Search for CP Violation with Spin Entangled Hyperon-Antihyperon Pairs at BESIII

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BESIII实验物理研讨会

Outline

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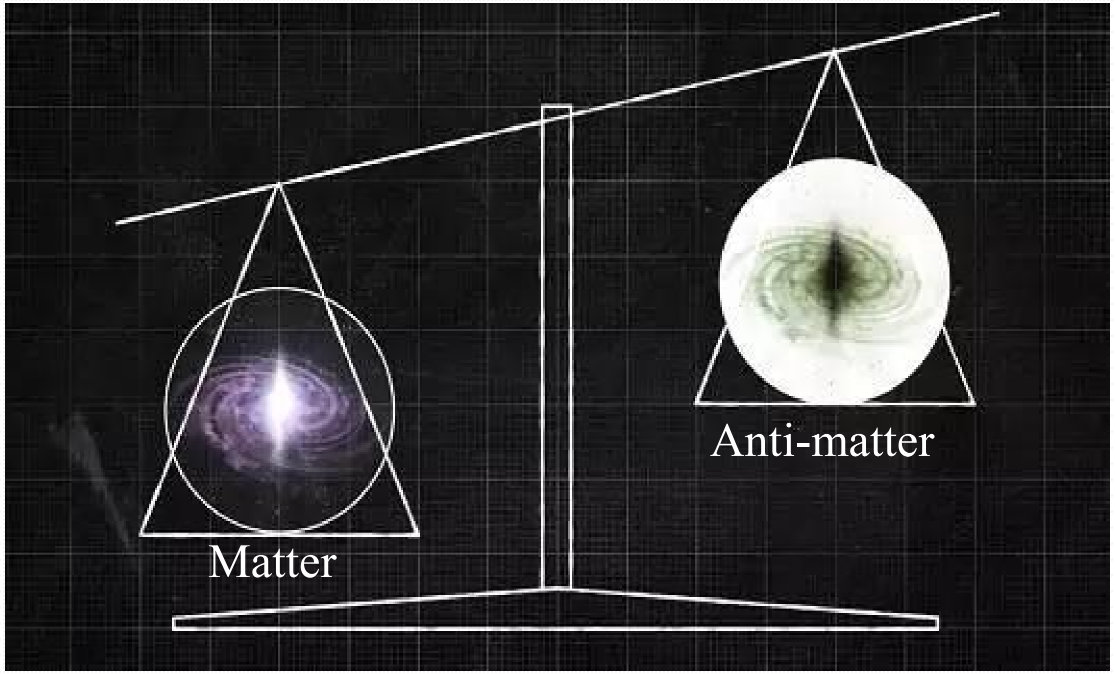
Mystery of matter-antimatter asymmetry



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

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

- The standard model predicted value：

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

- Why has the anti-matter 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.**
- **Before 21 Mar 2025, there is no observation of CPV in the baryon system.**

BABAR

BELLE

5.2σ CPV in Λ_b decay:
$\Lambda_b \to p\pi^+\pi^-K^-$

K meson CPV	B meson CPV	D meson CPV	Λ_b baryon	Hyperon?
1964	2001	2019	2025	

James Watson Cronin

Val Logsdon Fitch

LHCb

LHCb

[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)
[7] Nature **643** (2025) 8074, 1223-1228

Search for CP violation in hyperon decays

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

ordinary phases in QM		$\mathcal{CP}$ violating phases	
matter	antimatter	matter	antimatter
δ	δ	ξ	$-\xi$
same sign		opposite sign	

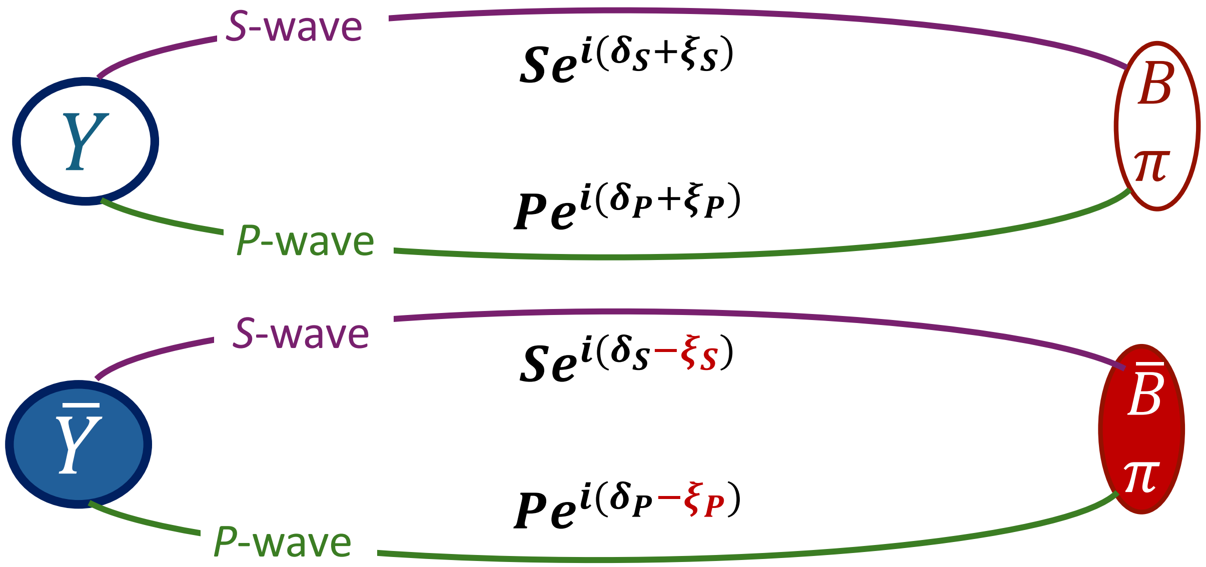
If only have one path:

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

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:

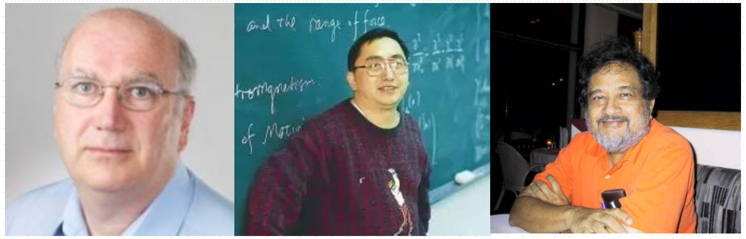
$$\alpha_Y = \frac{2\,\mathrm{Re}\,(S^* P)}{|S|^2 + |P|^2}, \quad \beta_Y = \frac{2\,\mathrm{Im}\,(S^* P)}{|S|^2 + |P|^2}, \quad \gamma_Y = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

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

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

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
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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}

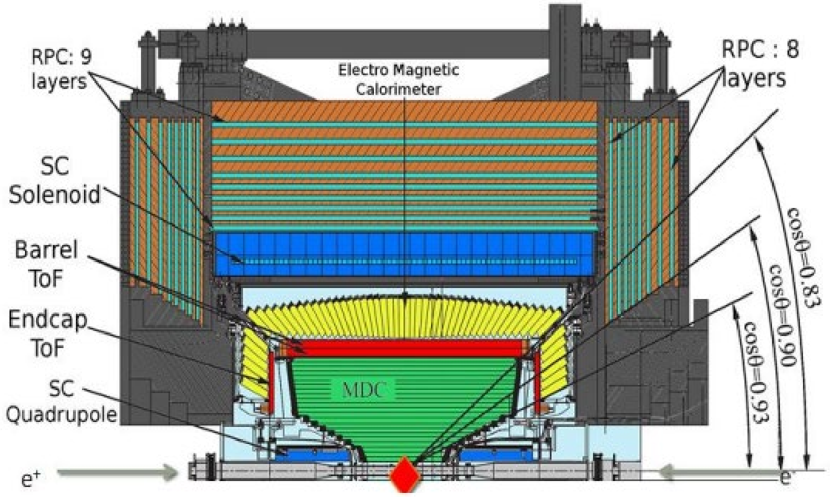
Polarization of decayed baryon needs to be measured → **Decay parameter difference** $B_{CP} = \frac{\beta+\bar{\beta}}{\alpha-\bar{\alpha}} \approx tan(\xi_P-\xi_S)$ 3.0×10^{-3}

Ξ^-, Ξ^0, Ω^- cascade decay

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)

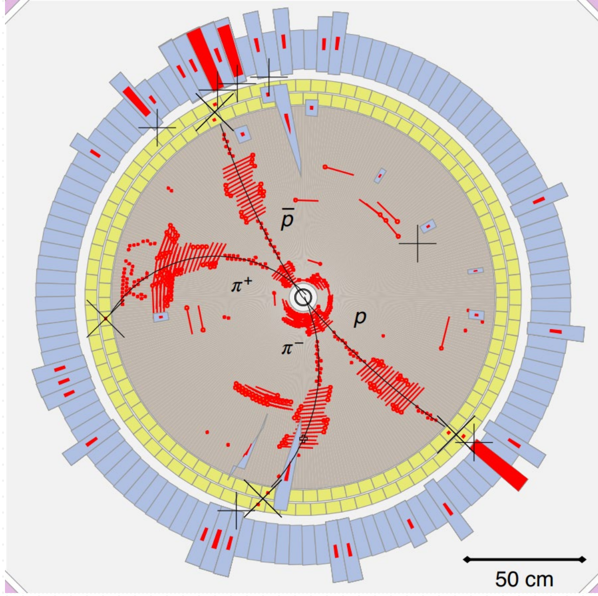
With 10 billion J/ψ collected at BESIII, $\sim 10^7$ spin-entangled hyperon pairs can be produced, which enables precise studies of the hyperon physics.

