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

北京谱仪上 Λ 超子量子关联产生与衰变性质的研究

第一届Lambda超子自旋极化跨系统研讨会

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Outline

- CP tests in hyperon decays
- Recent results from BESIII
- Hyperon CP test in future plans
- Summary and outlooks

CP tests in hyperon decays

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.**
- **No observation of CPV in the baryon system.**

Very recent news from LHCb!

3σ evidence in Λ_b decay:

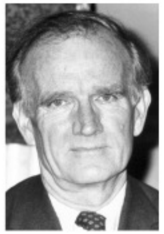
$\Lambda_b \to \Lambda K^+ K^-$

Phys. Rev. Lett. 134, (2025) 101802

K meson CPV | B meson CPV | D meson CPV | Baryon?

1964 | 2001 | 2019

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)

To generate the baryon asymmetry world, there should be a non-SM CPV source?

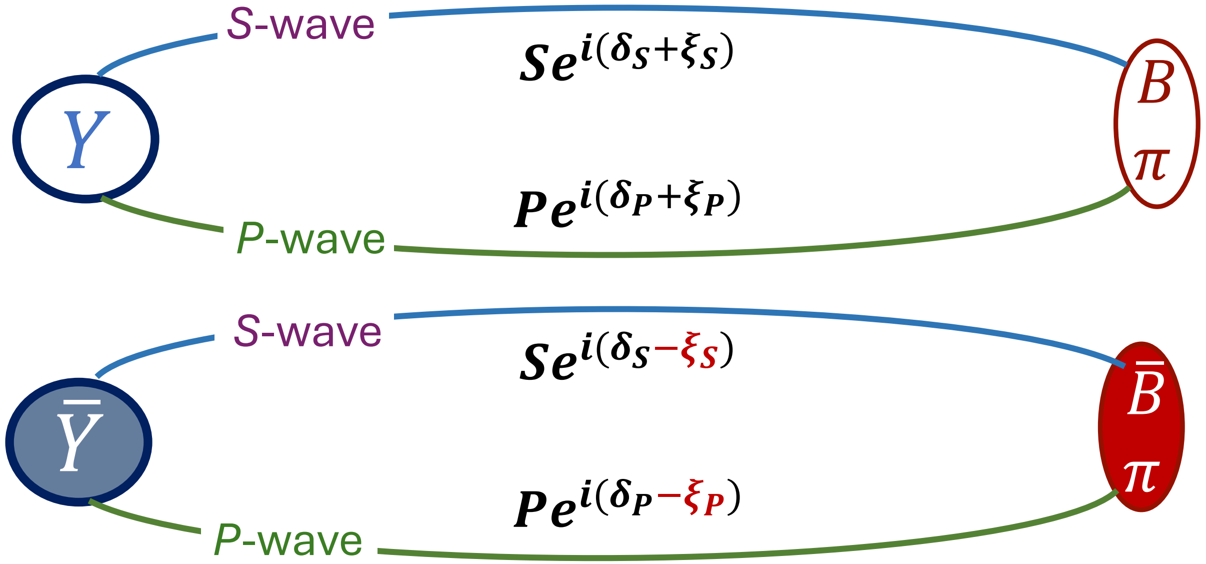
Two conditions for a measurable CP violation

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

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

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

Spin-1/2 hyperon



Spin-1/2 baryon

Suitable for CPV searches!

CPV measurement via Lee-Yang parameter

For spin-1/2 hyperon decay to spin-1/2 baryon and a spin-0 meson, the relation between parent (P_Y) and daughter (P_d) polarization vectors is:

$$\mathbf{P}_d = \frac{(\alpha_Y + \mathbf{P}_Y \cdot \hat{\mathbf{p}}_d)\,\hat{\mathbf{p}}_d + \beta_Y \mathbf{P}_Y \times \hat{\mathbf{p}}_d + \gamma_Y \hat{\mathbf{p}}_d \times (\mathbf{P}_Y \times \hat{\mathbf{p}}_d)}{(1 + \alpha_Y \mathbf{P}_Y \cdot \hat{\mathbf{p}}_d)}$$

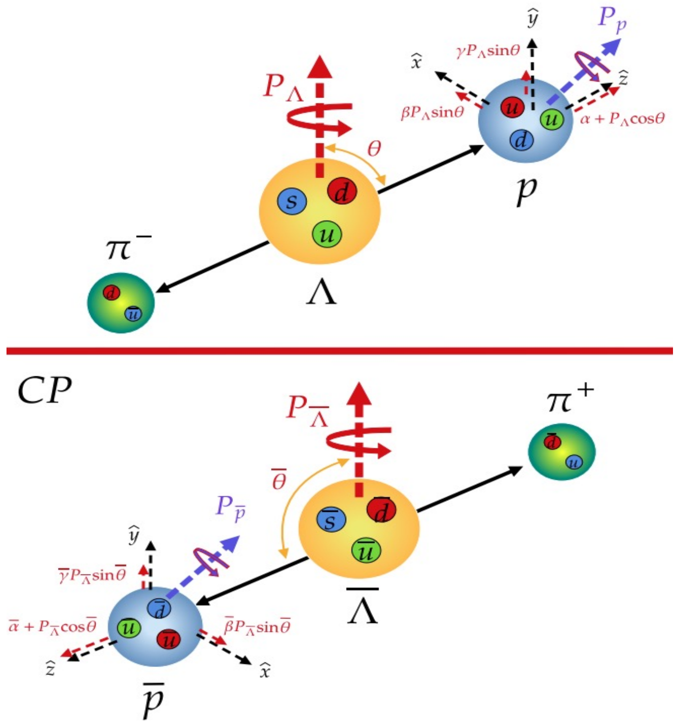
And the Lee-Yang parameters are defined by S and P wave:

$$\alpha_Y = \frac{2\,\mathrm{Re}\,(S^* P)}{|S|^2 + |P|^2},$$ — P_Y or P_d

$$\beta_Y = \frac{2\,\mathrm{Im}\,(S^* P)}{|S|^2 + |P|^2},$$ — P_Y and P_d

$$\gamma_Y = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$ — P_Y and P_d

Can be measured if



Phys. Rev. 108, 1645 (1957)

$$\alpha = \frac{2Re(S*P)}{|S|^2 + |P|^2},$$

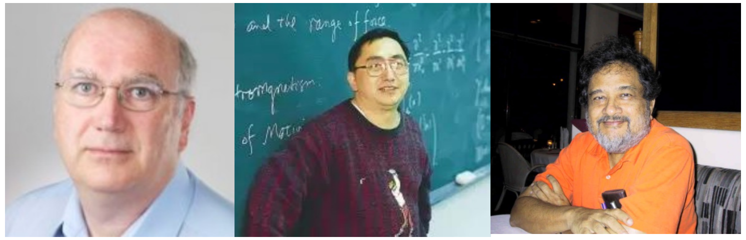
$$\beta = \frac{2Im(S*P)}{|S|^2 + |P|^2} = \sqrt{1 - \alpha^2} sin\phi$$

CP observables:

$$A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$

$$\phi_{CP} = \frac{\phi - \bar{\phi}}{2}$$

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
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(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

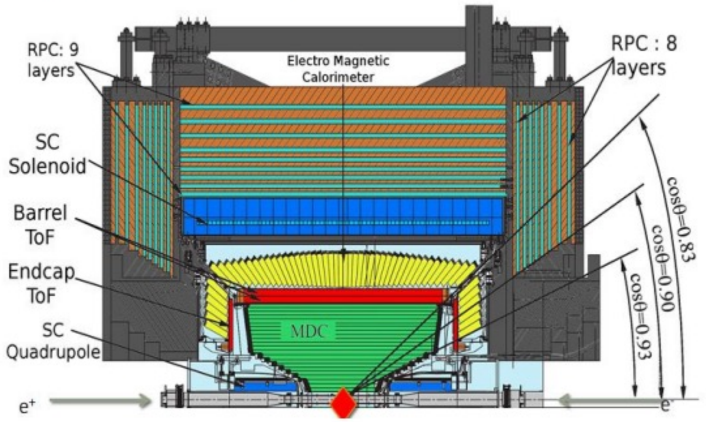
			SM Prediction of Λ decay
Not sensitive to *CPV*	**Decay width difference**	$\Delta = \frac{\Gamma-\bar{\Gamma}}{\Gamma+\bar{\Gamma}} \approx \sqrt{2}\frac{T_{\frac{3}{2}}}{T_{\frac{1}{2}}}\sin\Delta_s \sin\phi_{CP}$	-5.4×10^{-7}
Easiest to measure	**Decay parameter difference**	$A = \frac{\Gamma\alpha+\bar{\Gamma}\bar{\alpha}}{\Gamma\alpha-\bar{\Gamma}\bar{\alpha}} \approx \tan\Delta_s \tan\phi_{CP}$	-0.5×10^{-4}
Polarization of decayed baryon needs to be measured	**Decay parameter difference**	$B = \frac{\Gamma\beta+\bar{\Gamma}\bar{\beta}}{\Gamma\alpha-\bar{\Gamma}\bar{\alpha}} \approx \tan\phi_{CP}$	3.0×10^{-3}

Ξ^-, Ξ^0, Ω^- cascade decay

BESIII: a hyperon factory

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, $\sim 10^7$ 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.

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

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

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

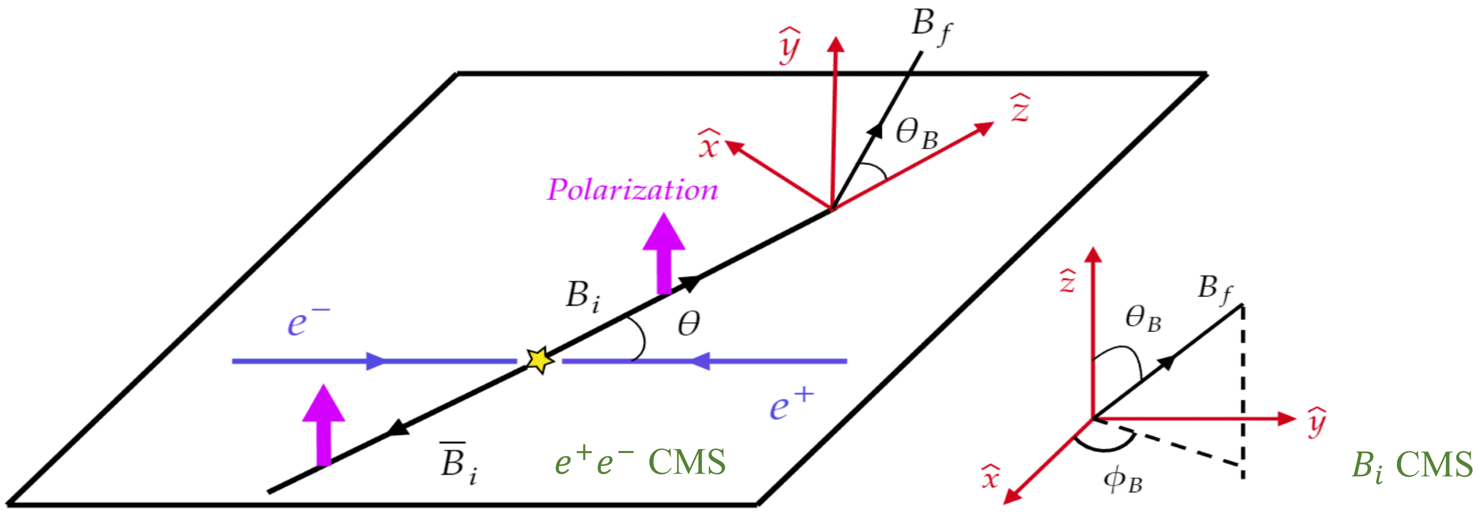
- The form factors G_E,G_M construct the production parameters:

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

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

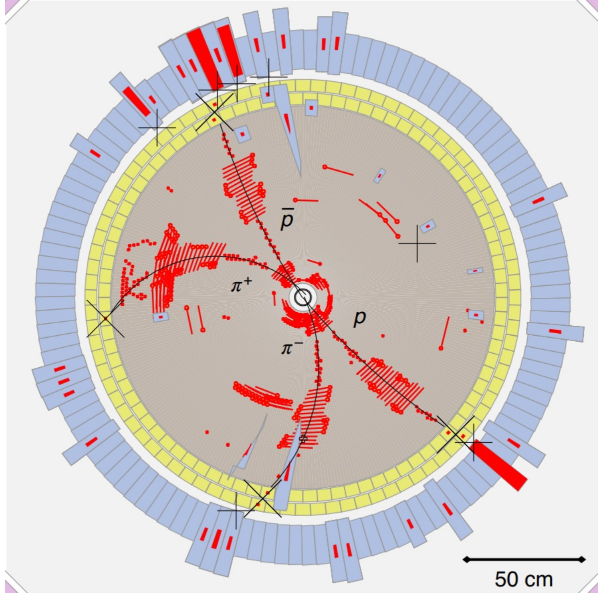
- Angular distribution

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



Recent results from BESIII

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



Differential cross-section of this process:

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

spin-correlation

polarization

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

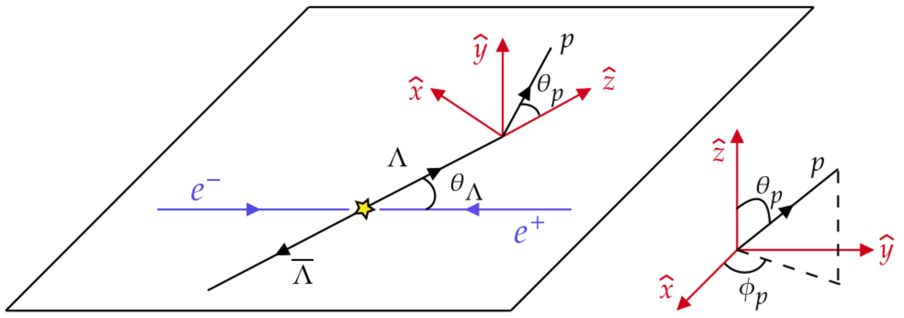
↓

Independent 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)



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

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

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

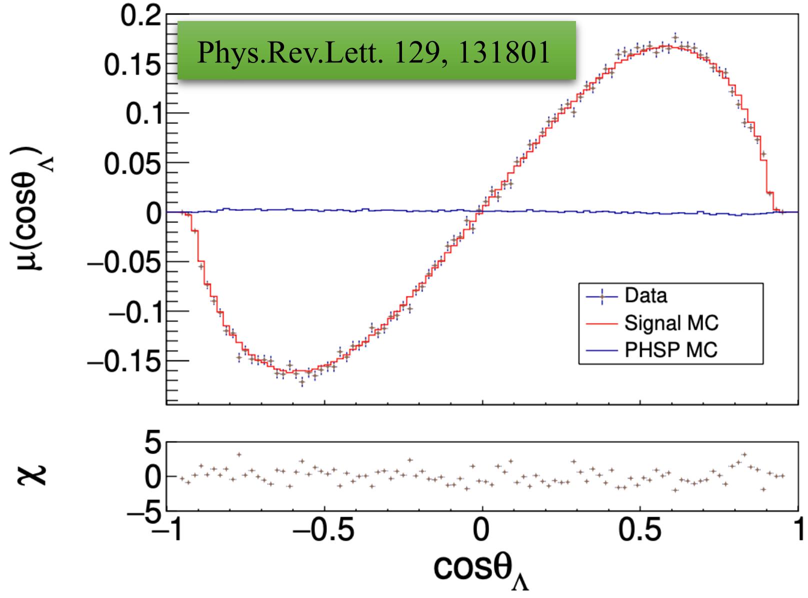
[2] 10 billion: Phys.Rev.Lett. 129 (2022) 13, 131801

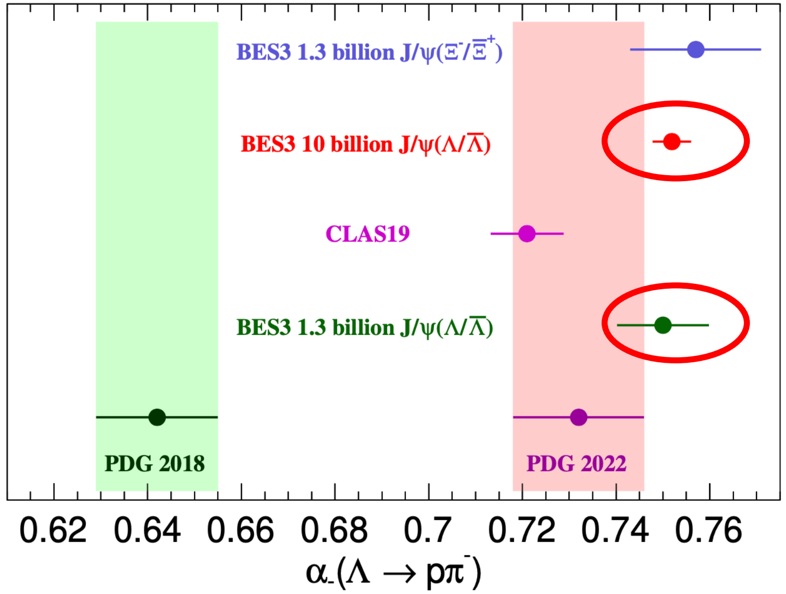
- Most precise values for Λ decay parameter
- One of the most precise CP test in the hyperon sector:

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

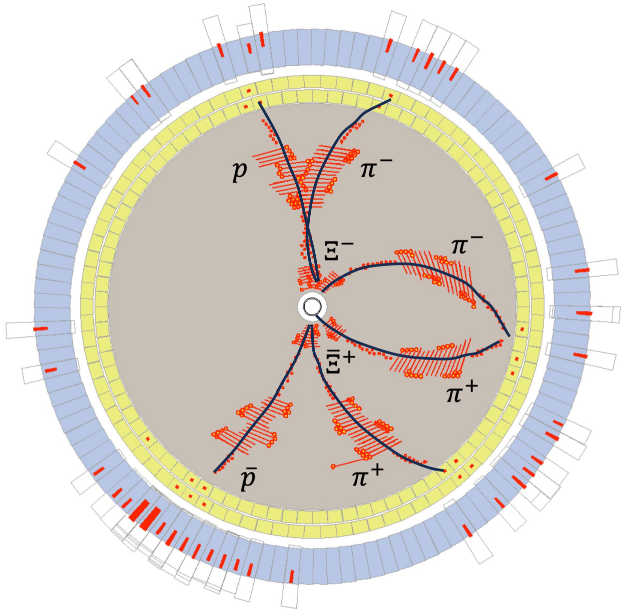
Standard mode prediction : $A_{CP} \sim 10^{-4}$ (PRD 34, 833 (1986))

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}	$0.7542 \pm 0.0010 \pm 0.0024$	-





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



- The 9 kinematical variables – 9 dimension PHSP

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

- The 8 free parameters

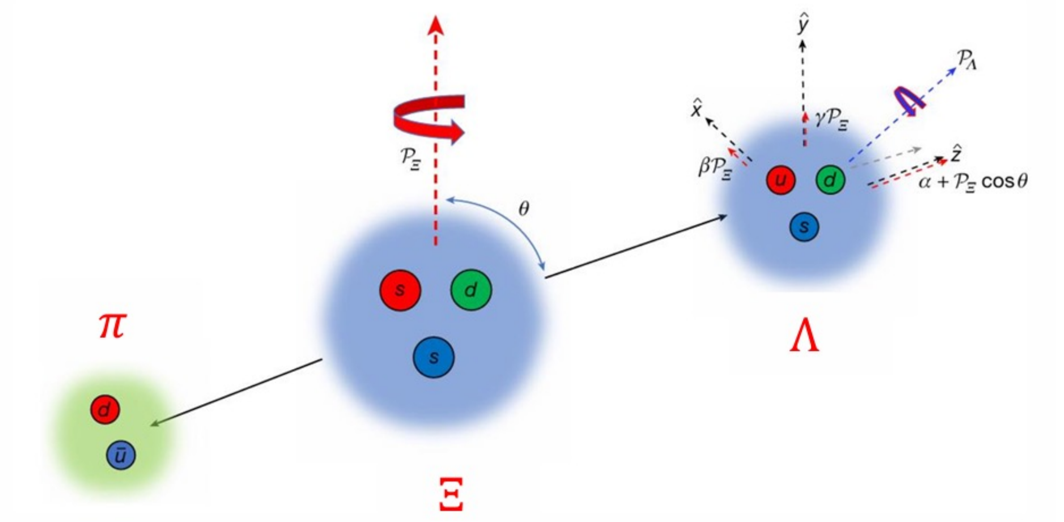
$$\boldsymbol{\omega} = (\alpha_{\psi}, \Delta\Phi, \alpha_{\Xi}, \phi_{\Xi}, \alpha_{\bar{\Xi}}, \phi_{\bar{\Xi}}, \alpha_{\Lambda}, \alpha_{\bar{\Lambda}})$$

Hyperon Production

Hyperon decays

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

Phys. Rev. D 99, 056008 (2019)

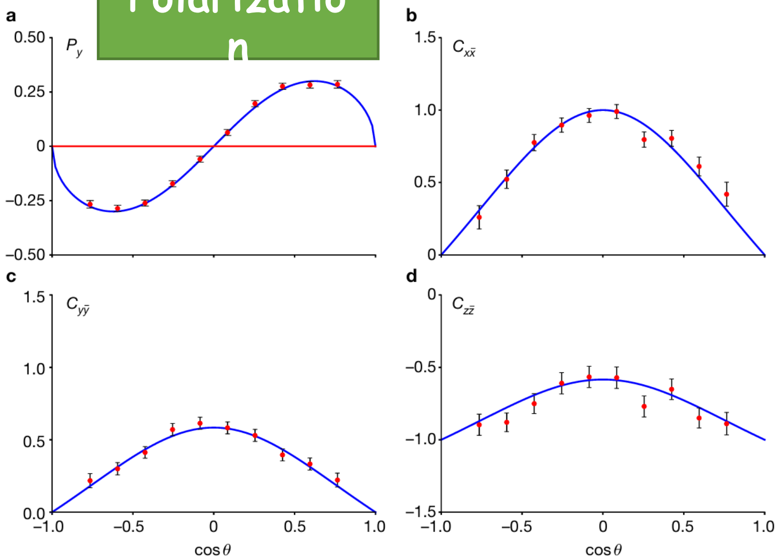


$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$

Nature Vol 606 2 June 2022 | 65

1.3 Billion J/ψ

Polarization



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

Spin Correlation

Parameter	This work	Previous result
α_ψ	0.586±0.012±0.010	0.58±0.04±0.08 [1]
$\Delta\Phi$	1.213±0.046±0.016 rad	–
α_Ξ	−0.376±0.007±0.003	−0.401±0.010 [2]
ϕ_Ξ	0.011±0.019±0.009 rad	−0.037±0.014 rad [2]
$\bar{\alpha}_\Xi$	0.371±0.007±0.002	–
$\bar{\phi}_\Xi$	−0.021±0.019±0.007 rad	–
α_Λ	0.757±0.011±0.008	0.750±0.009±0.004 [3]
$\bar{\alpha}_\Lambda$	−0.763±0.011±0.007	−0.758±0.010±0.007 [3]
$\xi_P - \xi_S$	(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 [4]
A^{Ξ}_{CP}	(6±13±6)×10^{-3}	–
$\Delta\phi^{\Xi}_{CP}$	(−5±14±3)×10^{-3} rad	–
A^{Λ}_{CP}	(−4±12±9)×10^{-3}	(−6±12±7)×10^{-3} [3]
$\langle\phi_\Xi\rangle$	0.016±0.014±0.007 rad	

1. Phys. Rev. D 93, 072003 (2016)
2. PDG 2020
3. Nat. Phys. 15, 631-634 (2019)
4. Phys. Rev. Lett. 93, 011802 (2004)

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

Nature Vol 606 2 June 2022 | 65

1.3 Billion J/ψ

- ✓ First measurement of Ξ polarization
- ✓ First determination of entangled $\Xi\bar{\Xi}$ decay parameters
- ✓ Independent measurement of the Λ decay parameters: in agreement with previous BESIII results
- ✓ First measurement of weak phase difference

$$(\xi_P - \xi_S)_{SM} = (-2.1 \pm 1.7)\times 10^{-4} \text{ rad}$$

Phys. Rev. D 105, 116022 (2022)

