nu}q_\nu H_\sigma + \gamma^\mu\gamma^5 F_A + \sigma^{\mu\nu}\gamma^5 q_\nu H_T\right)v(\lambda_2)$$



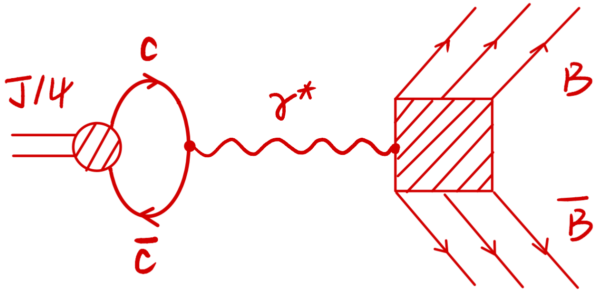
Dominant contribution
arXiv:hep-ph/0412158

Psionic form factor
F_V and H_σ
can also be represented as G_1 and G_2



P violation term

Complex form factor, $F_A \neq 0$ indicate P violation



H_T is included in this term

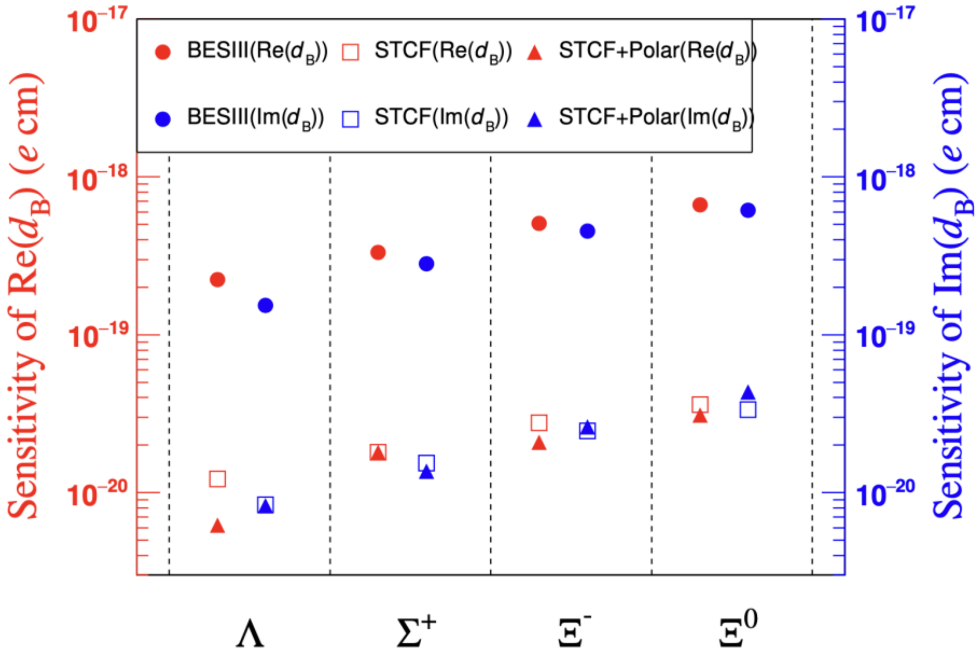
$$H_T(q^2) = \frac{2e}{3m_{J/\psi}^2} g_V d_B(q^2)$$

Assuming $d_B(q^2) \equiv d_B(0)$

$d_B(q^2)$: electric dipole form factor
$d_B(0)$: electric dipole moment
Physics Letters B 551 (2003) 16–26

Sensitivities of hyperon EDM at BESIII

reminder: $H_T = \frac{2e}{3M^2_{J/\psi}} g_V d_B$



(a)Sensitivity of $Re(d_B)$ and $Im(d_B)$

SM: $\sim 10^{-26}$ e cm

BESIII: milestone for hyperon EDM measurement
Λ 10^{-19}e cm (FermiLab 10^{-16} e cm)

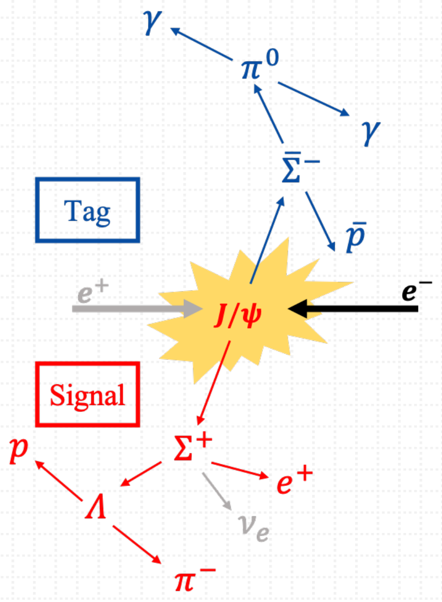
first achievement for Σ^+,Ξ^- and Ξ^0 at level of 10^{-19}e cm