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

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

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

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

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

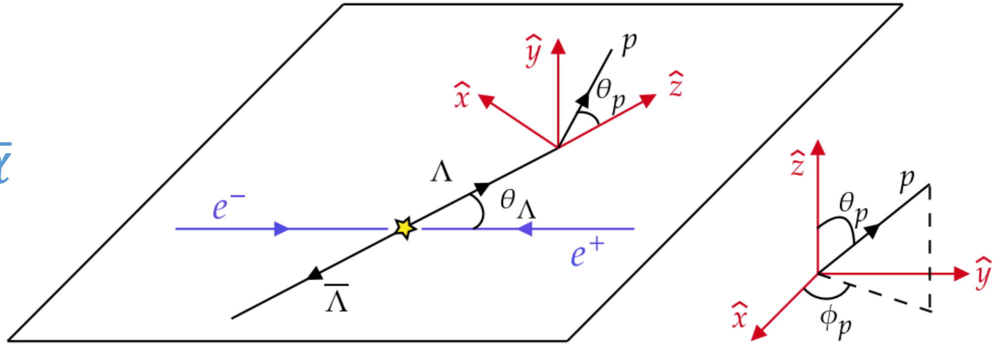
↓

Simultaneous determination of $\alpha, \bar{\alpha}$

↓

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)



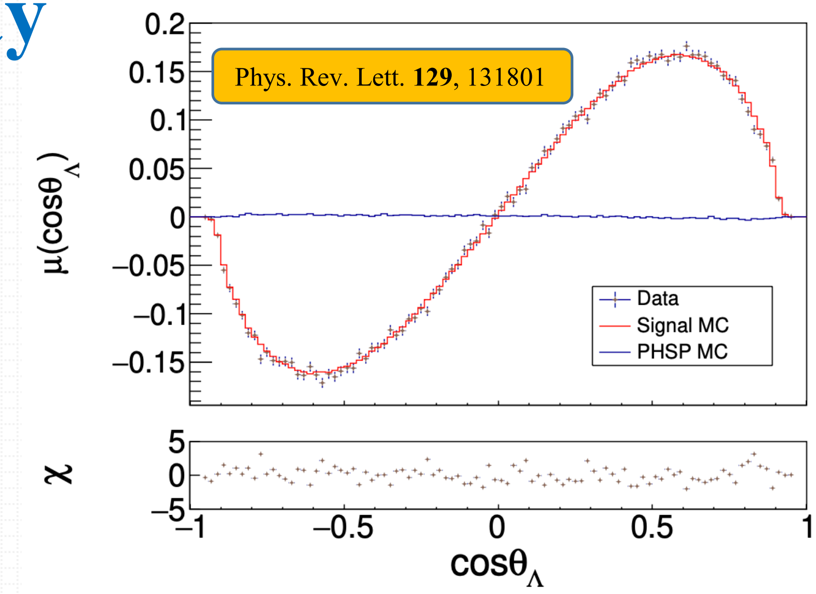
Search for CPV in Λ charged decay

Two BESIII papers have been published:

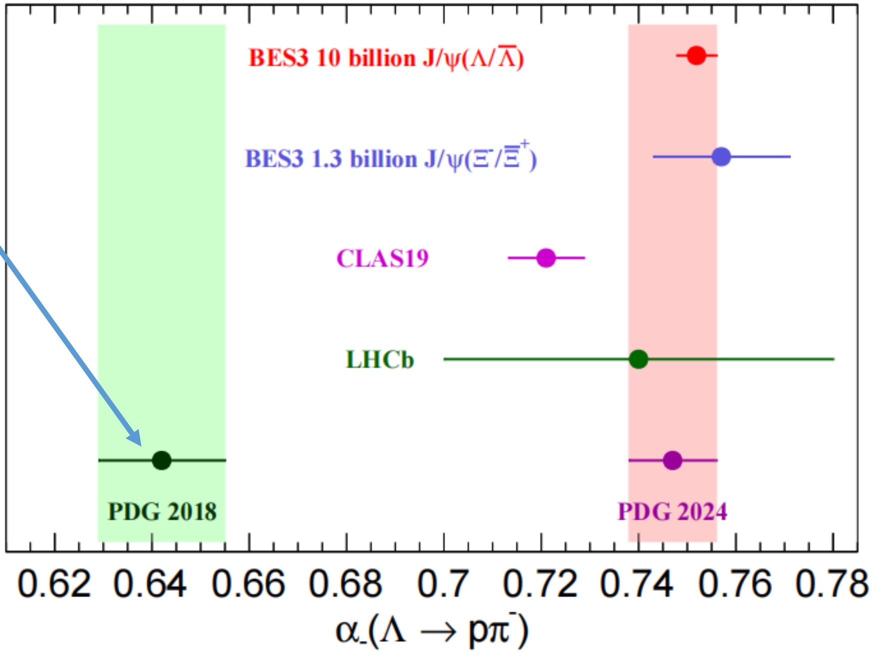
[1] 1.3 billion: Nature Phys 15(2019)631

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

Par.	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}	$0.7542 \pm 0.0010 \pm 0.0024$	-



17 ± 3% higher



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

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

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

Search for CPV in Λ neutral decay

[1] arXiv:2510.24333

[2] Phys.Rev.Lett. 132 (2024) 10, 101801

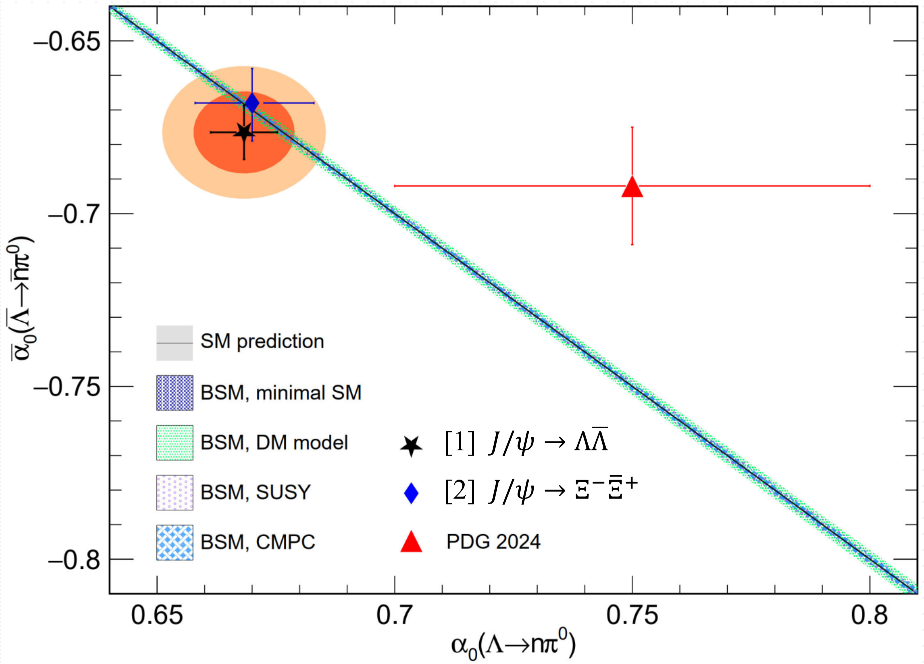
Two channels used to study $\Lambda \to n\pi^0$:

[1] $J/\psi \to \Lambda\bar{\Lambda} \to \boldsymbol{n\pi^0}\bar{p}\pi^+ + c.c$

[2] $J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda(\to \boldsymbol{n\pi^0})\pi^-\bar{\Lambda}(\to \bar{p}\pi^+)\pi^+ + c.c$

Parameter	[1] $J/\psi \to \Lambda\bar{\Lambda}$	[2] $J/\psi \to \Xi^-\bar{\Xi}^+$
α_-	$0.756 \pm 0.008 \pm 0.003$	$0.764 \pm 0.008^{+0.005}_{-0.006}$
α_+	$-0.764 \pm 0.008 \pm 0.001$	$-0.774 \pm 0.009^{+0.005}_{-0.005}$
α_0	$0.668 \pm 0.007 \pm 0.002$	$0.670 \pm 0.009^{+0.009}_{-0.008}$
$\bar{\alpha}_0$	$-0.677 \pm 0.007 \pm 0.003$	$-0.668 \pm 0.008^{+0.006}_{-0.008}$
A_{CP}^-	$-0.005 \pm 0.007 \pm 0.002$	$-0.007 \pm 0.008^{+0.002}_{-0.003}$
A_{CP}^0	$-0.006 \pm 0.007 \pm 0.002$	$0.001 \pm 0.009^{+0.005}_{-0.007}$
α_0/α_-	$0.884 \pm 0.013 \pm 0.006$	$0.877 \pm 0.015^{+0.014}_{-0.010}$
$\bar{\alpha}_0/\alpha_+$	$0.885 \pm 0.013 \pm 0.004$	$0.863 \pm 0.014^{+0.012}_{-0.008}$

$\Delta I = 1/2$ rule: $\frac{\alpha_0}{\alpha_-} = 1$



The most precise results of Λ neutral decay

43% and 27% improvement in $J/\psi \to \Lambda\bar{\Lambda}$ compared with $J/\psi \to \Xi^-\bar{\Xi}^+$

Most precise CP test in Λ neutral decay

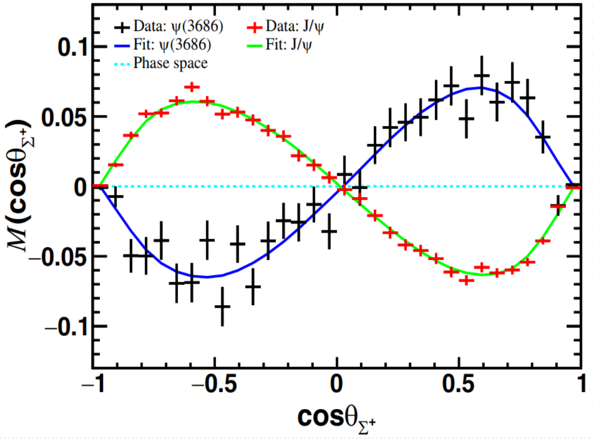
SM prediction: $A_{CP} \sim 10^{-5}$ (PRD 67, 056001(2003))

Deviate from unity more than 5σ, indicates the $\Delta I = 3/2$ contributions in Λ decay