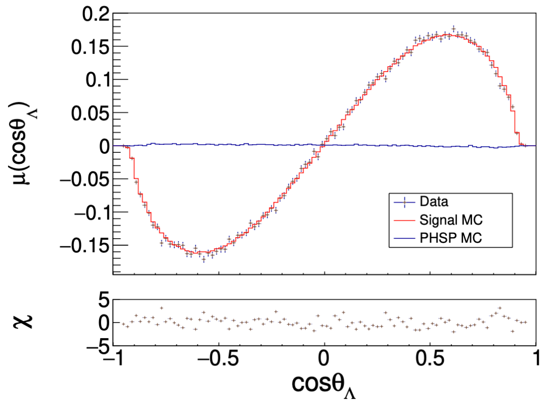
- ✓ First direct CP tests for Ξ hyperon

Parameter	This work	Previous result
α_ψ	$0.586\pm0.012\pm0.010$	$0.58\pm0.04\pm0.08$ [1]
$\Delta\Phi$	$1.213\pm0.046\pm0.016$ rad	–
α_Ξ	$-0.376\pm0.007\pm0.003$	-0.401 ± 0.010 [2]
ϕ_Ξ	$0.011\pm0.019\pm0.009$ rad	-0.037 ± 0.014 rad [2]
$\bar{\alpha}_\Xi$	$0.371\pm0.007\pm0.002$	–
$\bar{\phi}_\Xi$	$-0.021\pm0.019\pm0.007$ rad	–
α_Λ	$0.757\pm0.011\pm0.008$	$0.750\pm0.009\pm0.004$ [3]
$\bar{\alpha}_\Lambda$	$-0.763\pm0.011\pm0.007$	$-0.758\pm0.010\pm0.007$ [3]
$\xi_P-\xi_S$	$(1.2\pm3.4\pm0.8)\times10^{-2}$ rad	–
$\delta_P-\delta_S$	$(-4.0\pm3.3\pm1.7)\times10^{-2}$ rad	$(10.2\pm3.9)\times10^{-2}$ rad [4]
A_{CP}^{Ξ}	$(6\pm13\pm6)\times10^{-3}$	–
$\Delta\phi_{CP}^{\Xi}$	$(-5\pm14\pm3)\times10^{-3}$ rad	–
A_{CP}^{Λ}	$(-4\pm12\pm9)\times10^{-3}$	$(-6\pm12\pm7)\times10^{-3}$ [3]
$\langle\phi_\Xi\rangle$	$0.016\pm0.014\pm0.007$ rad	

1. Phys. Rev. D 93, 072003 (2016)
2. PDG 2020
3. Nat. Phys. 15, 631-634 (2019)
4. Phys. Rev. Lett. 93, 011802 (2004)

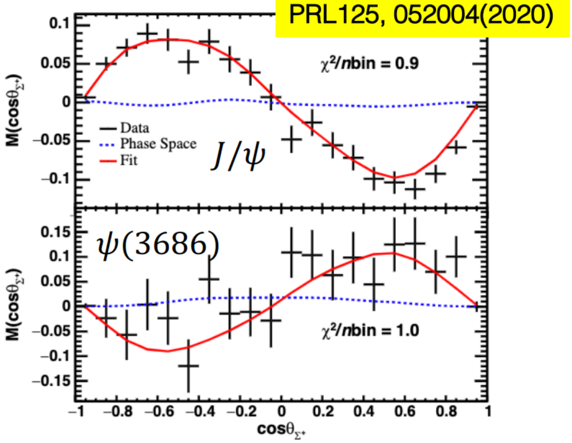
Polarization behavior in different hyperon pair productions

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



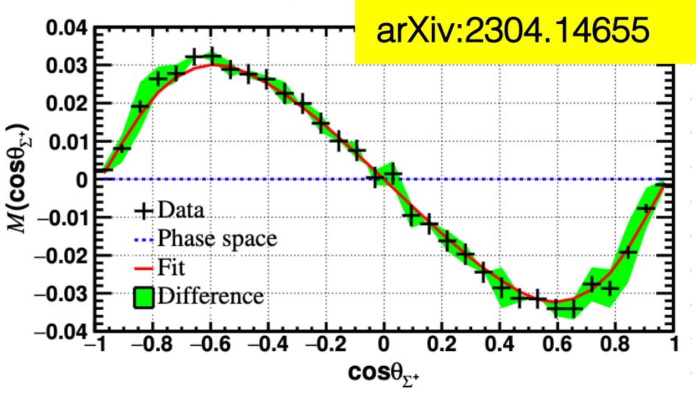
$\Delta\Phi = (0.7521 \pm 0.0042 \pm 0.0066)\,rad$
$A_{CP} = -0.0025 \pm 0.0046 \ \pm 0.0012$

$\psi \to \Sigma^+\bar{\Sigma}^- \to p\pi^0\bar{p}\pi^0$



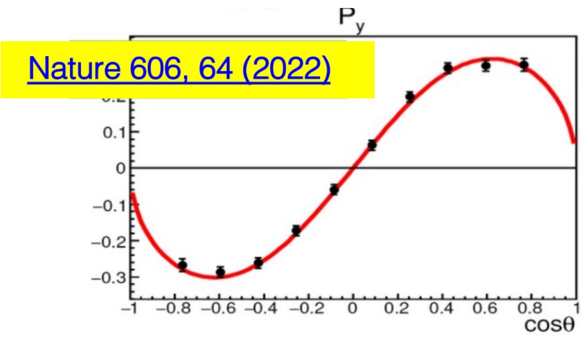
$\Delta\Phi(J/\psi) = (-15.5 \pm 0.7 \ \pm 0.5)^\circ$
$\Delta\Phi(\psi(2S)) = (21.7 \pm 4.0 \ \pm 0.8)^\circ$
$A_{CP} = -0.004 \pm 0.037 \ \pm 0.010$

$J/\psi \to \Sigma^+\bar{\Sigma}^- \to n\pi^+\bar{p}\pi^0$



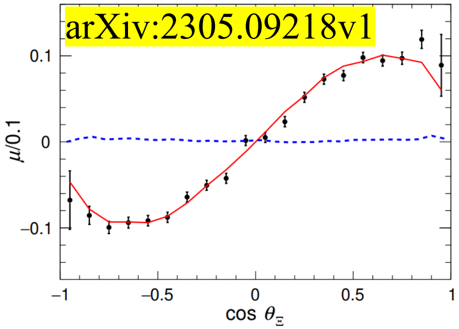
$\Delta\Phi = (-0.277 \pm 0.004 \pm 0.004)\,rad$
$A_{CP} = -0.080 \pm 0.052 \ \pm 0.028$

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



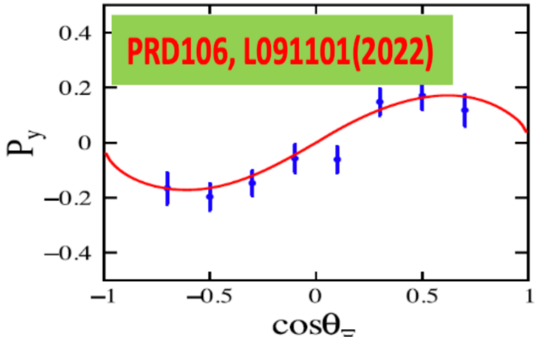
$\Delta\Phi = (1.213 \pm 0.046 \pm 0.016)\,rad$
$A_{CP} = -0.006 \pm 0.013 \ \pm 0.006$

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



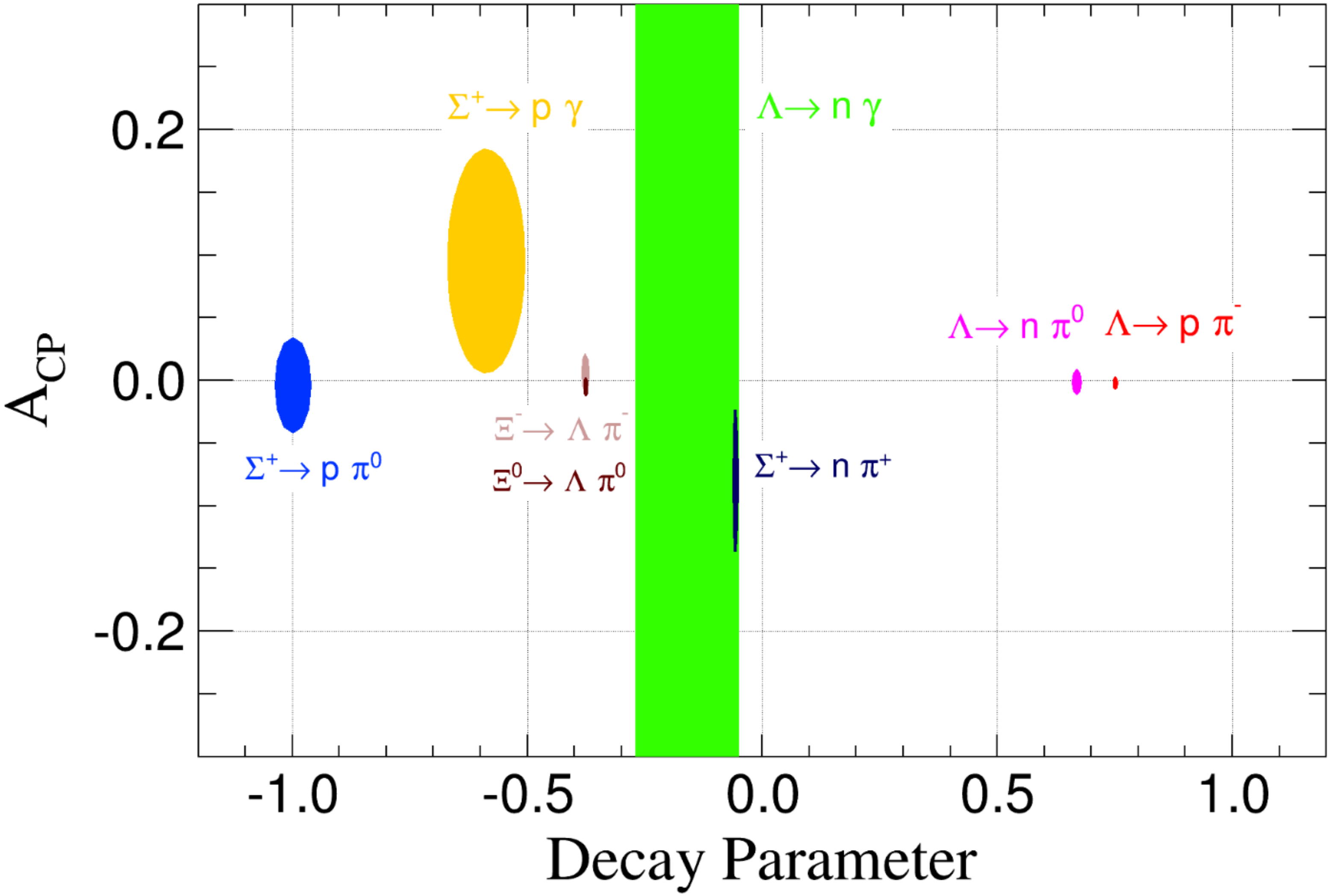
$\Delta\Phi = (1.168 \pm 0.019 \pm 0.018)\,rad$
$A_{CP} = -0.0054 \pm 0.0065 \ \pm 0.0031$

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



$\Delta\Phi = (0.667 \pm 0.111 \pm 0.058)\,rad$
$A_{CP} = -0.015 \pm 0.051 \ \pm 0.010$

Summary of BESIII achievement on hyperon decay



First complete measurement of Λ E&M form-factors

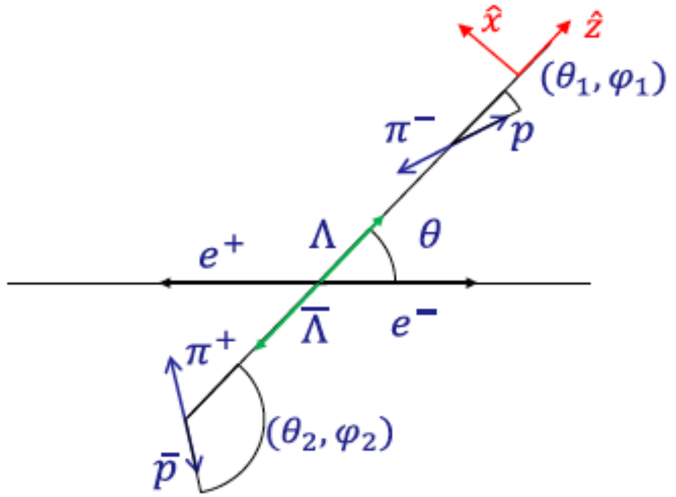
First measurement of the relative phase
(E_{cm}=2.396 GeV , $\mathcal{L}$=66.9 pb^{-1})