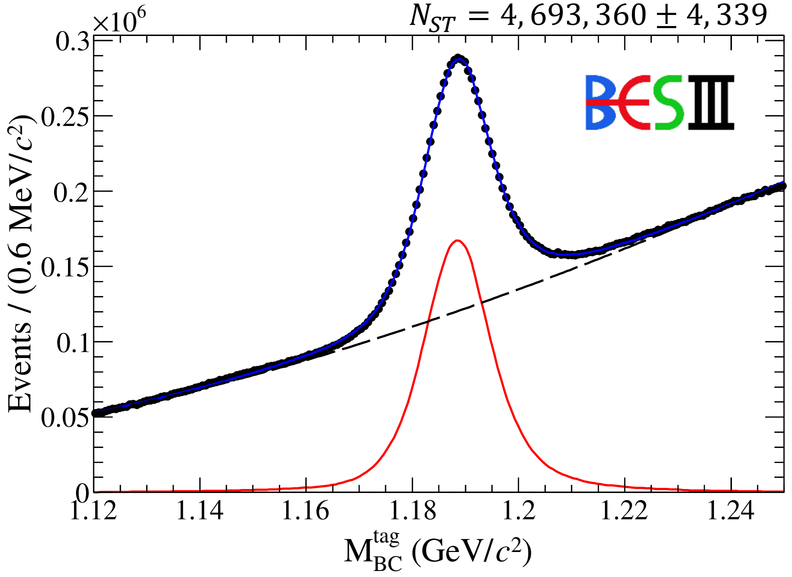
a litmus test for new physics

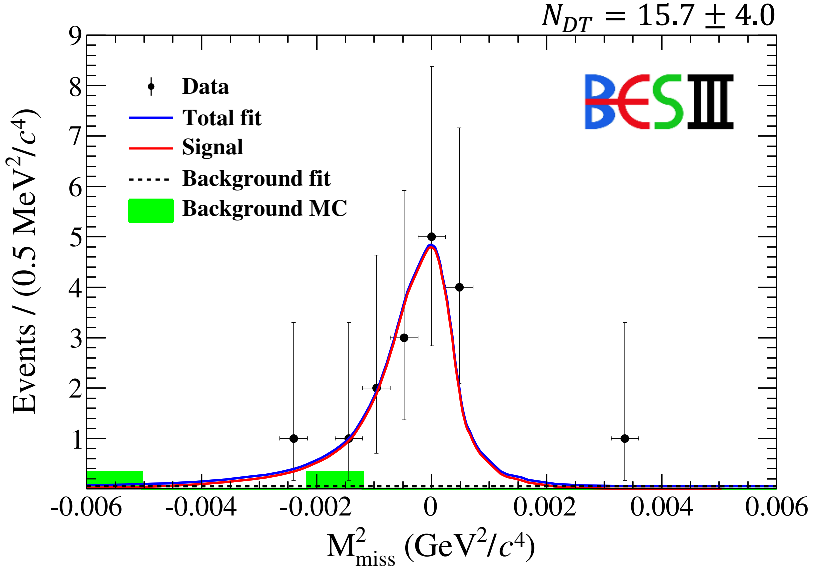
STCF: improved by 2 order of magnitude

Phys. Rev. D 108 (9), L091301 (2023)

Absolute BF measurement of $\Sigma^+ \to \Lambda e^+ \nu_e$







First derect measurement of absolute BF

$$\mathcal{B}(\Sigma^+ \to \Lambda e^+ \nu_e) = (2.93 \pm 0.74 \pm 0.13) \times 10^{-5}$$

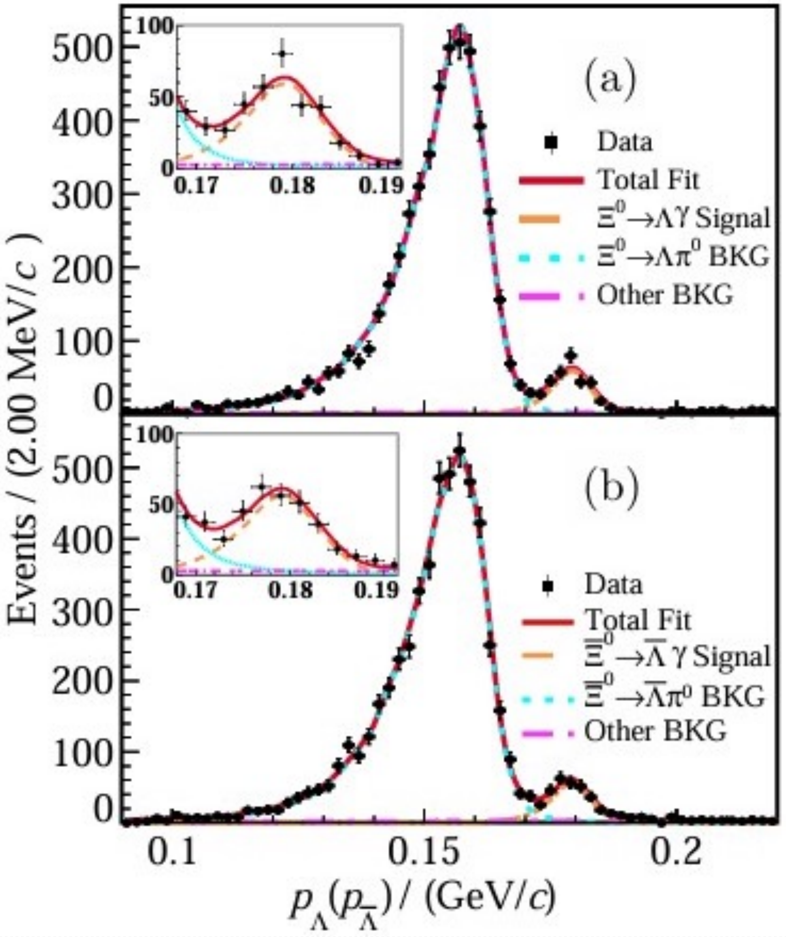
- ✓ Update measurement after about 50 years break
- ✓ The first study at a collider experiment
- ✓ The most precise result in a single experiment