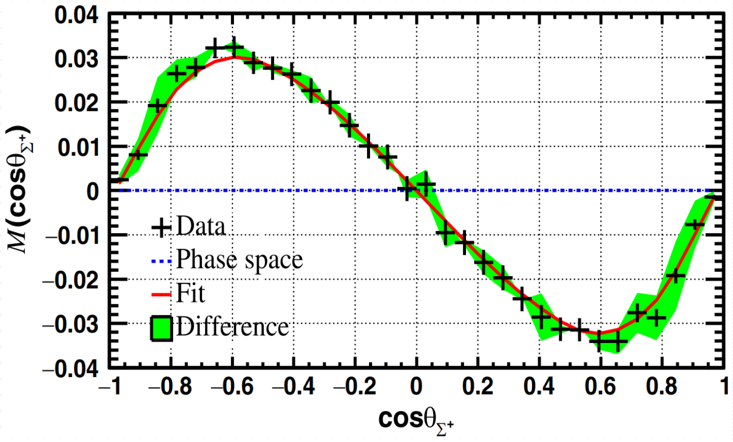
Search for CPV in Σ^+ decay

[1] Phys.Rev.Lett. 135 (2025) 14, 141804
[2] Phys.Rev.Lett. 131 (2023) 19, 191802

[1] $J/\psi[\psi(3686)] \to \Sigma^+\bar{\Sigma}^- \to p\pi^0\bar{p}\pi^0$ [2] $J/\psi \to \Sigma^+(\to n\pi^+)\bar{\Sigma}^-(\to \bar{p}\pi^0) + c.c.$



10B J/ψ and 2.7B $\psi(3686)$



10B J/ψ

Polarization of Σ^+

Opposite direction of the Σ^+ polarization in J/ψ and $\psi(3686)$

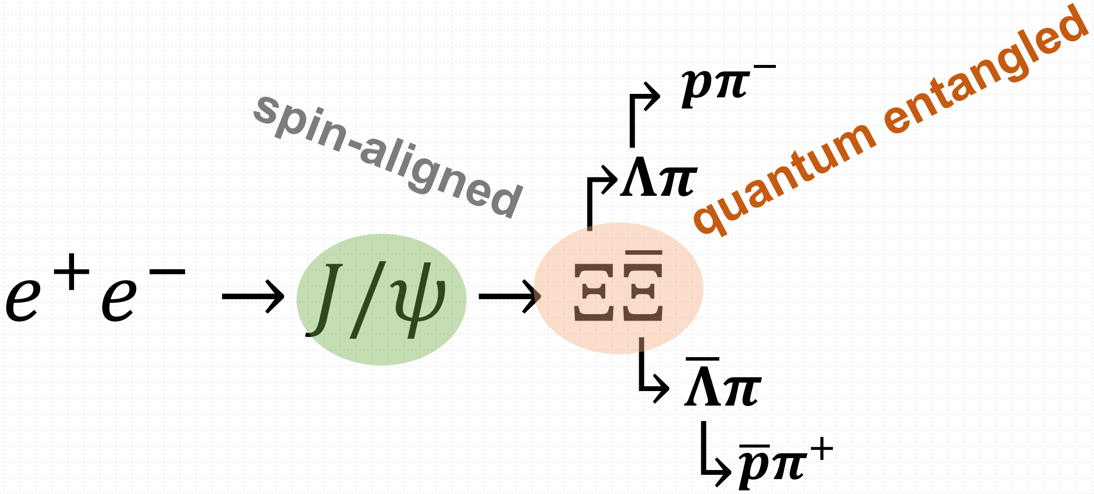
Parameter	[1] $\Sigma^+ \to p\pi^0, \bar{\Sigma}^- \to \bar{p}\pi^0$	[2] $\Sigma^+ \to p\pi^0, \bar{\Sigma}^- \to \bar{n}\pi^- + c.c.$
$\alpha_{J/\psi}$	$-0.5047 \pm 0.0018 \pm 0.0010$	$-0.5156 \pm 0.0030 \pm 0.0061$
$\Delta\Phi_{J/\psi}$	$-0.2744 \pm 0.0033 \pm 0.0010$	$-0.2772 \pm 0.0044 \pm 0.0041$
$\alpha_{\psi(3686)}$	$0.7133 \pm 0.0094 \pm 0.0065$	–
$\Delta\Phi_{\psi(3686)}$	$0.427 \pm 0.022 \pm 0.003$	–
$\alpha_0(\Sigma^+ \to p\pi^0)$	$-0.975 \pm 0.011 \pm 0.002$	–
$\bar{\alpha}_0(\bar{\Sigma}^- \to \bar{p}\pi^0)$	$0.999 \pm 0.011 \pm 0.004$	–
$\alpha_+(\Sigma^+ \to n\pi^+)$	–	$0.0481 \pm 0.0031 \pm 0.0019$
$\alpha_-(\bar{\Sigma}^- \to \bar{n}\pi^-)$	–	$-0.0565 \pm 0.0047 \pm 0.0022$

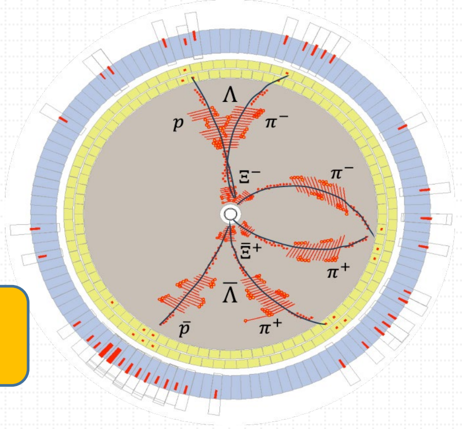
The most precise CP test in Σ sector:

$$A_{CP}(\Sigma^+ \to p\pi^0) = \frac{\alpha_0 + \bar{\alpha}_0}{\alpha_0 - \bar{\alpha}_0} = -0.0118 \pm 0.0083 \pm 0.0028$$

$$A_{CP}(\Sigma^+ \to n\pi^+) = \frac{\alpha_+ + \bar{\alpha}_-}{\alpha_+ - \bar{\alpha}_-} = -0.080 \pm 0.052 \pm 0.028$$

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} (CPV phase) can be directly measured!

Big branching ratio.

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
$\xi_P-\xi_S$	$(1.2\pm3.4\pm0.8)\times10^{-2}$ rad	–
$\delta_P-\delta_S$	$(-4.0\pm3.3\pm1.7)\times10^{-2}$ rad	$(10.2\pm3.9)\times10^{-2}$ rad
A^Ξ_{CP}	$(6\pm13\pm6)\times10^{-3}$	–
$\Delta\phi^\Xi_{CP}$	$(-5\pm14\pm3)\times10^{-3}$ rad	–
A^Λ_{CP}	$(-4\pm12\pm9)\times10^{-3}$	$(-6\pm12\pm7)\times10^{-3}$
$\langle\phi_\Xi\rangle$	0.016±0.014±0.007 rad	

The results of 10B J/ψ is on the way!

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^Ξ_{CP}	$(-5.4 \pm 6.5 \pm 3.1) \times 10^{-3}$
$\Delta\phi^\Xi_{CP}$(rad)	$(-0.1 \pm 6.9 \pm 0.9) \times 10^{-3}$
A^Λ_{CP}	$(6.9 \pm 5.8 \pm 1.8) \times 10^{-3}$
$\langle\alpha_\Xi\rangle$	$-0.3770 \pm 0.0024 \pm 0.0014$
$\langle\phi_\Xi\rangle$(rad)	$0.0052 \pm 0.0069 \pm 0.0016$
$\langle\alpha_\Lambda\rangle$	$0.7499 \pm 0.0029 \pm 0.0013$

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

Three CP tests in Ξ^-/Ξ^0 decays

PRD(L) Editor's Suggestion

Search for CPV in Ξ decay

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

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(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 $\phi_\Xi = (-2.39 \pm 0.64 \pm 0.64)°$ 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 $(4.6 \pm 1.4 \pm 1.2)°$.

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 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 $\psi(3686)$

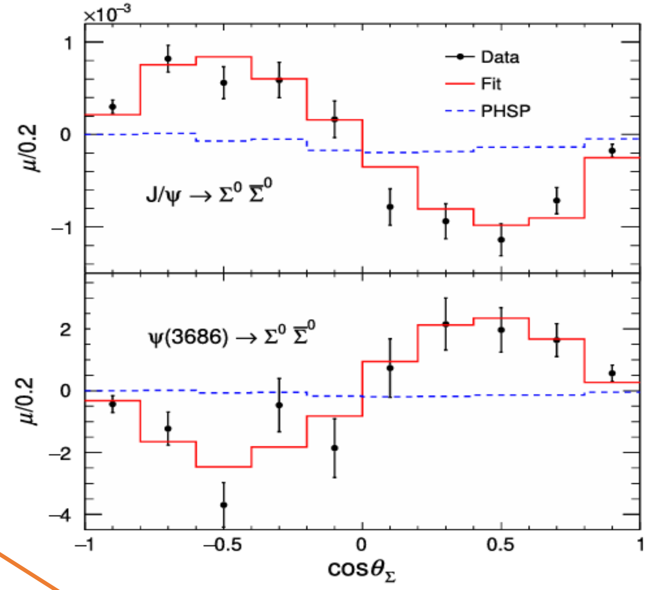
$e^+e^- \to J/\psi, \psi(3686) \to \Sigma^0(\to \Lambda\gamma)\bar{\Sigma}^0(\to \bar{\Lambda}\gamma), \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$

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

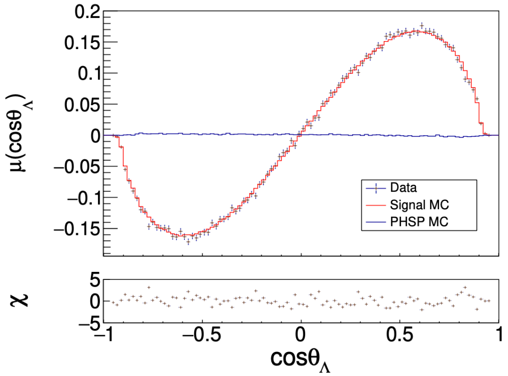
The first attempt to measure the P-violating decay parameter of $\Sigma^0 \to \Lambda\gamma$.

The first strong-CP test in hyperon decays.