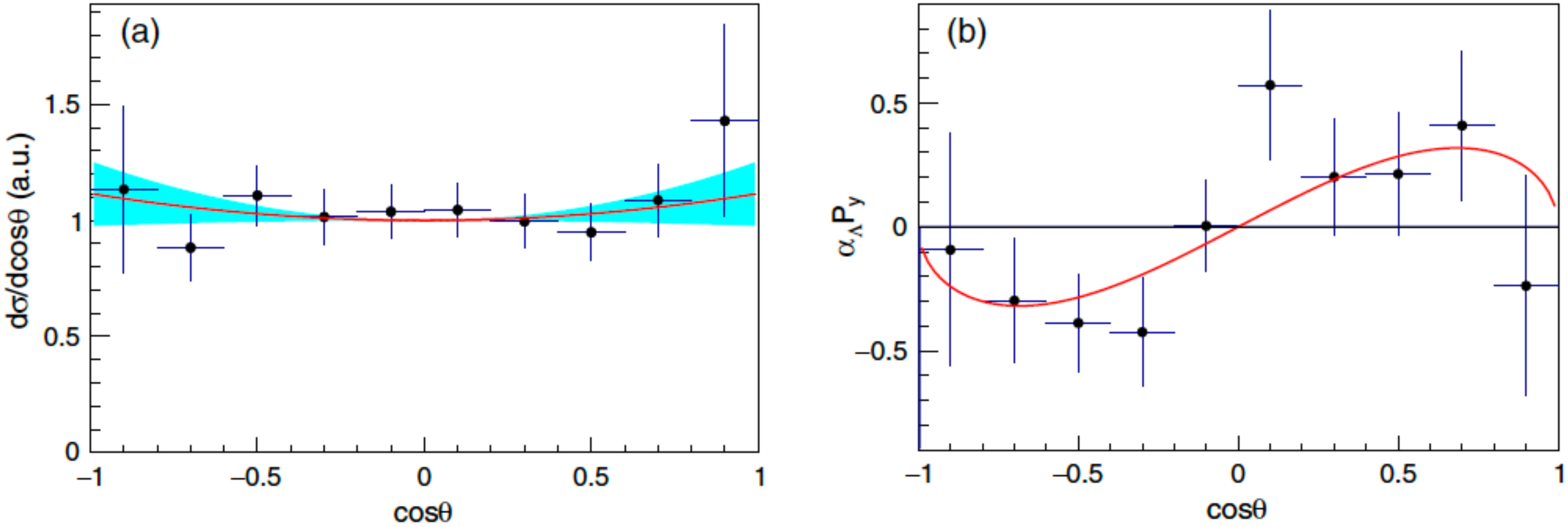
$$R = |\frac{G_E}{G_M}| = 0.96 \pm 0.14 \pm 0.02$$

$$\Delta\phi = 37^0 \pm 12^0 \pm 6^0$$

(Phase between E&M form-factors)

$$\sigma(e^+e^- \to \Lambda\bar{\Lambda}) = 118.7 \pm 5.3 \pm 5.1 pb$$





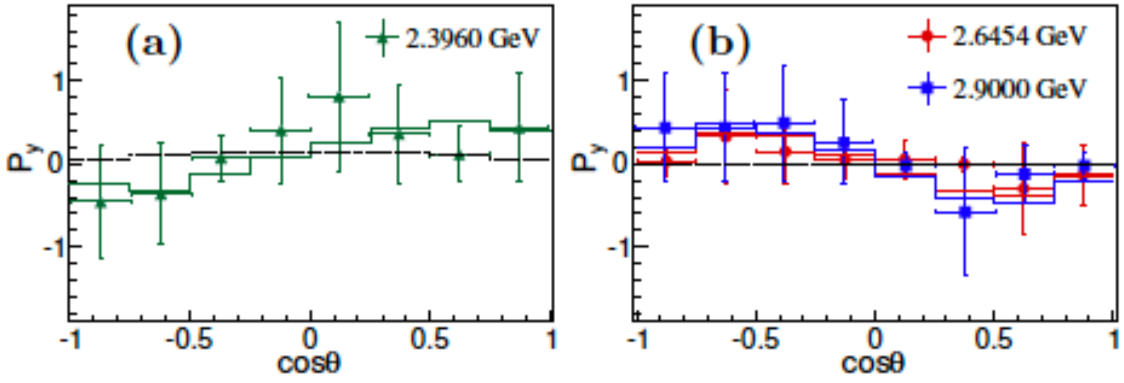
BESIII: PRL 123 (2019) 122003

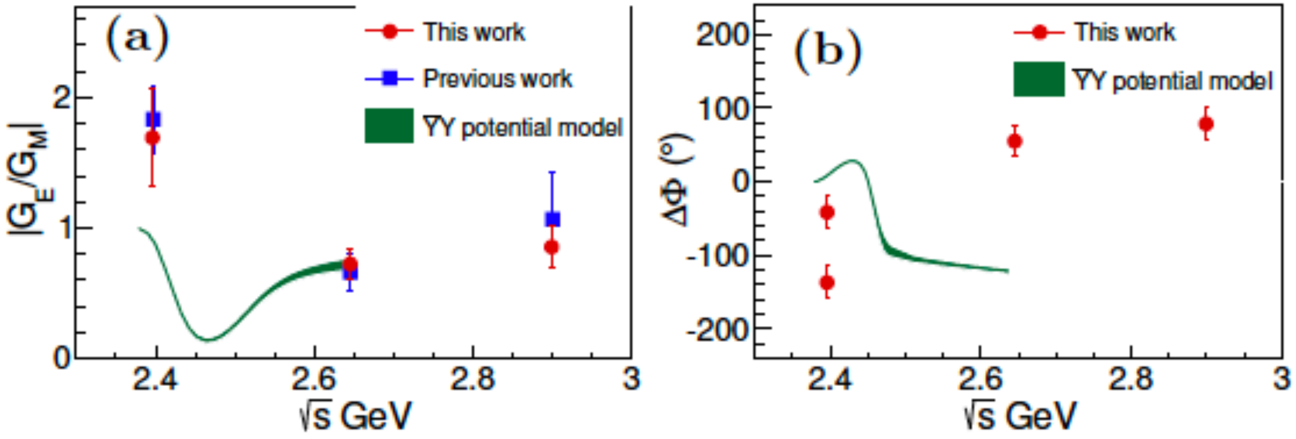
First complete measurement of Σ^+ E&M form-factors

BESIII: *Phys.Rev.Lett.* 132 (2024) 8, 081904

Polarization measurements at different center of mass energies

First measurement of the relative phase $\Delta\Phi$ between G_E and G_M form factors

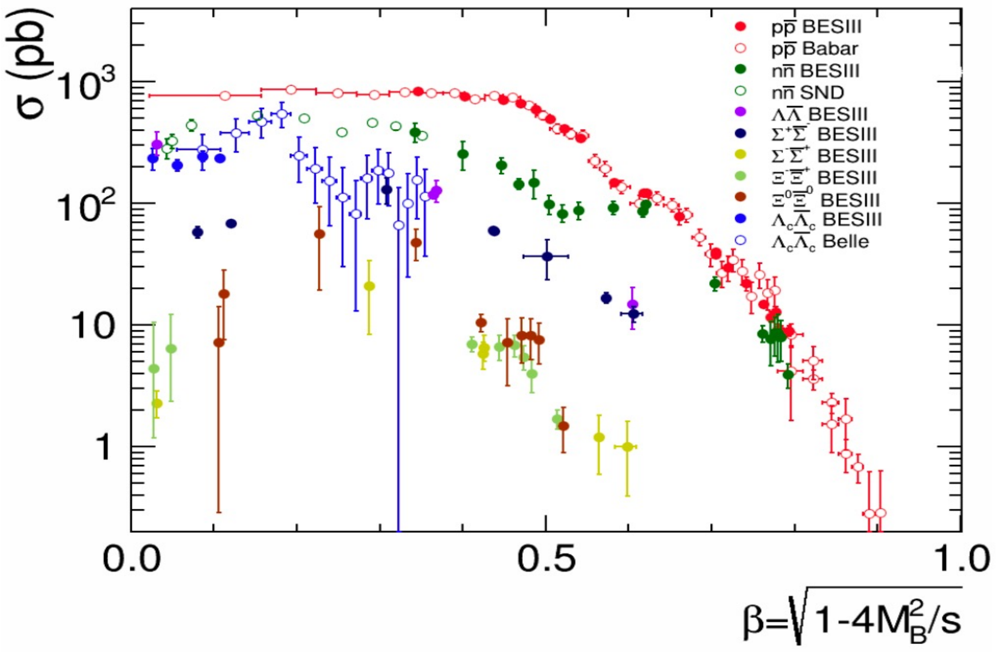


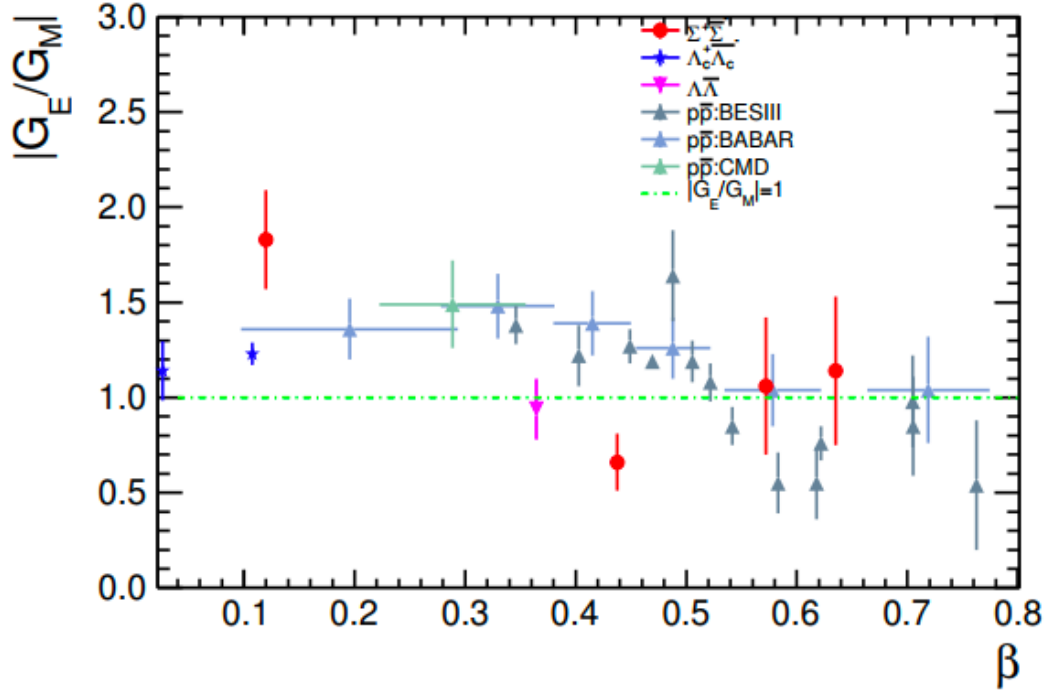


$\sqrt{s}$ (GeV)	2.3960	2.6454	2.9000
α	-0.47 ± 0.18 ± 0.09	0.41 ± 0.12 ± 0.06	0.35 ± 0.17 ± 0.15
$\Delta\Phi$ (°)	-42 ± 22 ± 14 (-138 ± 22 ± 14)	55 ± 19 ± 14	78 ± 22 ± 9
sin $\Delta\Phi$	-0.67 ± 0.29 ± 0.18		
$\lvert G_E/G_M \rvert$	1.69 ± 0.38 ± 0.20	0.72 ± 0.11 ± 0.06	0.85 ± 0.16 ± 0.15

Such an evolution will be an important input for understanding its asymptotic behavior and the dynamics of baryons. Moreover, the fact that the relative phase is still increasing at 2.9 GeV indicates that the asymptotic threshold has not yet been reached. A. Mangoni, S. Pacetti, and E. Tomasi-Gustafsson, Phys. Rev. D 104, 116016 (2021).

