Highlight on CPV test of hyperon at BESIII

轻强子专题研讨会-安阳

张剑宇

University of Chinese Academy of Sciences, Beijing, China

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.**

Breaking news from LHCb!

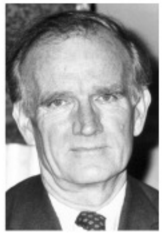
5.2σ CPV in $\Lambda_b \to p\pi^+\pi^-K^-$

arXiv:2503.16954

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

matter	antimatter
δ	δ

same sign

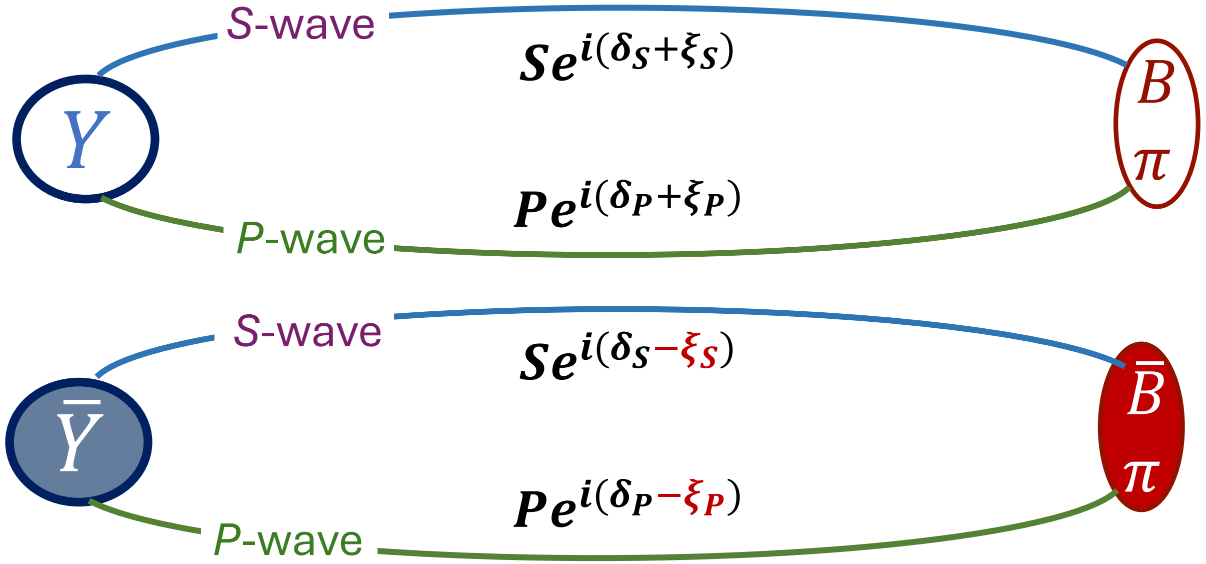
$\mathcal{CP}$ violating phases

matter	antimatter
ξ	$-\xi$

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:

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

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

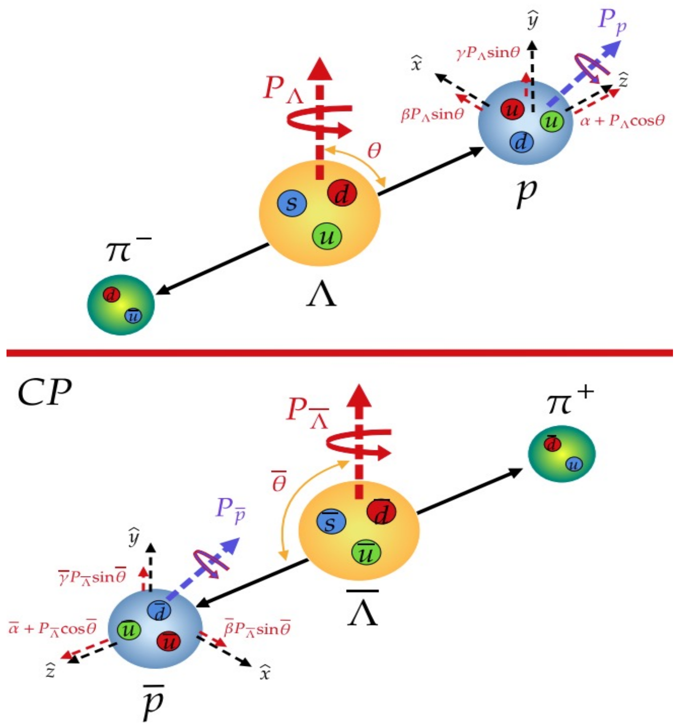
$$\alpha_Y = \frac{2\,\mathrm{Re}\left(S^* P\right)}{|S|^2 + |P|^2},$$