Spin polarization of different hyperons

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

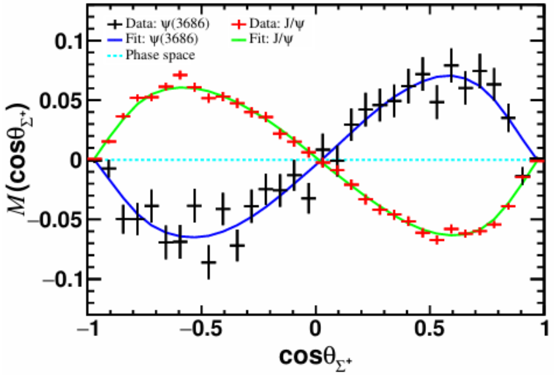
PRL129, 131801(2022)



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

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

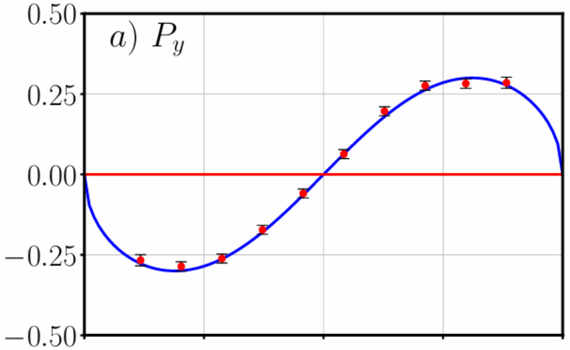
Phys. Rev. Lett. 135 (2025) 14, 141804



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

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

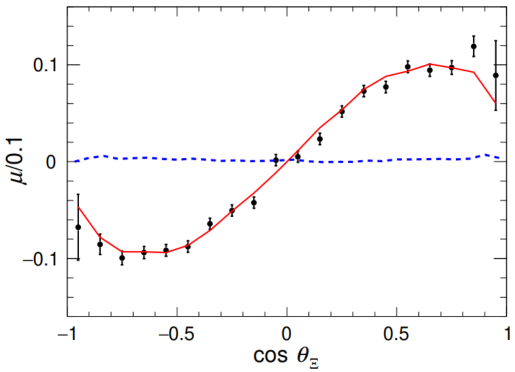
Nature 606, 64 (2022)



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

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

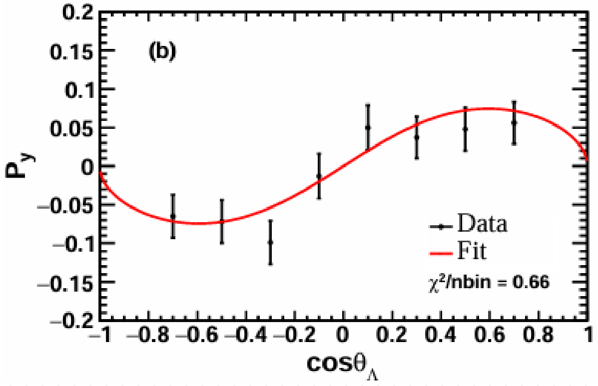
Phys. Rev. D 108, L031106 (2023)



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

$\psi(3686) \to \Lambda\bar{\Lambda}$

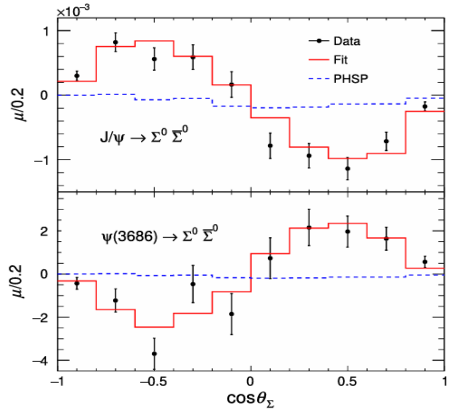
arXiv:2509.15276



$\Delta\Phi = (0.366 \pm 0.064 \pm 0.013)$ rad

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

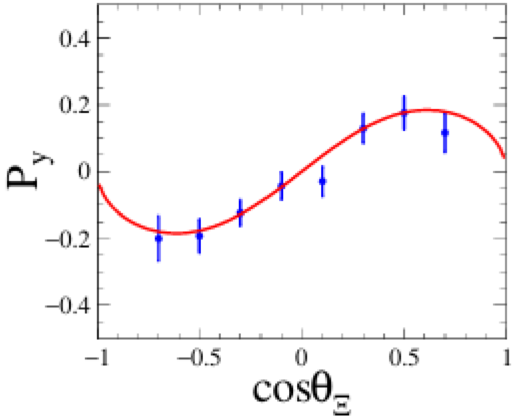
Phys. Rev. Lett. 133 (2024) 10, 101902



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

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

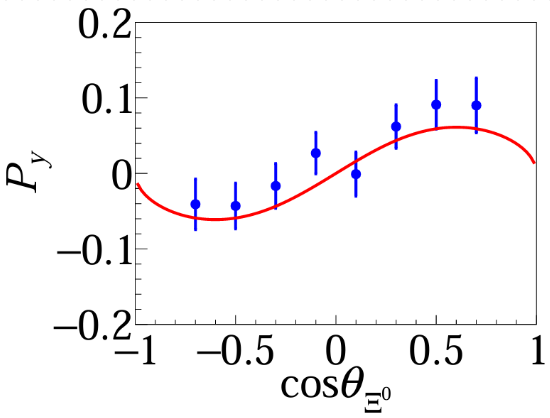
Phys. Rev. D 106, L091101 (2022)



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

$\psi(3686) \to \Xi^0\bar{\Xi}^0$

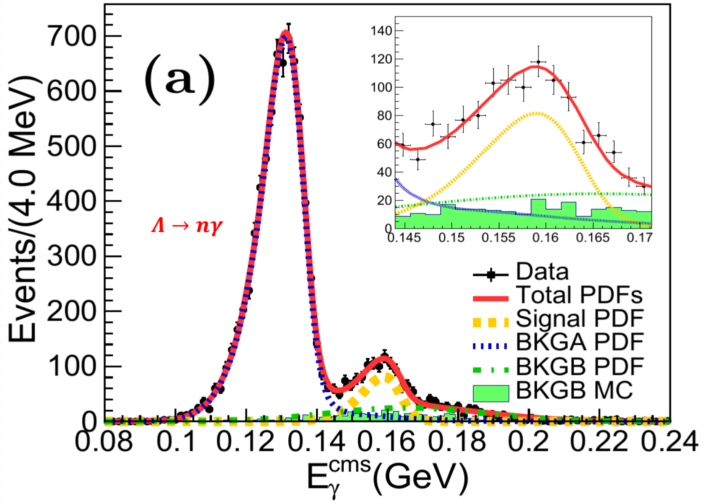
arXiv:2510.19571

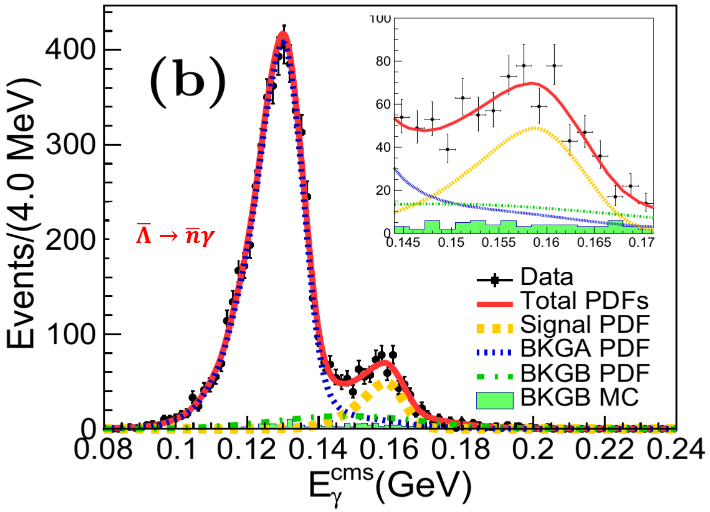


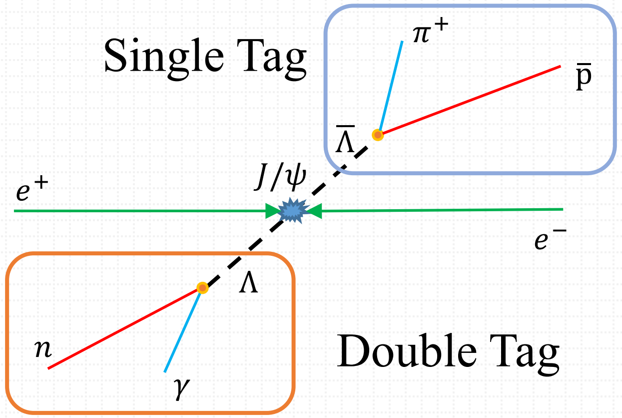
$\Delta\Phi = (0.257 \pm 0.061 \pm 0.009)$ rad

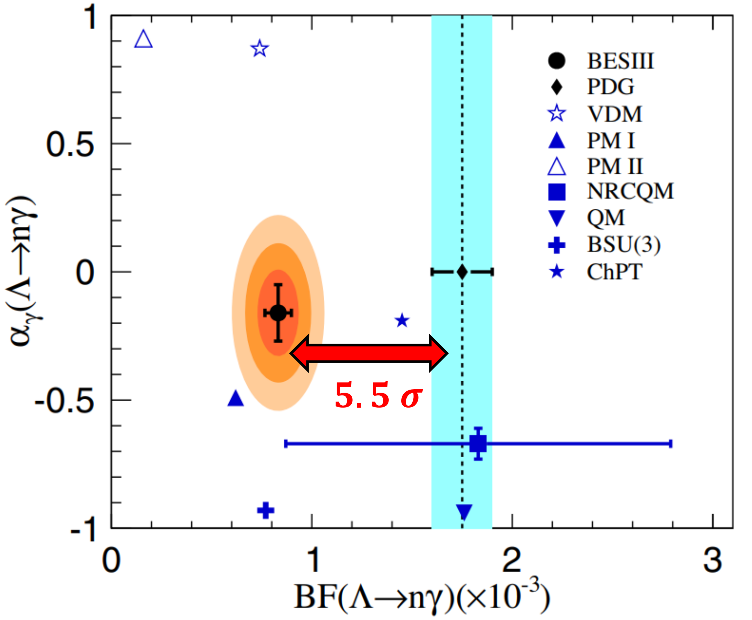
Radiative decay: $\Lambda \rightarrow n\gamma$ in $J/\psi \rightarrow \Lambda\bar{\Lambda}$