Time-like baryon E&M form-factors





- Abnormal threshold effects observed in various baryon pair production: $p\bar{p},\ \Lambda\bar{\Lambda},\ \Lambda_c^+\bar{\Lambda}_c^-\ \ldots$
- $|G_E/G_M|$ ratio significantly larger than 1 at low beta for p, Λ_c^+, Σ^+, indicating large D-wave near threshold.
- Relative phase angle of form factor $\Delta\phi(\sin\Delta\phi)$ measured for Λ, Λ_c^+.

Determine Nucleon Polarization at e^+e^- collider

How to determine nucleon polarization at existing collider experiments?

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(Dated: January 7, 2025)

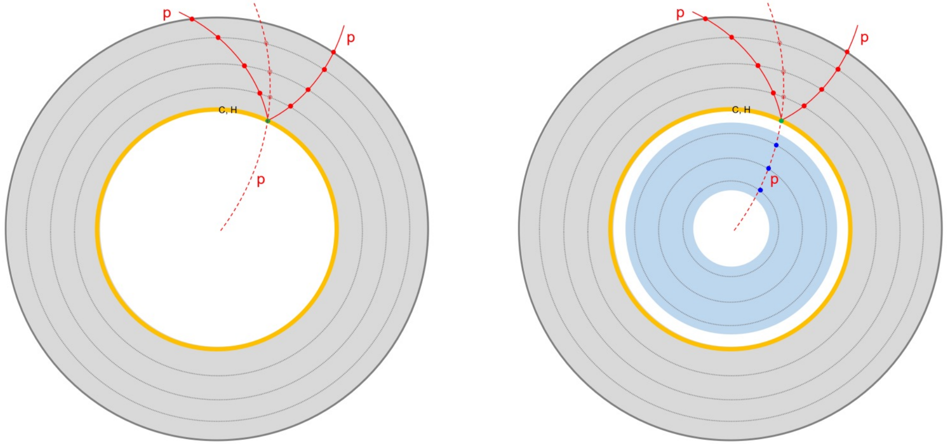
We propose a novel approach to measure spin polarization of nucleons produced in electron–positron collisions. Using existing tracking devices and supporting structure material, general-purpose spectrometers can be utilized as a large-acceptance polarimeter without hardware upgrade. With the proposed approach, the spin polarization of nucleons can be revealed, providing a complementary and accurate description of the final-state particles. This could have far-reaching implications, such as enabling the complete determination of the time-like electromagnetic form factors of nucleons.

arxiv: 2501.02439

Unpolarized cross section

$$\frac{d\sigma}{d\phi d\cos\theta} = \frac{1}{2\pi}\frac{d\sigma_0}{d\cos\theta}[1 + P_y A_N(\theta)\cos\phi]$$

P_y: Transverse polarization of proton
$A_N(\theta)$: Analyzing power



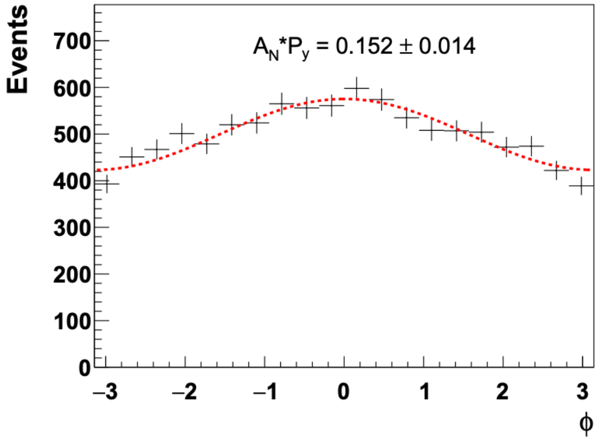
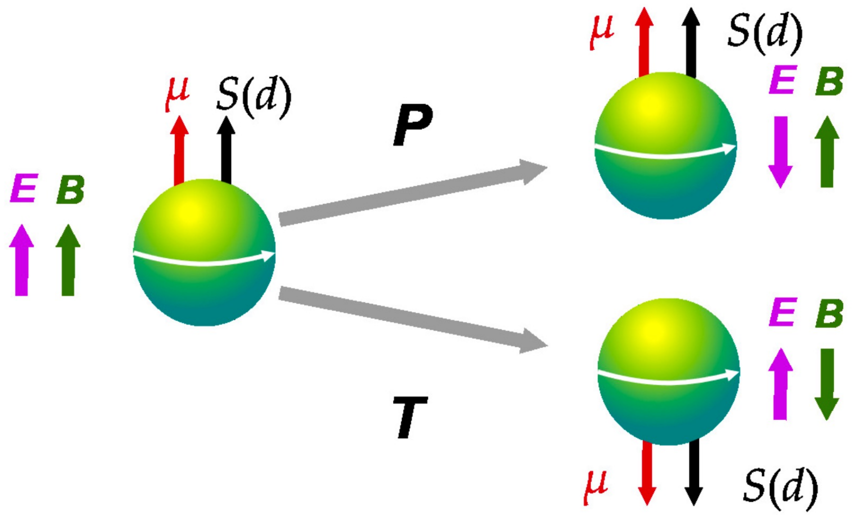


FIG. 3. Single spin asymmetry (A_{SS}) extracted from the ϕ distribution. In MC, an input transverse polarization of 0.3 and an analyzing power of 0.5 is assumed.

Hyperon CP test in future plans

Electric Dipole Moment

μ: magnetic dipole moment
d: electric dipole moment
S: particle spin



$$\mathcal{H} = -\boldsymbol{\mu}\cdot\mathbf{B} - \boldsymbol{\delta}\cdot\mathbf{E} \xrightarrow{P} \mathcal{H} = -\boldsymbol{\mu}\cdot\mathbf{B} + \boldsymbol{\delta}\cdot\mathbf{E}$$

$$\mathcal{H} = -\boldsymbol{\mu}\cdot\mathbf{B} - \boldsymbol{\delta}\cdot\mathbf{E} \xrightarrow{T} \mathcal{H} = -\boldsymbol{\mu}\cdot\mathbf{B} + \boldsymbol{\delta}\cdot\mathbf{E}$$

Non-zero EDM will violate P and T symmetry:
T violation ↔ CP violation, if CPT holds.

The contribution of the Standard Model to EDM is very small:

- CKM: highly suppressed by loop level (≥ 3) interaction
- QCD $\bar{\theta}$ term: main SM contributors to the EDM, $\bar{\theta} < 10^{-10}$
  - limited by neutron EDM:

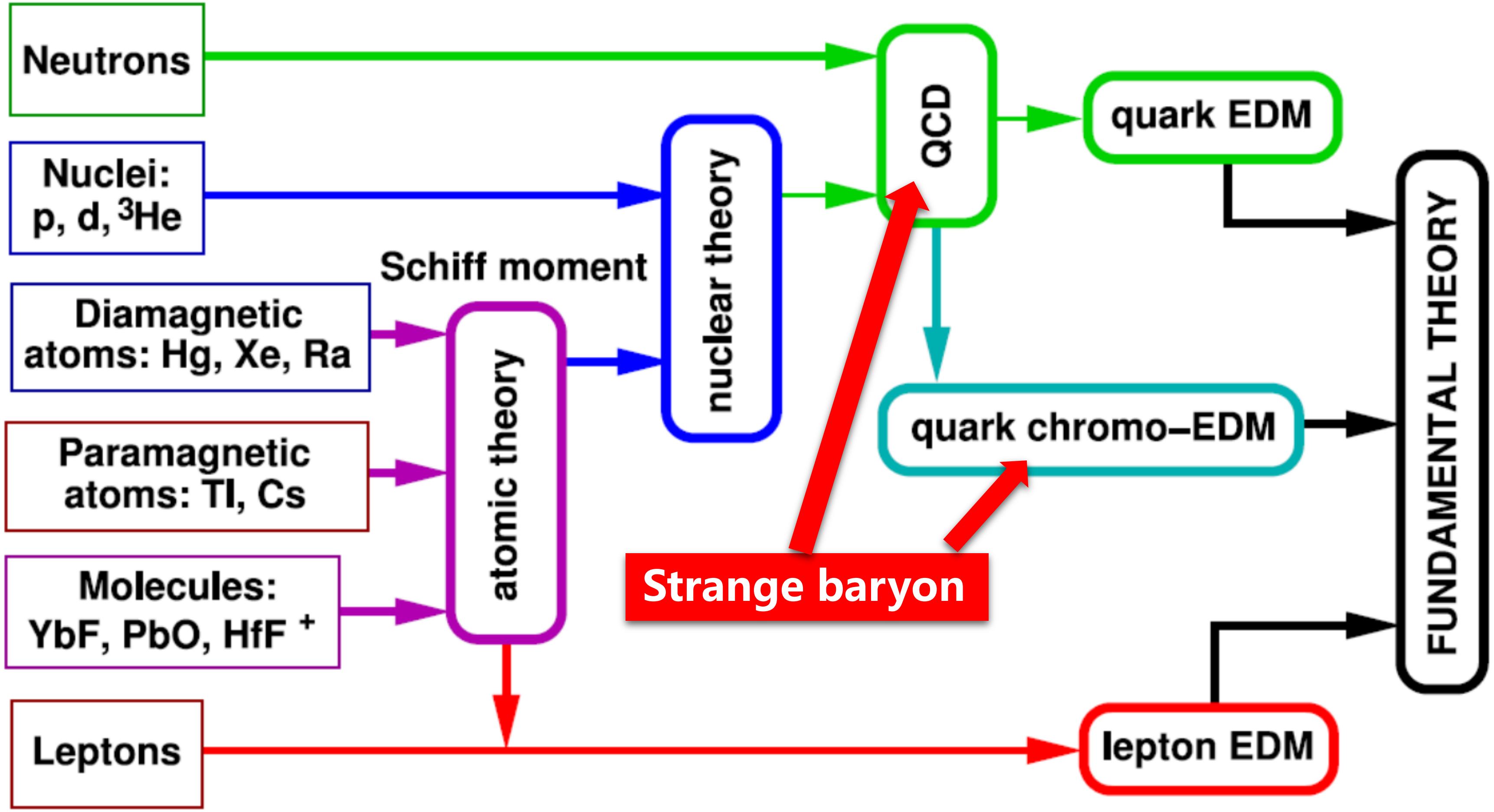
$$d_n < 1.6\times10^{-26}\ ecm$$

$$\mathcal{L}_{\mathrm{CPV}} = \mathcal{L}_{\mathrm{CKM}} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\mathrm{BSM}}^{\mathrm{eff}}$$

Very sensitive to BSM physics, large windows of opportunity for observing New Physics!