$$\beta_Y = \frac{2\,\mathrm{Im}\left(S^* P\right)}{|S|^2 + |P|^2},$$

$$\gamma_Y = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

Can be measured if

- α_Y: P_Y or P_d
- β_Y: P_Y and P_d
- γ_Y: P_Y and P_d



Phys. Rev. 108, 1645 (1957)

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

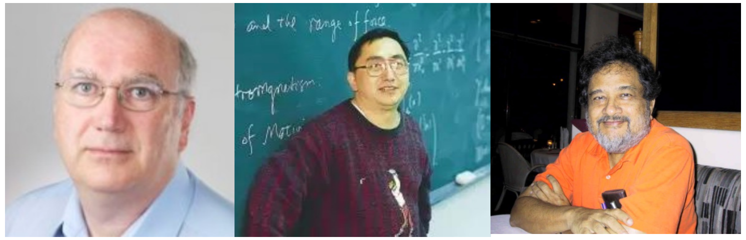
$$\beta = \frac{2Im(S * P)}{|S|^2 + |P|^2} = \sqrt{1 - \alpha^2} sin\phi$$

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
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

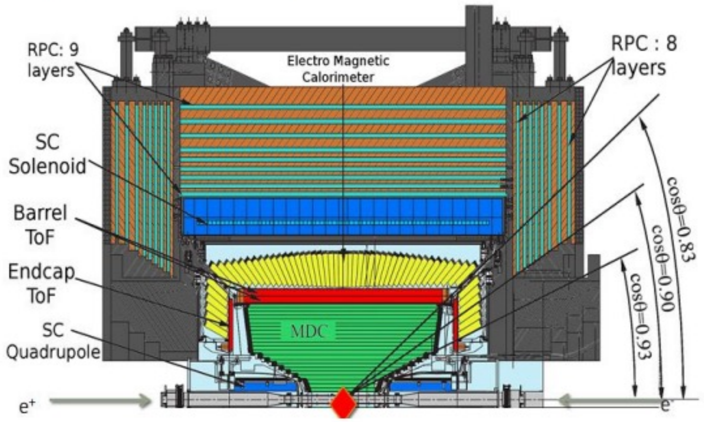
			SM Prediction of Λ decay
Not sensitive to *CPV*	**Decay width difference**	$\Delta = \frac{\Gamma-\bar{\Gamma}}{\Gamma+\bar{\Gamma}} \approx \sqrt{2}\frac{T_{\frac{3}{2}}}{T_{\frac{1}{2}}}\sin\Delta_s \sin\phi_{CP}$	-5.4×10^{-7}
Easiest to measure	**Decay parameter difference**	$A = \frac{\Gamma\alpha+\bar{\Gamma}\bar{\alpha}}{\Gamma\alpha-\bar{\Gamma}\bar{\alpha}} \approx \tan\Delta_s \tan\phi_{CP}$	-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, $\sim10^7$ entangled hyperon pairs can be produced, which enables precise studies of the hyperon physics.

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

Decay mode	$B(\times10^{-3})$	$N_B(\times10^6)$
$J/\psi \to \Lambda\bar{\Lambda}$	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.