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







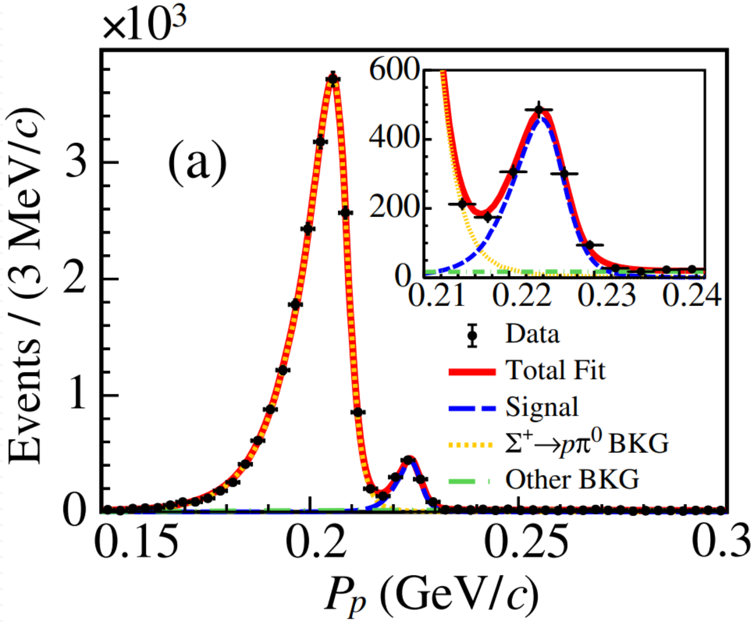


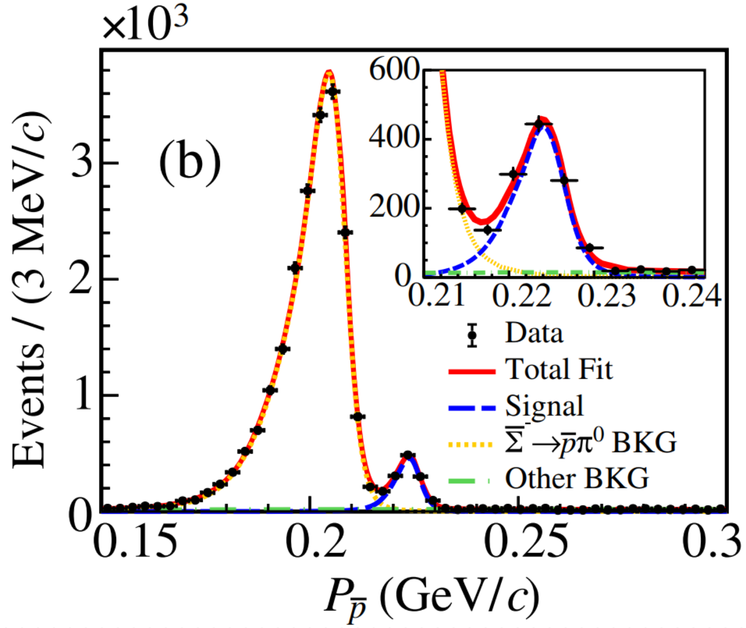
Variables	$\Lambda \rightarrow \gamma n (\times 10^{-3})$	$\bar{\Lambda} \rightarrow \gamma\bar{n} (\times 10^{-3})$	Combined$(\times 10^{-3})$
BF	$0.834 \pm 0.046 \pm 0.064$	$0.876 \pm 0.071 \pm 0.082$	$0.832 \pm 0.038 \pm 0.054$
α_γ	$-0.13 \pm 0.13 \pm 0.02$	$0.21 \pm 0.15 \pm 0.06$	$-0.16 \pm 0.10 \pm 0.05$
Δ_{CP}	$-0.025 \pm 0.049 \pm 0.060$		
A_{CP}	$-0.25 \pm 0.61 \pm 0.15$		

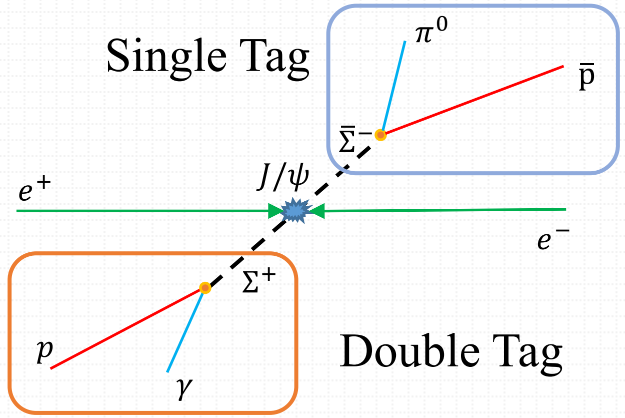
BF of $\Lambda \rightarrow n\gamma$, with improved precision, smaller than PDG value by 5.5σ

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

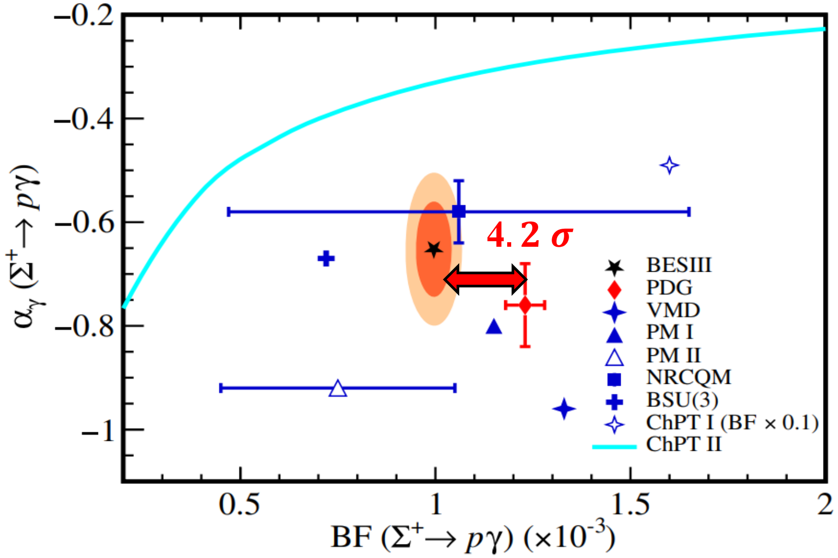
Phys. Rev. Lett. 130, 211901(2023)







The decay rate deviates from previous value by 4.2σ



The most precise branching fraction and decay parameter of $\Sigma^+ \to p\gamma$:

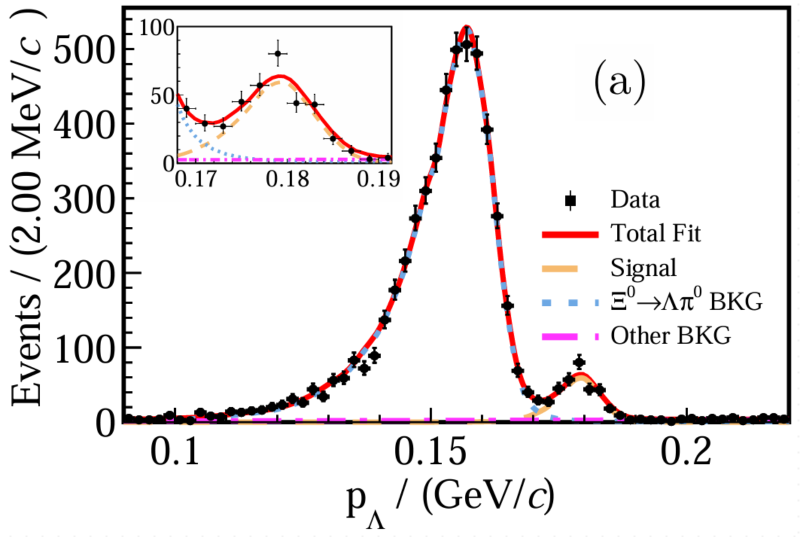
- $\mathcal{B}(\Sigma^+ \to p\gamma) = (0.996 \pm 0.021 \pm 0.018) \times 10^{-3}$
- $\alpha_\gamma = -0.652 \pm 0.056 \pm 0.020$

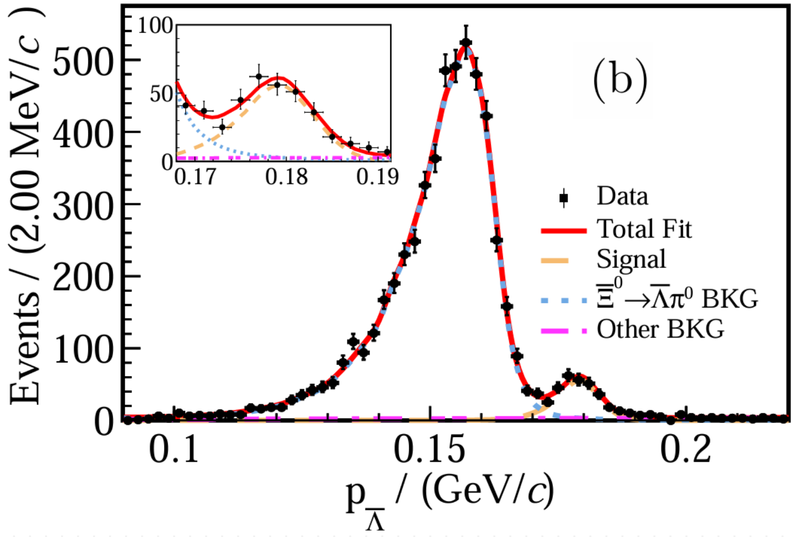
The CP asymmetry is calculated to be:

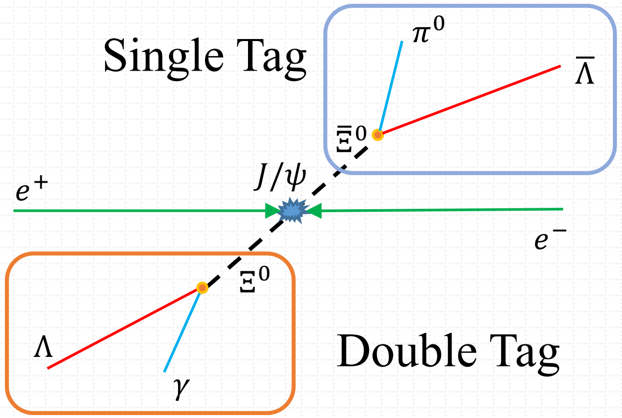
- $A_{CP} = (\alpha_- + \alpha_+)/(\alpha_- - \alpha_+) = 0.095 \pm 0.087 \pm 0.018$
- $\Delta_{CP} = (\mathcal{B}_+ - \mathcal{B}_-)/(\mathcal{B}_+ + \mathcal{B}_-) = 0.006 \pm 0.011 \pm 0.004$

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

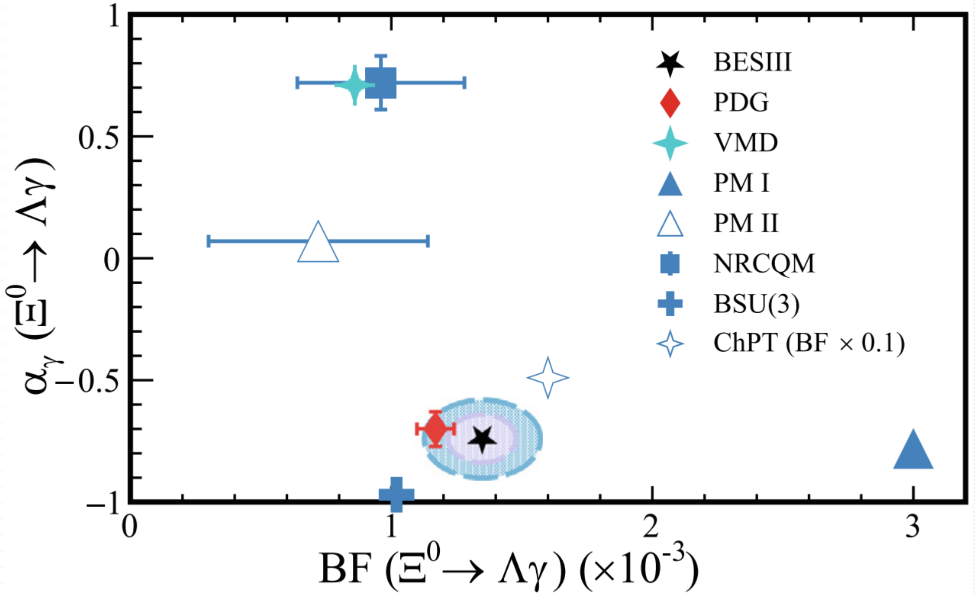
Sci. Bull. 70 (2025) 454-459







$$\mathcal{B}(\Xi^0 \to \Lambda\gamma) = \frac{N_{DT}}{N_{ST}} \times \frac{\epsilon_{ST}}{\epsilon_{DT}} \times \frac{1}{\mathcal{B}(\Lambda \to p\pi^-)}$$

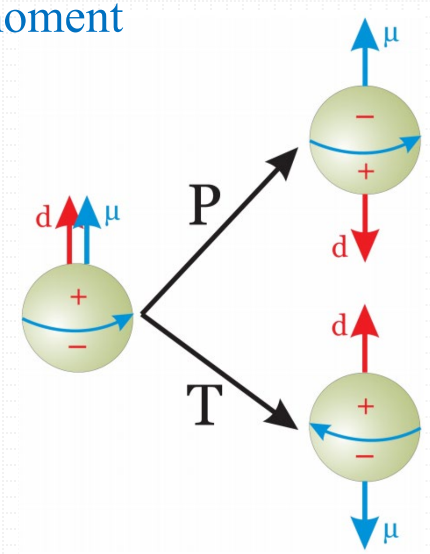


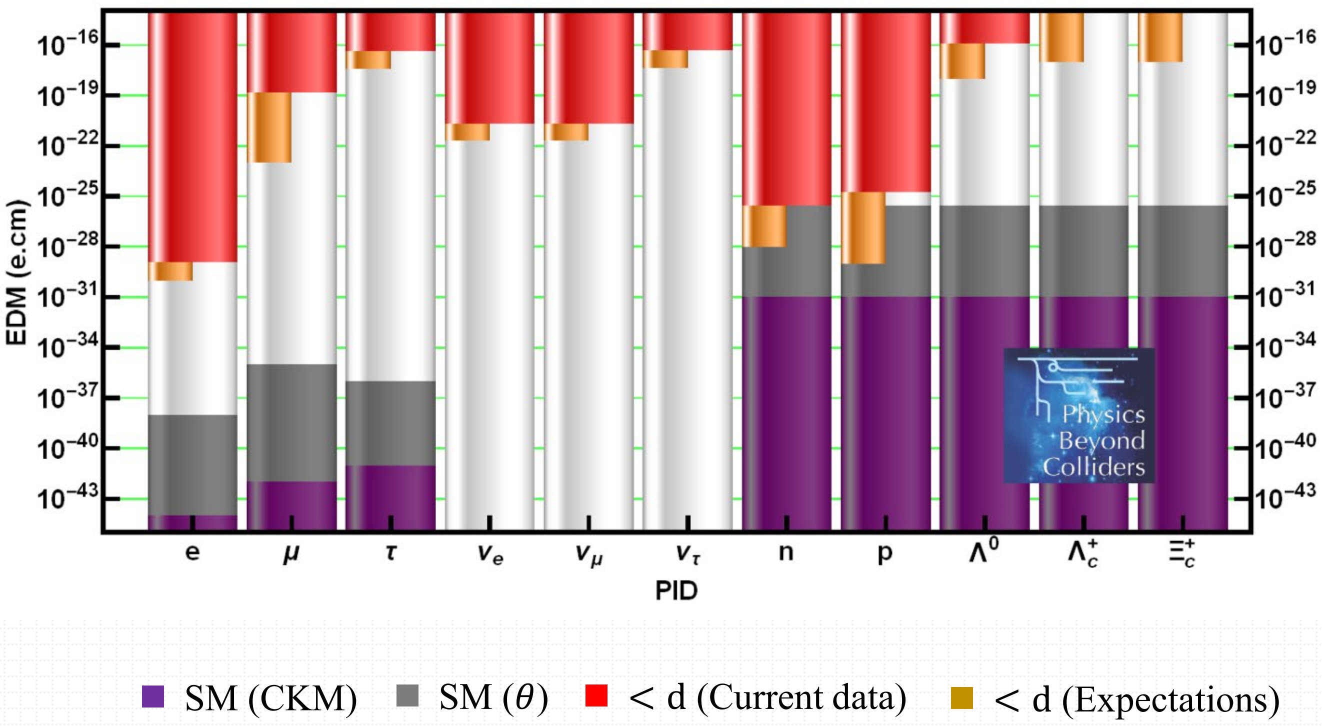
Channels	$\Xi^0 \to \Lambda\gamma$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$
Individual BF(10^{-3})	$1.348 \pm 0.090 \pm 0.054$	$1.326 \pm 0.098 \pm 0.066$
Combined BF(10^{-3})	$1.347 \pm 0.066 \pm 0.054$	
Individual $\alpha_\gamma(\bar{\alpha}_\gamma)$	$-0.652 \pm 0.092 \pm 0.016$	$0.830 \pm 0.080 \pm 0.044$
Combined α_γ	$-0.741 \pm 0.062 \pm 0.019$	

First CP test in $\Xi^0 \to \Lambda\gamma$: $A_{CP} = -0.120 \pm 0.084 \pm 0.029$

Search for hyperon electric dipole moments at BESIII

μ: magnetic moment
d: EDM





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

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.

Traditional approach and its Limitations

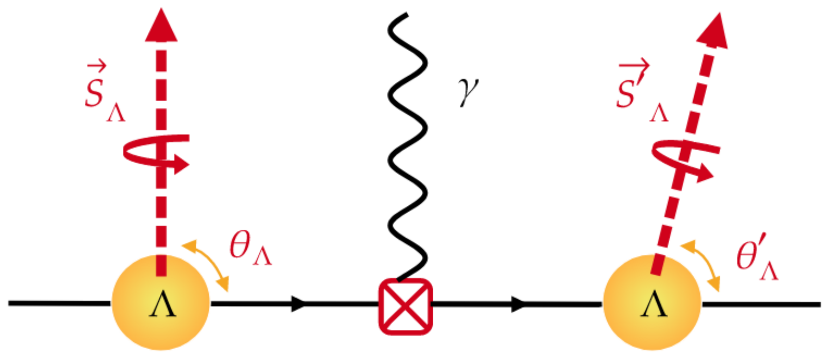
$H = -\mu \cdot B - d \cdot E$

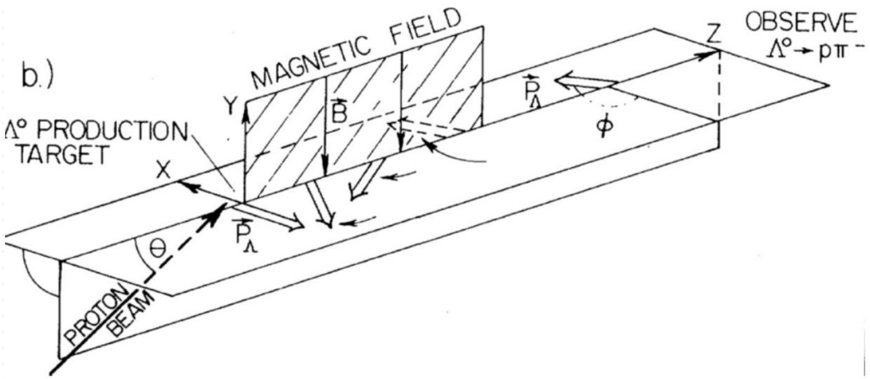
- Method: Measure EDM via spin precession induced by an external EM field
  - $\vec{S}_\Lambda$ and $\vec{S}'_\Lambda$: Spin directions of the Λ before and after precession
  - θ_Λ and θ'_Λ: Angles between spin and momentum

- Applications: Successfully applied to electrons, neutrons, protons, etc.