Map of EDM

The identification of the nature of the fundamental CP-violating mechanisms requires the study of EDMs in various systems

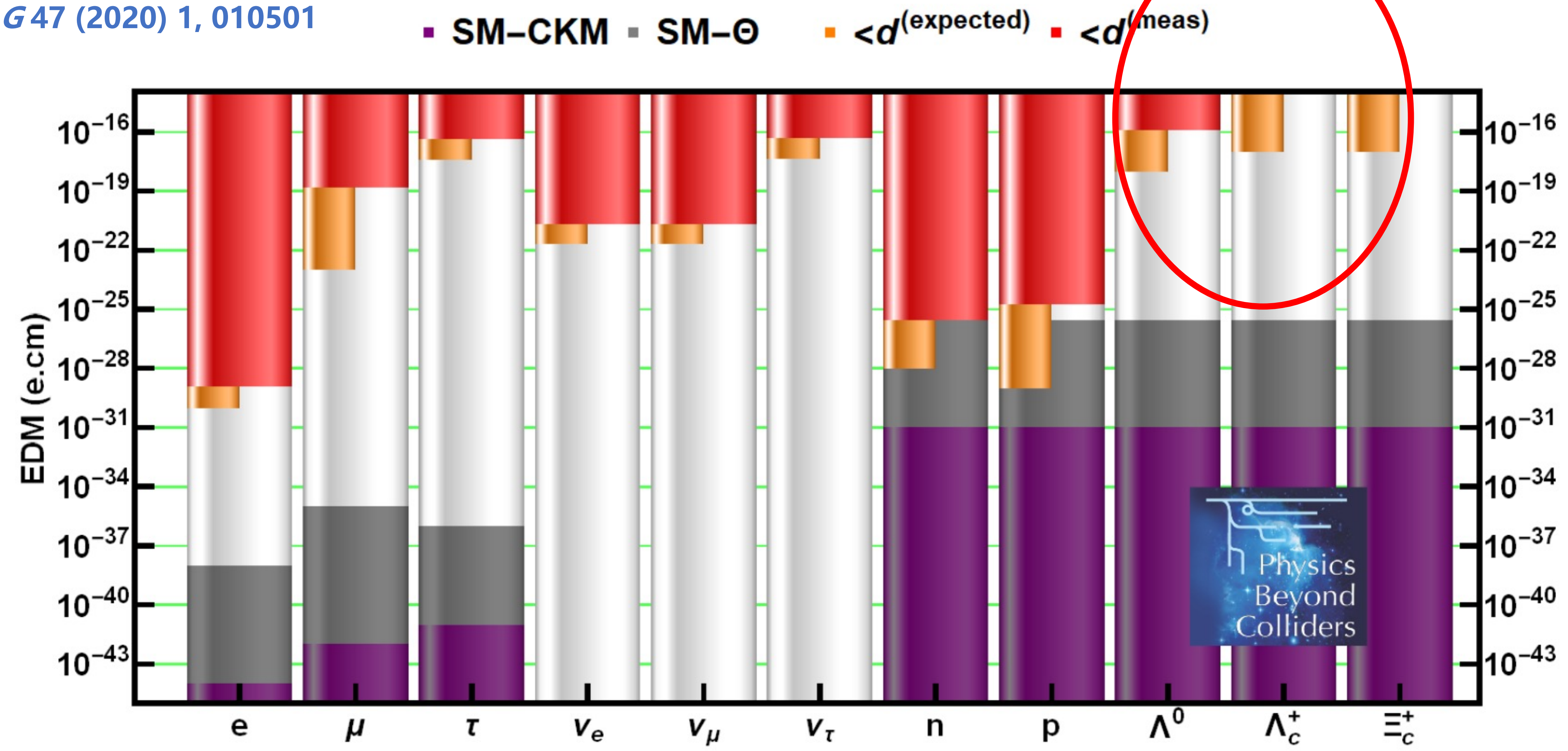


C. R. Physique 13 168 (2012)

EDM Status

Only Λ hyperon has been measured with a large uncertainty!

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



What can BESIII / STCF do for EDM?

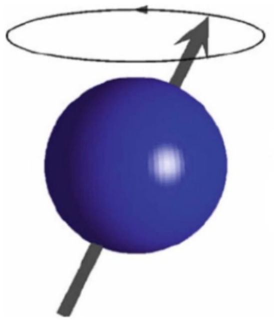
- Direct approach： spin procession 难以用来测量短寿命粒子的EDM

$$\frac{d\mathbf{s}}{dt} = \mathbf{s} \times \mathbf{\Omega}$$

$$\mathbf{\Omega} = \mathbf{\Omega}_{\mathrm{MDM}} + \mathbf{\Omega}_{\mathrm{EDM}} + \mathbf{\Omega}_{\mathrm{TH}}$$

$$\mathbf{\Omega}_{\mathrm{MDM}} = \frac{g\mu_B}{\hbar}\left(\mathbf{B} - \frac{\gamma}{\gamma+1}(\boldsymbol{\beta}\cdot\mathbf{B})\boldsymbol{\beta} - \boldsymbol{\beta}\times\mathbf{E}\right)$$

$$\Omega_{\mathrm{EDM}} = \frac{d\mu_B}{\hbar}\left(\mathbf{E} - \frac{\gamma}{\gamma+1}(\boldsymbol{\beta}\cdot\mathbf{E})\boldsymbol{\beta} - \boldsymbol{\beta}\times\mathbf{B}\right)$$



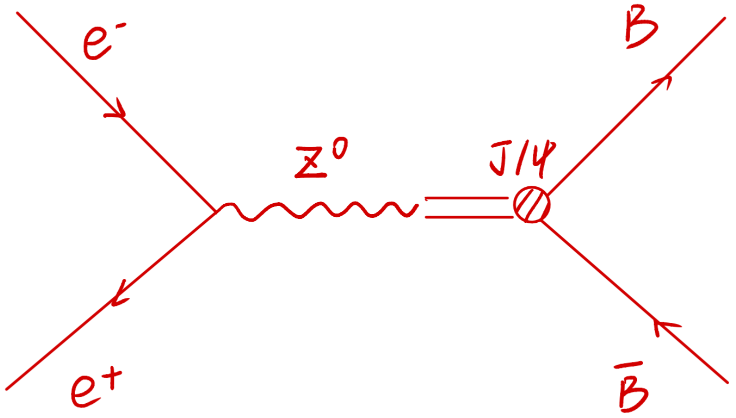
- Indirect approach： time-like dipole form factors ($q^2 \neq 0$)

$$L_{\mathrm{dipole}} = i\frac{d_\Lambda}{2}\bar{\Lambda}\sigma_{\mu\nu}\gamma_5\Lambda F^{\mu\nu}$$

$$L_{c-\Lambda} = -\frac{2}{3M^2}ed_\Lambda(p_1^\mu - p_2^\mu)\bar{c}\gamma_\mu c\bar{\Lambda}i\gamma_5\Lambda$$

X.G.He, J.P. Ma, Bruce McKellar, Phys.Rev.D47(1993)1744
X.G.He, J.P. Ma, Phys.Lett.B 839(2023)137834

Polarization of J/ψ



Considering Z^0 contribution:
J/ψ has longitude polarization:
denoted by P_L

$\rho_{mm'}$: J/ψ spin density matrix

No beam polarization:

$$P_L = \frac{\rho_{++} - \rho_{--}}{\rho_{++} + \rho_{--}}$$

$$P_L = \mathcal{A}_{LR}^0 = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{-\sin^2\theta_W^{\mathrm{eff}} + 3/8}{2\sin^2\theta_W^{\mathrm{eff}}\cos^2\theta_W^{\mathrm{eff}}}\frac{M_{J/\psi}^2}{m_Z^2}$$

With beam polarization:

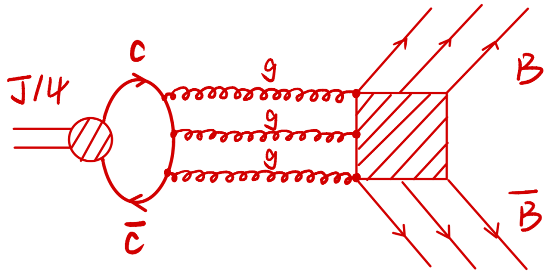
$$\xi = \frac{\sigma_R(1+P_e)/2 - \sigma_L(1-P_e)/2}{\sigma_R(1+P_e)/2 + \sigma_L(1-P_e)/2} = \frac{\mathcal{A}_{LR}^0 + P_e}{1 + P_e\mathcal{A}_{LR}^0} \approx P_e$$

Can be used for precise measurement beam polarization

Dynamics in $J/\psi \to B\bar{B}$

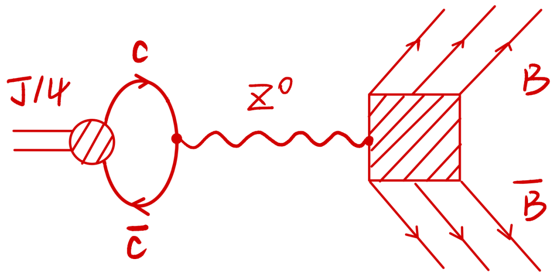
Detailed dynamics in J/ψ decay to hyperon pair, have been studied: X.G.He, J.P. Ma, Phys.Lett.B 839(2023)137834

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



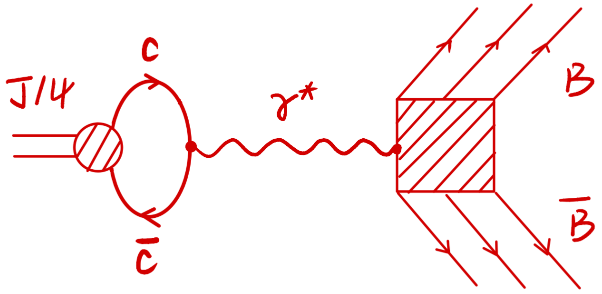
Dominant contribution
arXiv:hep-ph/0412158

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



F_A : P violation term

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



H_T: CP violation 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

Full angular helicity amplitude of $e^+e^- \to J/\psi \to B\bar{B}$

Angular formular based on helicity amplitude are developed:

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

$$R(\lambda_1,\lambda_2;\lambda_1',\lambda_2') \propto \sum_{m,m'} \rho_{m,m'} d^{j=1}_{m,\lambda_1-\lambda_2}(\theta) d^{j=1}_{m',\lambda_1'-\lambda_2'}(\theta) \mathcal{M}_{\lambda_1,\lambda_2} \mathcal{M}^*_{\lambda_1',\lambda_2'} \delta_{m,m'}$$

Total angular distribution of J/ψ to spin-1/2 baryon pair:

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

$$\frac{d\sigma}{d\Omega_k d\Omega_p d\Omega_{\bar{p}}} = \boldsymbol{N} \sum_{[\lambda]} \boldsymbol{R(\lambda_1,\lambda_2;\lambda_1',\lambda_2')} \boldsymbol{D^{j=1/2}_{\lambda_1,\lambda_p}(\theta_1,\phi_1) D^{*j=1/2}_{\lambda_1',\lambda_p}(\theta_1,\phi_1) \left|h_{\lambda_p}\right|^2 D^{j=1/2}_{\lambda_2,\lambda_{\bar{p}}}(\theta_2,\phi_2) D^{*j=1/2}_{\lambda_2',\lambda_{\bar{p}}}(\theta_2,\phi_2) \left|h_{\lambda_{\bar{p}}}\right|^2}$$

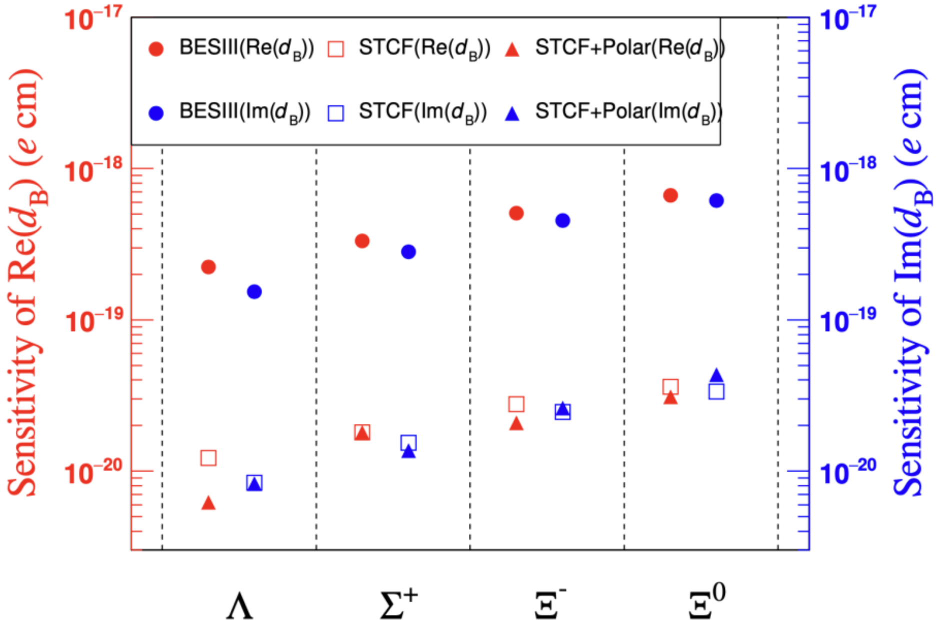
- $J/\psi \to B\bar{B}, B = \Xi^0, \Xi^-$

$$\frac{d\sigma}{d\Omega_k d\Omega_\Lambda d\Omega_{\bar{\Lambda}} d\Omega_p d\Omega_{\bar{p}}} = \boldsymbol{N} \sum_{[\lambda]} \boldsymbol{R(\lambda_1,\lambda_2;\lambda_1',\lambda_2')} \boldsymbol{D^{*j=1/2}_{\lambda_1,\lambda_\Lambda}(\theta_1,\phi_1) D^{j=1/2}_{\lambda_1',\lambda'_\Lambda}(\theta_1,\phi_1) \mathcal{H}_{\lambda_\Lambda} \mathcal{H}^*_{\lambda_\Lambda'} D^{*j=1/2}_{\lambda_2,\lambda_{\bar{\Lambda}}}(\theta_2,\phi_2)}$$

$$\boldsymbol{D^{j=1/2}_{\lambda_2',\lambda'_{\bar{\Lambda}}}(\theta_2,\phi_2) \mathcal{H}_{\lambda_{\bar{\Lambda}}} \mathcal{H}^*_{\lambda_{\bar{\Lambda}}'} D^{*j=1/2}_{\lambda_\Lambda,\lambda_p}(\theta_3,\phi_3) D^{*j=1/2}_{\lambda_\Lambda',\lambda_p}(\theta_3,\phi_3) \left|h_{\lambda_p}\right|^2 D^{*j=1/2}_{\lambda_{\bar{\Lambda}},\lambda_{\bar{p}}}(\theta_4,\phi_4) D^{j=1/2}_{\lambda_{\bar{\Lambda}}',\lambda_{\bar{p}}}(\theta_4,\phi_4) \left|h_{\lambda_{\bar{p}}}\right|^2}$$