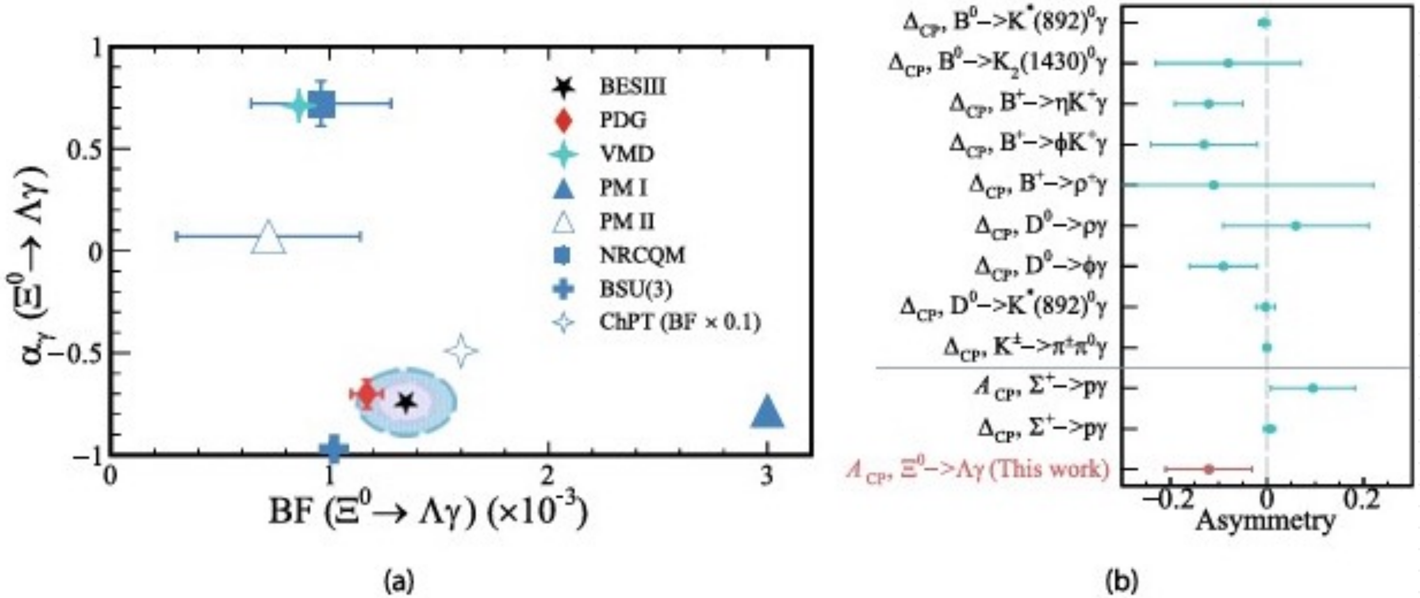
Phys. Rev. D 107 (2023) 7, 072010

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

Signal side: momentum distributions of Λ in the rest frame of Ξ^0:

Sci. Bull. 70, 454 (2025)





Vars	$\Xi^0 \to \Lambda\gamma(\times 10^{-3})$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma(\times 10^{-3})$	**Combined**$(\times 10^{-3})$
BF	$1.348 \pm 0.090 \pm 0.054$	$1.326 \pm 0.098 \pm 0.066$	$1.347 \pm 0.066 \pm 0.054$
α_γ	$-0.652 \pm 0.092 \pm 0.016$	$0.830 \pm 0.080 \pm 0.044$	$-0.741 \pm 0.062 \pm 0.0019$
Δ_{CP}	$-0.033 \pm 0.049 \pm 0.031$		
A_{CP}	$-0.120 \pm 0.084 \pm 0.029$		