- Challenges:
  - Short lifetime: $\sim 10^{-10} s$, limiting precession time
  - Low polarization: Difficult to produce highly polarized hyperon beams

- Current Status: Only the EDM of the Λ hyperon has been explored. The most stringent upper limit, 1.5×10^{-16} e·cm, comes from a 1981 Fermilab experiment, with significant room for improvement.





Phys. Rev. D23 (1981) 814

$d_\Lambda < 1.5\times10^{-16} e$ cm @ 95% C.L.

Phys. Rev. Lett. 41 (1978) 1348

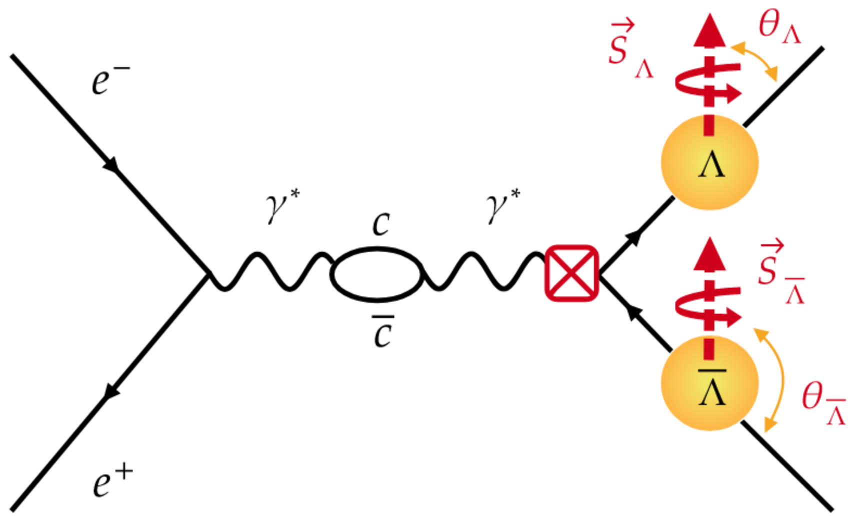
$\mu_\Lambda = (-0.613 \pm 0.004)\mu_N$

New method: prob EDM by using entangled hyperon pairs

- Core idea: Exploit spin-entangled hyperon pairs produced in the process $e^+e^- \to J/\psi \to B\bar{B}$

- Mechanism:
  - The $J/\psi \to B\bar{B}$ decay involves strong, electromagnetic (QED), and weak interactions
  - The dominant contributions arise from non-perturbative QCD
  - The internal structure and dynamics of B are encoded in energy-dependent form factors

- Source of CPV: characterized by CPV FF H_T, which primarily originates from B EDM (d_B) mediated by virtual photon exchange



Extract EDM through CP-violating FF $H_T(q^2)$

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

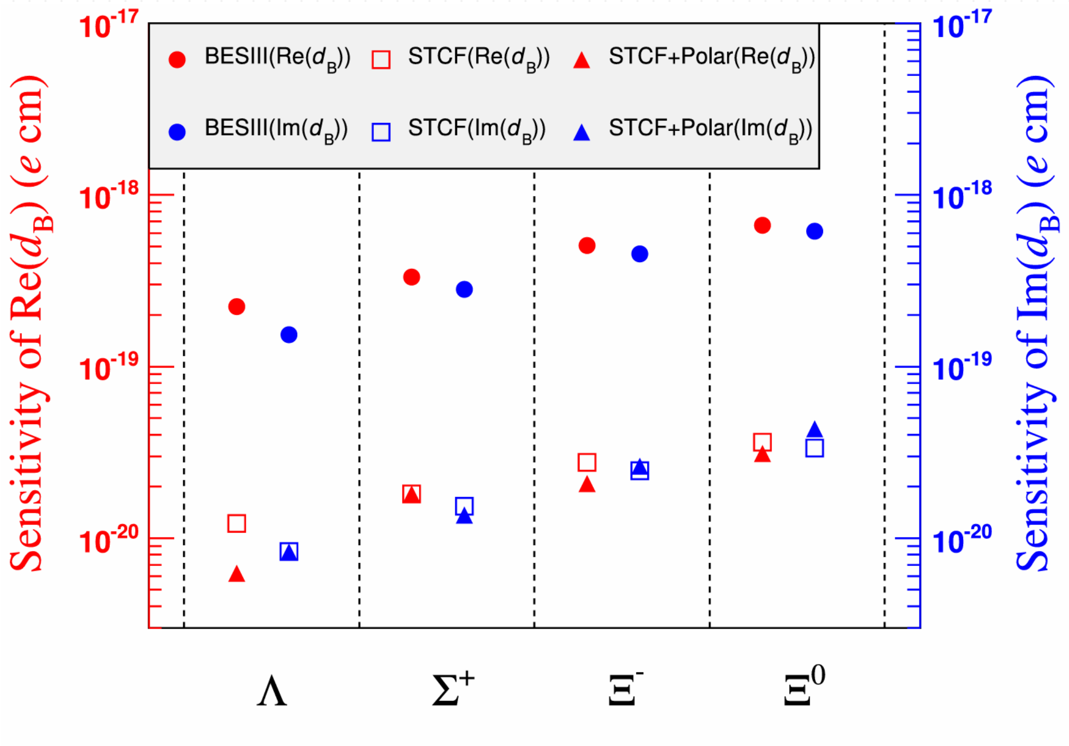
Assuming $d_B(q^2) \equiv d_B(0)$

Proposed by

X.G. He, J.P. Ma, Phys. Lett. B 839(2023)137834

X.G. He, J.P. Ma, B. McKellar, Phys. Rev. D 47 (1993) R1744-R1746

Sensitivities of hyperon EDM at BESIII



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

J. Fu, H.B. Li, J. Wang, F. Yu, and J. Zhang, PhysRevD.108.L091301

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 more than one order of magnitude

World's most precise Λ EDM measurement

- 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:

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

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

BESIII: arXiv:2506.19180

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

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

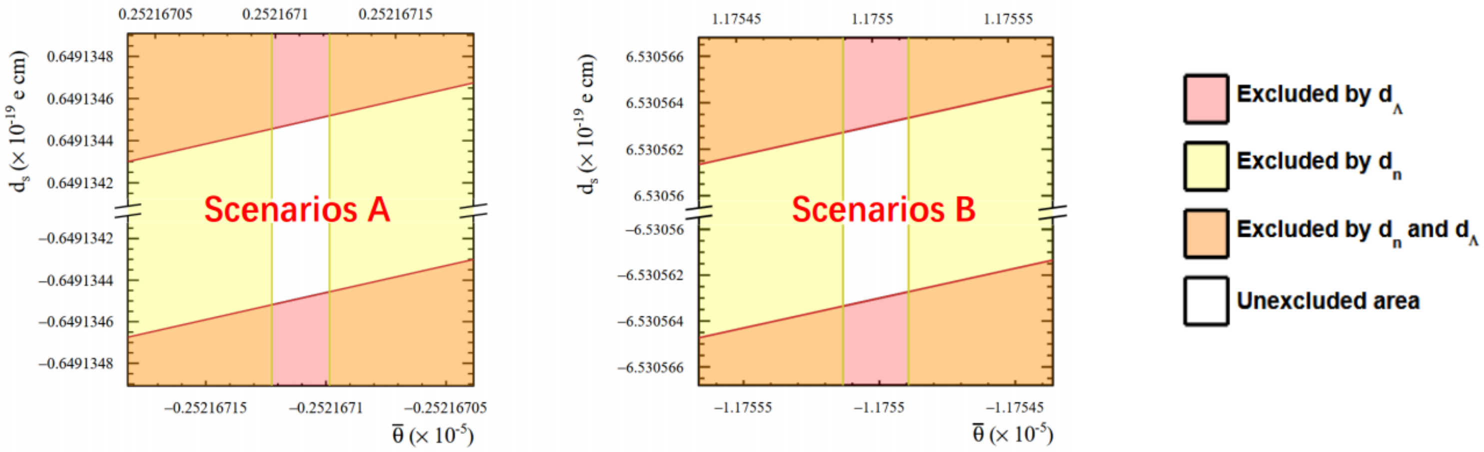
- The Λ EDM is sensitive to the **QCD vacuum angle ($\bar{\theta}$)** and the **strange quark EDM (d_s).**
- **Effective EDM relation** from theory**:**

$$d_\Lambda = (-2.6 \pm 0.4) \times 10^{-16} \bar{\theta}\, e\, \mathrm{cm} + d_s$$
$$d_n = -(1.5 \pm 0.7) \times 10^{-16} \bar{\theta}\, e\, \mathrm{cm} - (0.20 \pm 0.01) d_u + (0.78 \pm 0.03) d_d + (0.0027 \pm 0.0016) d_s$$

- Combining Λ and neutron EDM constraints allows tighter exclusion of BSM scenarios.