Sensitivity of hyperon EDM measurements

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



(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

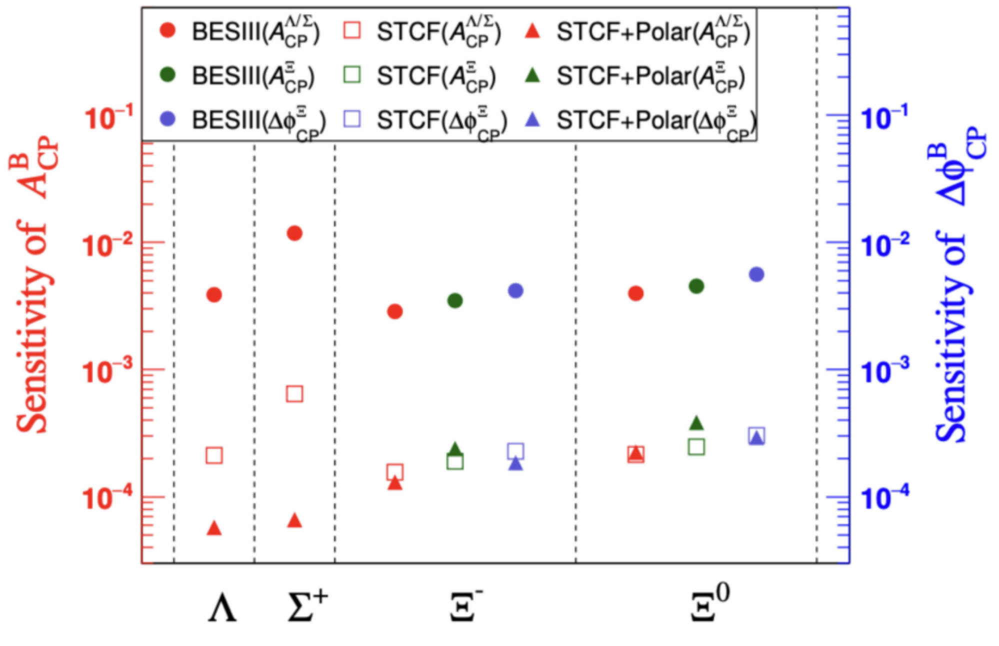
Sensitivity of CP violation in hyperon decay

N.G.Deshpande et al, PLB326(1994)307
J.Tandean et al, PRD67(2003)056001
J.F.Donoghue et al, PRD34(1986)833

reminder: $A^B_{CP} = (\alpha_B + \bar{\alpha}_B)/(\alpha_B - \bar{\alpha}_B)$

$\Delta\phi^B_{CP} = (\phi_B + \bar{\phi}_B)/2$

SM: $10^{-4} \sim 10^{-5}$



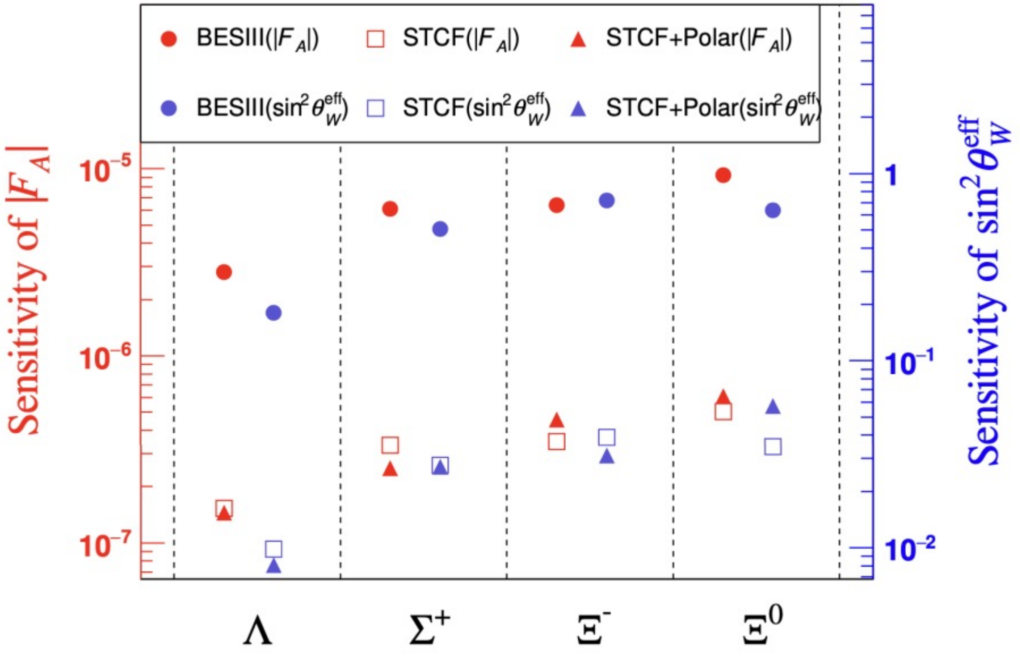
(b)Sensitivity of A^B_{CP} and $\Delta\phi^B_{CP}$

STCF:

SM prediction can be reached and further improved with a longitudinally polarized electron beam

Sensitivity of F_A and $\sin^2\theta_W^{eff}$ measurements

reminder: $F_A \approx -\frac{1}{6} D g_V \frac{g^2}{4\cos^2\theta_W^{eff}} \frac{1-8\sin^2\theta_W^{eff}/3}{m_Z^2}$



(c)Sensitivity of $|F_A|$ and $\sin^2\theta_W^{eff}$

SM: $F_A \sim 10^{-6}$

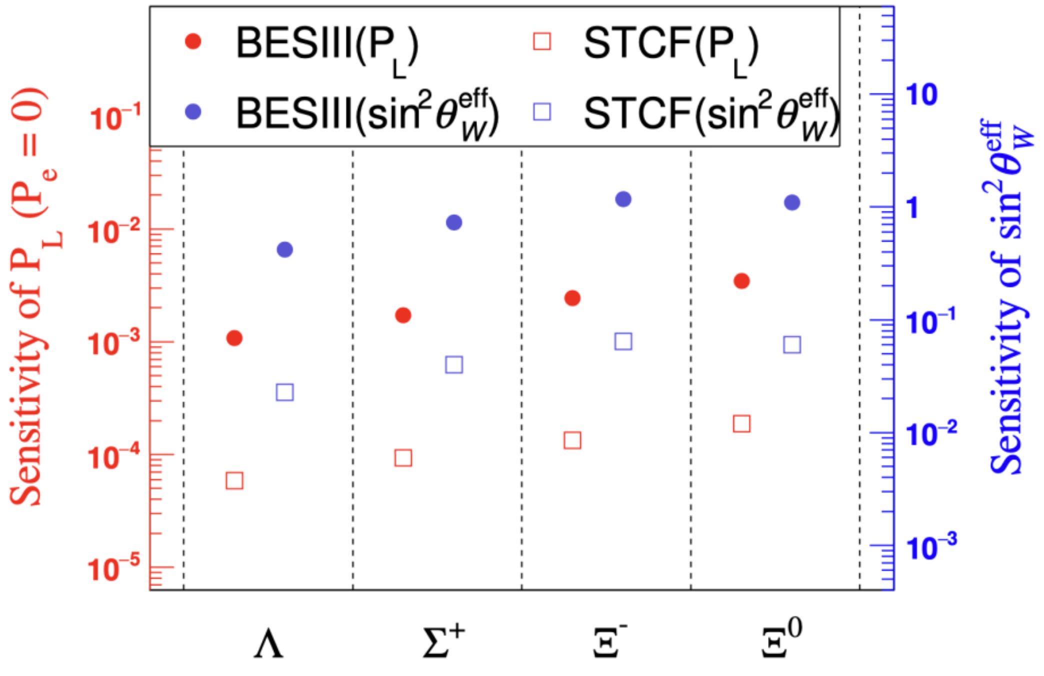
$\sin^2\theta_W^{eff} \sim 0.235$

STCF:

Weak mixing angle at $Q = M_{J/\psi}$ can be determined at the level of 8×10^{-3}

Sensitivity of P_L and $\sin^2\theta_W^{\text{eff}}$ measurements

reminder: $$P_L = \mathcal{A}^0_{LR} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{-\sin^2\theta_W^{\text{eff}} + 3/8}{2\sin^2\theta_W^{\text{eff}}\cos^2\theta_W^{\text{eff}}}\frac{M^2_{J/\psi}}{m_Z^2}$$



(d)Sensitivity of P_L

SM: $P_L \sim 10^{-4}$

$\sin^2\theta_W^{\text{eff}} \sim 0.235$

STCF:

Weak mixing angle at $Q = M_{J/\psi}$ can be determined at the level of 2×10^{-2}