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

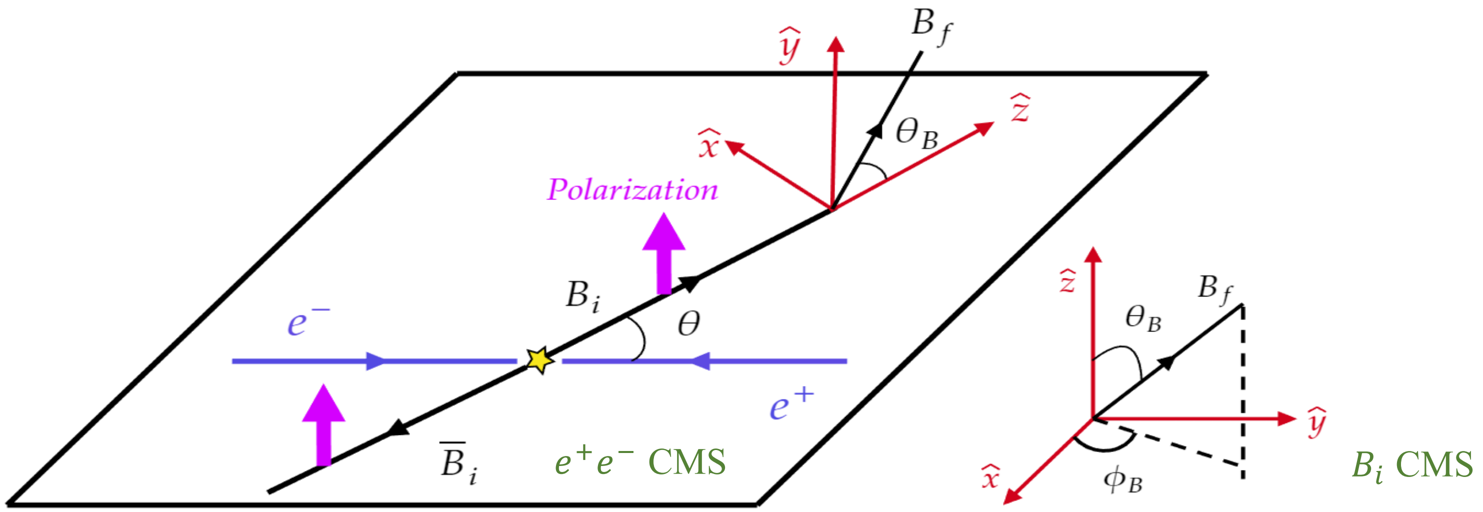
- The form factors G_E,G_M construct the production parameters:

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

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

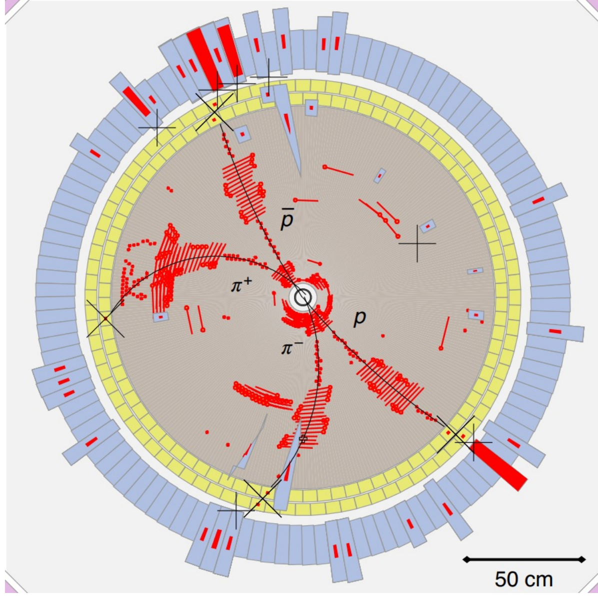
- Angular distribution

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



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:

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

spin-correlation

polarization

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

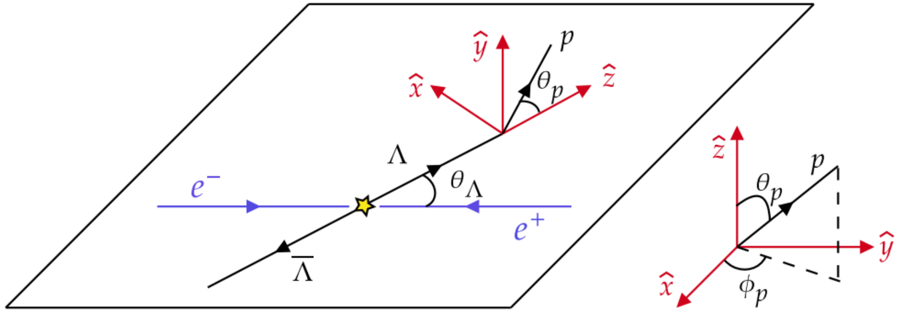
↓

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

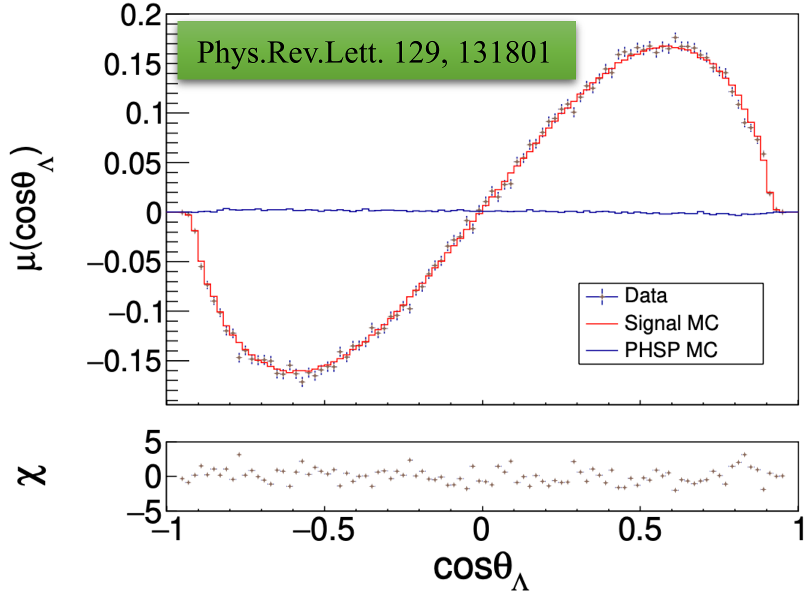
[2] 10 billion: Phys.Rev.Lett. 129 (2022) 13, 131801

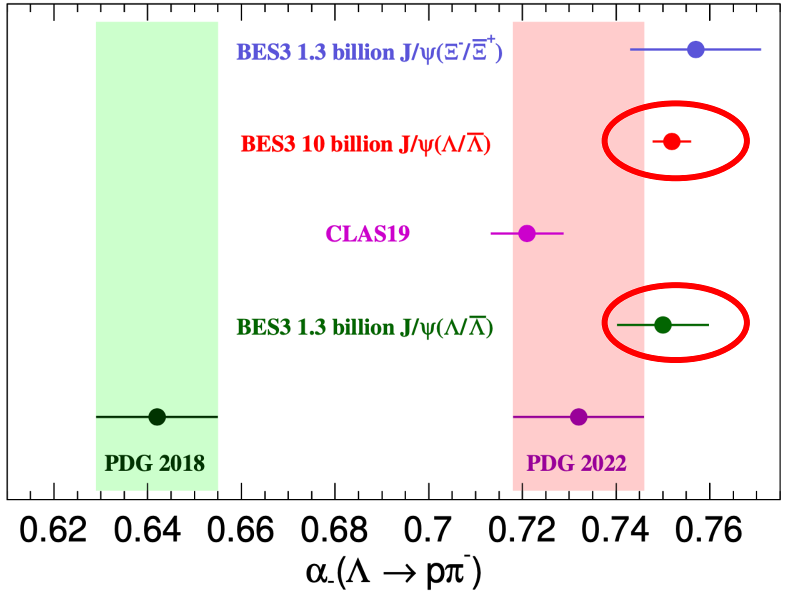
- Most precise values for Λ decay parameter
- One of the most precise CP test in the hyperon sector:

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

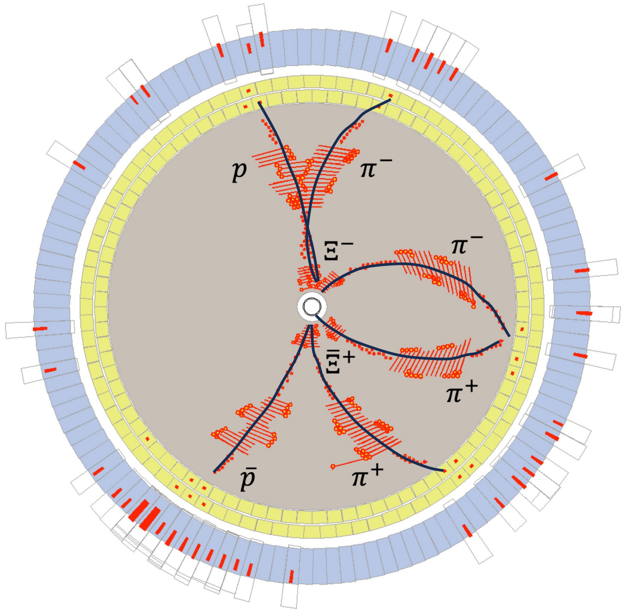
Standard mode prediction : $A_{CP} \sim 10^{-4}$ (PRD 34, 833 (1986))

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}	$-0.0025 \pm 0.0046 \pm 0.0012$	$0.006 \pm 0.012 \pm 0.007$
$\alpha_{\rm avg}$	$0.7542 \pm 0.0010 \pm 0.0024$	-





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



- 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

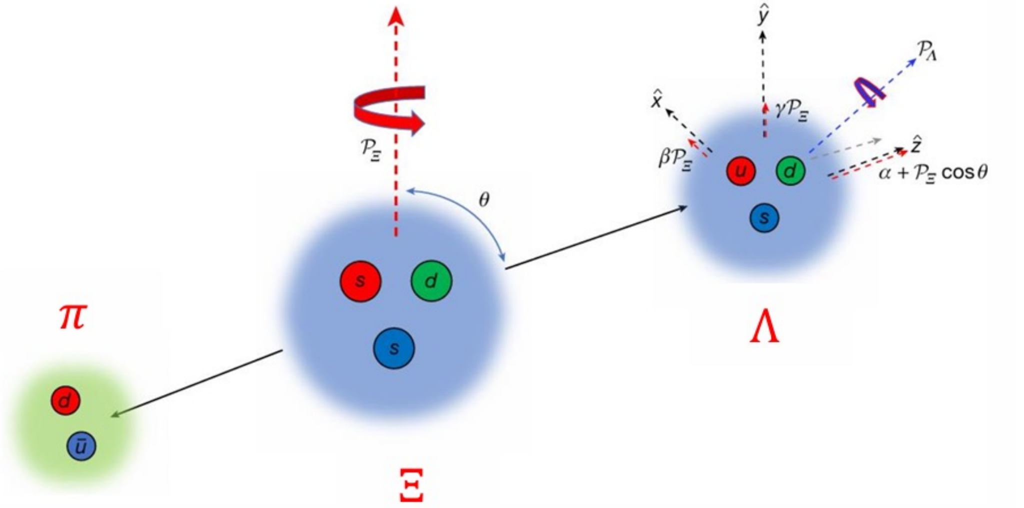
$$\boldsymbol{\omega} = (\alpha_\psi, \Delta\Phi, \alpha_\Xi, \phi_\Xi, \alpha_{\bar{\Xi}}, \phi_{\bar{\Xi}}, \alpha_\Lambda, \alpha_{\bar{\Lambda}})$$

Hyperon Production

Hyperon decays

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

Phys. Rev. D 99, 056008 (2019)