A. With SU(3) flavor symmetry: $d_u = d_d = d_s$

B. Without SU(3) symmetry: $d_s \gg d_u, d_d$



Complementarity of Λ hyperon and neutron EDMs

K. C. Chen, X. G. He, J. P. Ma, X. B. Tong, Phys. Rev. Lett. 136 (2026) 5, 051902

$\tilde{d}$: chromo-electric dipole moments

$$d_\Lambda = 5.29 \times 10^{-4} d_s + 4.61 \times 10^{-5}(d_u + d_d) + 6.21 \times 10^{-5} e\tilde{d}_s + 1.98 \times 10^{-5} e\tilde{d}_d - 2.14 \times 10^{-5} e\tilde{d}_u$$

$$d_n = -(0.20 \pm 0.01)d_u + (0.78 \pm 0.03)d_d + (0.0027 \pm 0.0016)d_s - (0.55 \pm 0.28)e\tilde{d}_u - (1.1 \pm 0.55)e\tilde{d}_d$$

The QCD theta-term is neglected

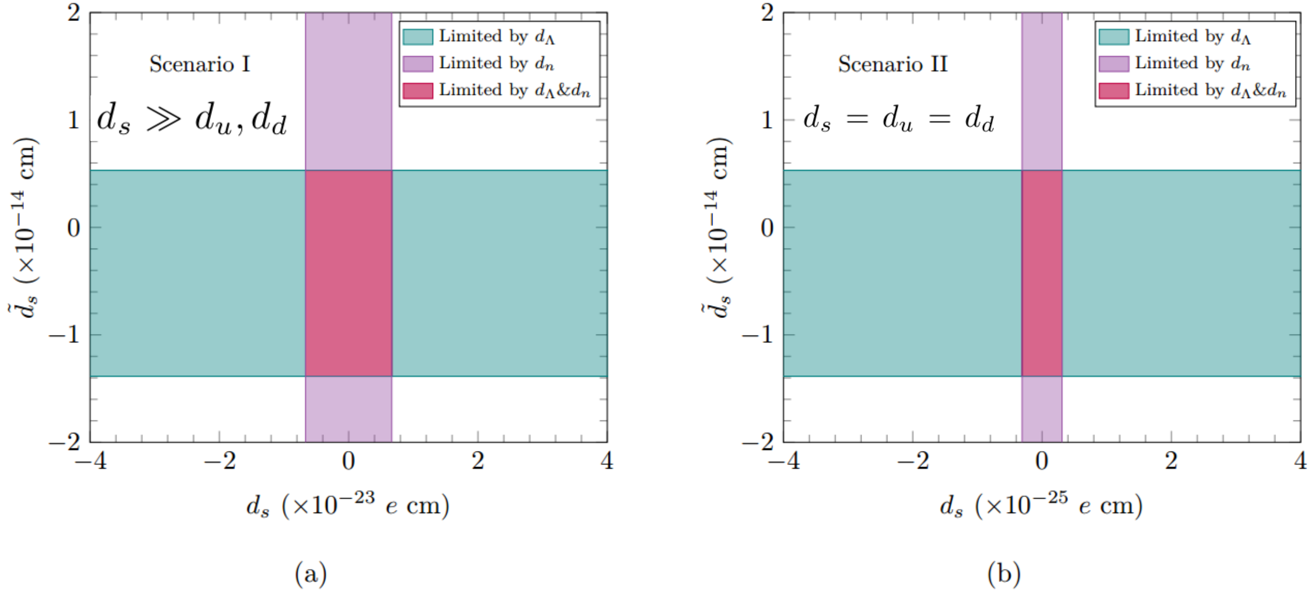


Figure 2: Constraints on the s-quark EDM d_s and CEDM $\tilde{d}_s$ from the measurements on the Λ and n EDMs.

Limitations of the Neutron EDM:

- Sensitive mainly to the EDMs of up and down quarks.
- Insensitive to the chromo-EDM of the strange quark ($\tilde{d}_s$)

Unique Advantage of the Λ Hyperon EDM:

- Particularly sensitive to the strange quark chromo-EDM

Complementary Information:

- Λ EDM provides information on the strange quark chromo-EDM that cannot be accessed via the neutron EDM

Summary

- BESIII has made fruitful achievements in hyperon CP study!
  - CP tests in hyperon non-leptonic decays
  - BF measurements and CP tests in hyperon radiative decays
  - Hyperon EDM measurements

- More exciting hyperon results are expected in the near future.
  - EDM measurements for Σ, Ξ, Ω are on the way

Thank you!

Backup

Test of $\Delta I = 1/2$ rule in hyperon decays

- In the weak interaction, the isospin is not a conserved quantity, however, there is an experimentally well-established empirical rule -- $\Delta I = 1/2$ rule.

- The $\Delta I = 1/2$ rule allows only those decay transitions in which the change in the total isospin is 1/2.

- Originally, this rule is found in the kaon decays $K \to \pi\pi$, which give the ratio between the $\Delta I = 3/2$ amplitude and the $\Delta I = 1/2$ amplitude: $\frac{Re(A2)}{Re(A0)} = 0.0445 \pm 0.0001 \approx 1/22.47$. In hyperon decays, there are no observations of the existence of the $\Delta I = 3/2$ component before the BESIII measurements.

V. Cirigliano, G. Ecker, H. Neufeld, A. Pich, and J. Portoles, Rev. Mod. Phys. 84, 399 (2012).

Dynamics of the Standard Model, section XII–6

DOI: 10.1017/9781009291033

$$W(\theta) = 1 + \alpha \mathbf{P}_B \cdot \hat{\mathbf{p}}_{B'}, \qquad \alpha = \frac{2\mathrm{Re}\,(A^* \bar{B})}{|A|^2 + |\bar{B}|^2}, \tag{6.4}$$

and the polarization $\langle \mathbf{P}_{B'} \rangle$ of the final-state baryon,

$$\langle \mathbf{P}_{B'} \rangle = \frac{(\alpha + \mathbf{P}_B \cdot \hat{\mathbf{p}}_{B'})\, \hat{\mathbf{p}}_{B'} + \beta\,(\mathbf{P}_B \times \hat{\mathbf{p}}_{B'}) + \gamma\,[\hat{\mathbf{p}}_{B'} \times (\mathbf{P}_B \times \hat{\mathbf{p}}_{B'})]}{W(\theta)},$$

$$\beta = \frac{2\mathrm{Im}(A^* \bar{B})}{|A|^2 + |\bar{B}|^2}, \qquad \gamma = \frac{|A|^2 - |\bar{B}|^2}{|A|^2 + |\bar{B}|^2} = \pm\sqrt{1 - \alpha^2 - \beta^2}, \tag{6.5}$$

where $\mathbf{P}_B$ is the polarization of B and $\hat{\mathbf{p}}_{B'}$ is a unit vector in the direction of motion of B'. Experimental studies of these distributions lead to the amplitudes listed in Table XII–5.

The nonleptonic amplitudes may be decomposed into isospin components in a notation where superscripts refer to $\Delta I = 1/2,\ 3/2$,

$$\begin{aligned}
A_{\Lambda\to p\pi^-} &= \sqrt{2}\, A_\Lambda^{(1)} - A_\Lambda^{(3)}, & A_{\Sigma^-\to n\pi^-} &= A_\Sigma^{(1)} + A_\Sigma^{(3)},\\
A_{\Lambda\to n\pi^0} &= -A_\Lambda^{(1)} - \sqrt{2}\, A_\Lambda^{(3)}, & A_{\Sigma^+\to n\pi^+} &= \frac{1}{3}A_\Sigma^{(1)} - \frac{2}{3}A_\Sigma^{(3)} + X_\Sigma,\\
A_{\Xi^0\to\Lambda\pi^0} &= -A_\Xi^{(1)} - \sqrt{2}\, A_\Xi^{(3)}, & \sqrt{2}\, A_{\Sigma^+\to p\pi^0} &= -\frac{2}{3}A_\Sigma^{(1)} + \frac{4}{3}A_\Sigma^{(3)} + X_\Sigma,\\
A_{\Xi^-\to\Lambda\pi^-} &= \sqrt{2}\, A_\Xi^{(1)} - A_\Xi^{(3)},
\end{aligned} \tag{6.6}$$

and X_Σ is of mixed symmetry. Similar relations hold for the B amplitudes. From

A stands for S-wave amplitude
B stands for P-wave amplitude

If only $\Delta I = 1/2$ component exists:

$$A_{\Lambda\to p\pi^-} = -\sqrt{2} A_{\Lambda\to n\pi^0},$$
$$B_{\Lambda\to p\pi^-} = -\sqrt{2} B_{\Lambda\to n\pi^0},$$

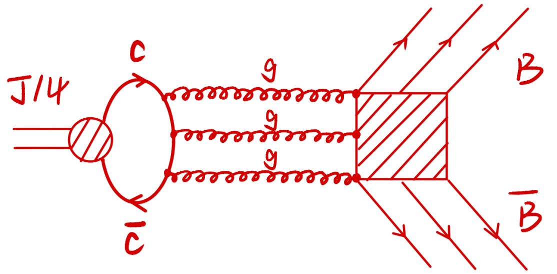
then $\alpha_{\Lambda\to p\pi^-} = \alpha_{\Lambda\to n\pi^0}$

Searching for hyperon EDM at BESIII

Phys.Lett.B 839(2023)137834

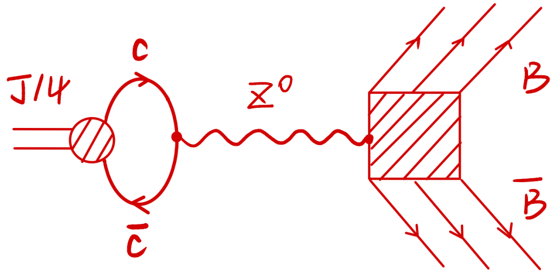
Detailed dynamics in J/ψ decay to hyperon pair, have been studied:

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



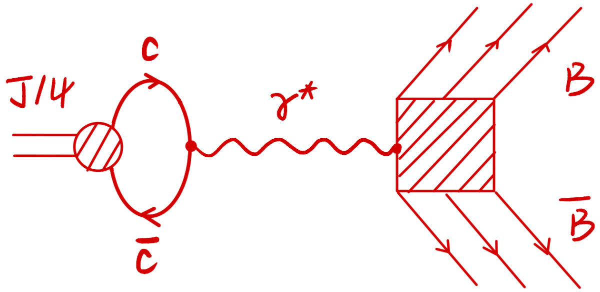
Dominant contribution
arXiv:hep-ph/0412158

Psionic form factor
$\boldsymbol{F_V}$ and $\boldsymbol{H_\sigma}$
can also be represented as $\boldsymbol{G_1}$ and $\boldsymbol{G_2}$



P violation term

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



$\boldsymbol{H_T}$ 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
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