Sensitivity of $\sin^2\theta_W^{\mathrm{eff}}$ by simultaneous fit

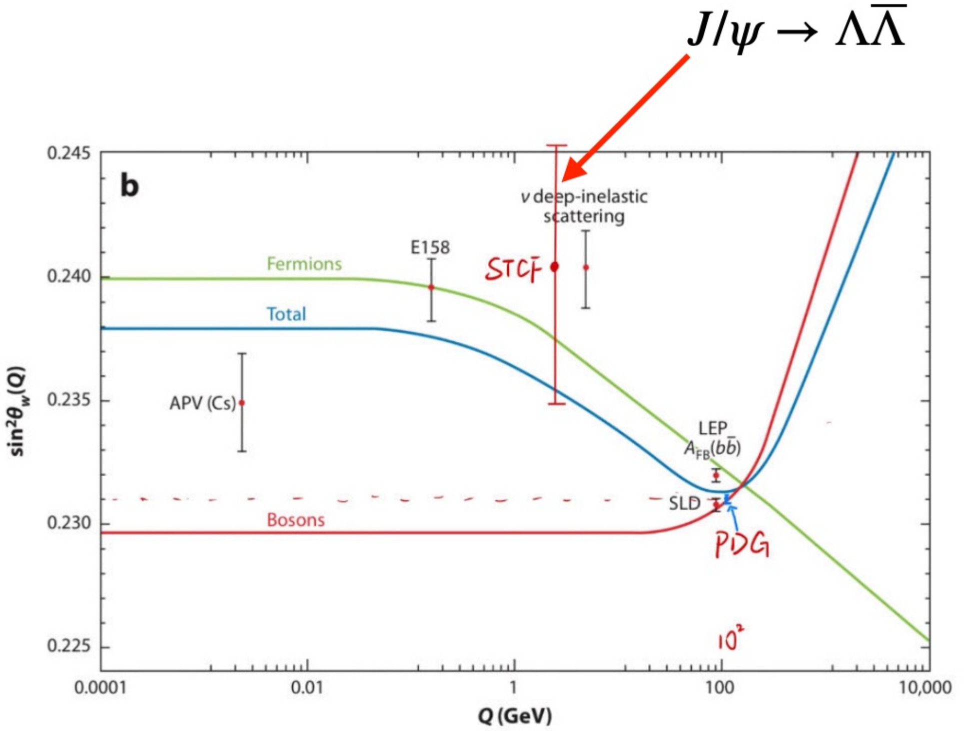


Figure 1

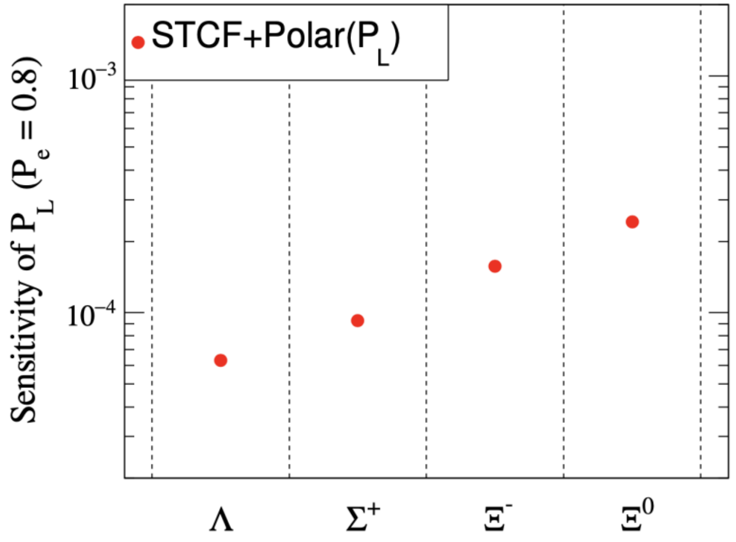
(*a*) $\sin^2\theta_W(\mu)_{\overline{MS}}$ (29) with an updated atomic parity violation (APV) result. (*b*) $\sin^2\theta_W(Q^2)$, a one-loop calculation dominated by $\gamma - Z^0$ mixing (52). The red and green curves represent the boson and fermion contributions, respectively.

K.S.Kumar et al, Ann.Rev.Nucl.Part.Sci. 63 (2013) 237-267

Weak mixing angle shared by F_A and P_L

Sensitivity improved at the level 5×10^{-3}

Sensitivity of beam polarization measurements



Precisely measured beam polarization (10^{-5}) as input value for $\sin^2\theta_W^{\mathrm{eff}}$ measurement

A. Bondar et al, JHEP 03 (2020) 076

$$\mathcal{A}_{\mathrm{LR}} \equiv \frac{\sigma_{\mathcal{P}_e} - \sigma_{-\mathcal{P}_e}}{\sigma_{\mathcal{P}_e} + \sigma_{-\mathcal{P}_e}} = \mathcal{A}^0_{\mathrm{LR}}\mathcal{P}_e$$

$$\sigma_{\mathcal{P}_e} = \frac{N_{\mathcal{P}_e}}{\mathcal{L}_{\mathcal{P}_e}\varepsilon_{\mathrm{eff}}}$$

$$\sigma_{-\mathcal{P}_e} = \frac{N_{-\mathcal{P}_e}}{\mathcal{L}_{-\mathcal{P}_e}\varepsilon_{\mathrm{eff}}}$$

analysis Bhabha scattering events

$$\mathcal{A}^0_{LR} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{-\sin^2\theta_W^{\mathrm{eff}} + 3/8}{2\sin^2\theta_W^{\mathrm{eff}}\cos^2\theta_W^{\mathrm{eff}}}\frac{M^2_{J/\psi}}{m_Z^2}$$

Summary and Outlooks

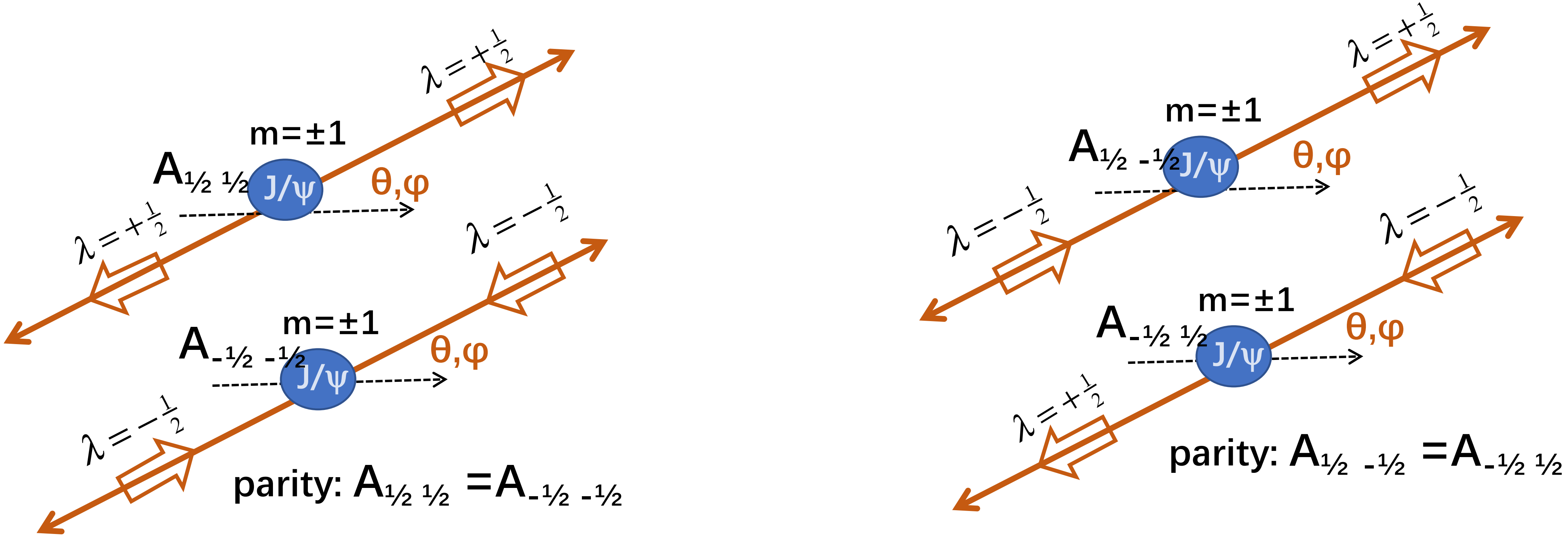
- **Polarization plays an important role in hyperon physics (at BESIII):**
  - **Precision measurements of hyperon decay parameters, polarization and CP:**
    - complementary to CPV studies with Kaons
    - BESIII has already rewritten the PDG book for Λ and Ξ decays
    - results of $\Sigma^{\pm}, \Xi$ with 10 billion J/ψ will be coming soon
  - **Hyperon electric dipole moments measurements:**
    - The prospect sensitivity of Λ EDM at BESIII is 1000 times higher than the world's best measurement under the same statistical condition.
    - BESIII has the opportunity of first measurements of the EDM of Σ^+, Ξ^-, Ξ^0 hyperons , and the sensitivity are at the order of 10^{-19}(BESIII) and 10^{-20}(STCF).


www.thank you.com

Backup

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

Production: 2 independent helicity amplitudes: $A_{½\ ½}$, $A_{½\ -½}$



ΔΦ= complex phase between $A_{½\ ½}$ and $A_{½\ -½}$

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

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 $\Xi^- \to \Lambda\pi$ decay

decay rate difference

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

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

decay asymmetry difference

$$\alpha_{\mp} = \pm \frac{2\,\mathrm{Re}(S^* P)}{|S|^2 + |P|^2} = \pm \frac{2|S||P|\cos\left(\Delta_S \pm \phi_{CP}\right)}{|S|^2 + |P|^2}$$

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

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

final-state polarization difference

$$\beta_{\mp} = \pm \frac{2\,\mathrm{Im}(S^* P)}{|S|^2 + |P|^2} = \pm \frac{2|S||P|\sin\left(\Delta_S \pm \phi_{CP}\right)}{|S|^2 + |P|^2}$$

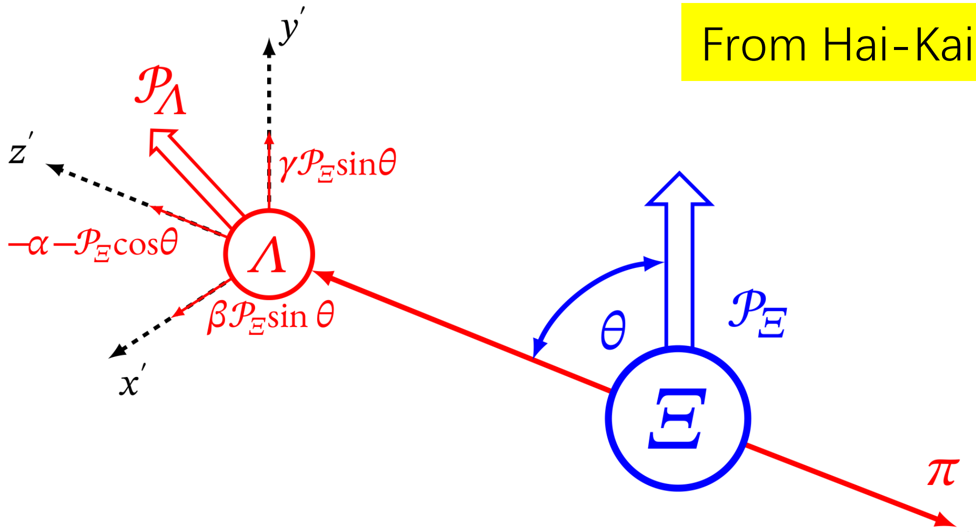
$$\frac{\beta_- + \beta_+}{\alpha_- - \alpha_+} = \frac{\cos\Delta_S \sin\phi_{CP}}{\cos\Delta_S \cos\phi_{CP}} = \tan\phi_{CP}$$

← Strong phase cancels out

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

← measures the strong phase

} big advantage for Ξ over Λ



From Hai-Kai Sun

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

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

$$\alpha^2+\beta^2+\gamma^2 = 1 \qquad \tan\phi_\Xi = \frac{\beta}{\gamma}$$

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

$$\alpha_\mp = \pm\frac{2\mathrm{Re}(S^*\cdot P)}{|S|^2+|P|^2} = \pm\frac{|S||P|\cos(\Delta_s\pm\Delta_w)}{|S|^2+|P|^2} \qquad \beta_\mp = \pm\frac{2\mathrm{Im}(S^*\cdot P)}{|S|^2+|P|^2} = \pm\frac{|S||P|\sin(\Delta_s\pm\Delta_w)}{|S|^2+|P|^2}$$

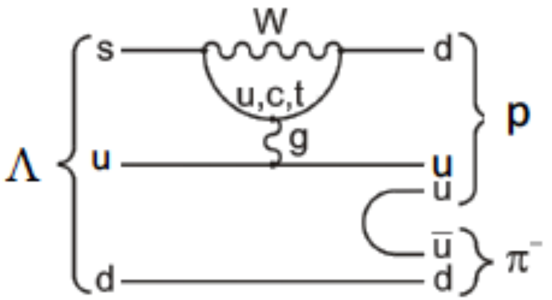


Sandip PAKVASA | X.G. He | John Donoghue

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

Constraints from Kaon decays

He & Valencia PRD 52, 5257

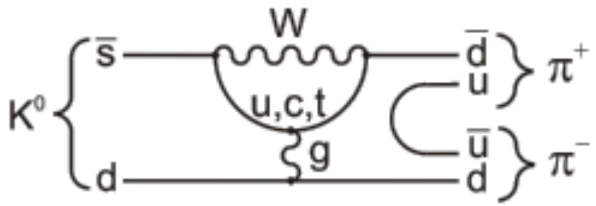


S- and P-waves
(parity violating
& conserving)

$\Lambda \rightarrow p\pi^-$	A_{NP}	
S-wave	$<6\mathrm{x}10^{-5}$	parity violating
P-wave	$<3\mathrm{x}10^{-4}$	parity conserving

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

$\mathrm{Re}(\varepsilon'/\varepsilon)=(1.6+0.3)\mathrm{x}10^{-3}$



S-wave only
(parity violating)

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.