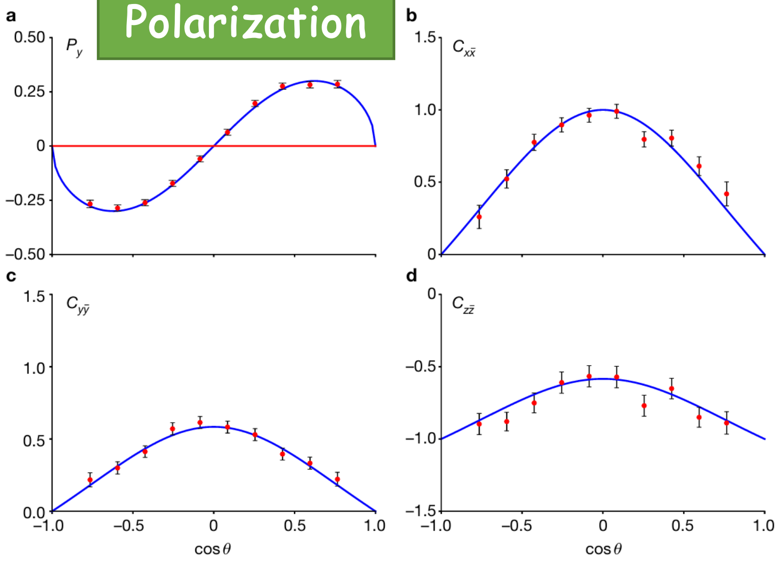


$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$

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_{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} [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

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

Phys. Rev. D 105, 116022 (2022)

- ✓ First direct CP tests for Ξ hyperon

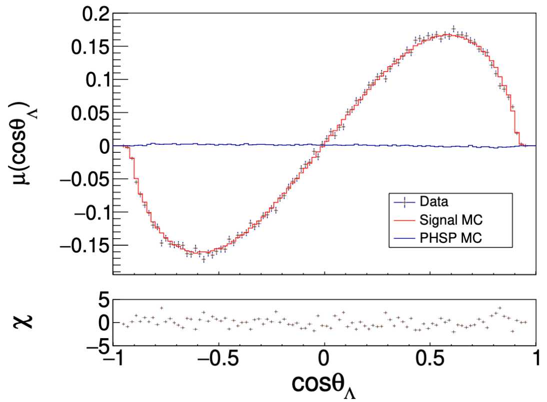
Parameter	This work	Previous result
α_ψ	0.586±0.012±0.010	0.58±0.04±0.08 [1]
$\Delta\Phi$	1.213±0.046±0.016 rad	–
α_Ξ	−0.376±0.007±0.003	−0.401±0.010 [2]
ϕ_Ξ	0.011±0.019±0.009 rad	−0.037±0.014 rad [2]
$\bar{\alpha}_\Xi$	0.371±0.007±0.002	–
$\bar{\phi}_\Xi$	−0.021±0.019±0.007 rad	–
α_Λ	0.757±0.011±0.008	0.750±0.009±0.004 [3]
$\bar{\alpha}_\Lambda$	−0.763±0.011±0.007	−0.758±0.010±0.007 [3]
$\xi_P-\xi_S$	$(1.2\pm3.4\pm0.8)\times10^{-2}$ 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±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)

Polarization behavior in different hyperon pair productions

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

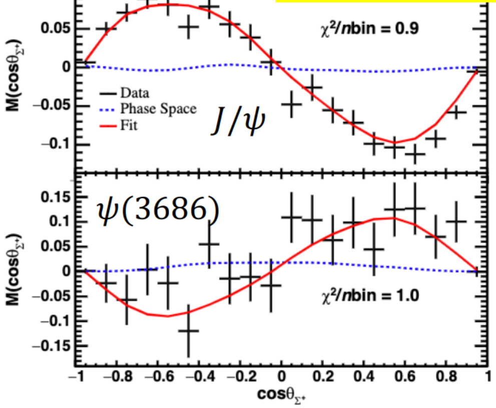
PRL129, 131801(2022)



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

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

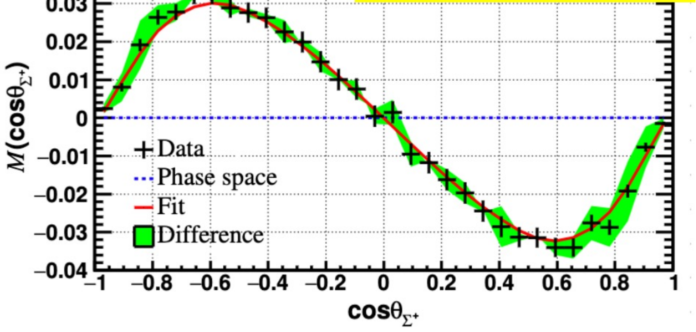
PRL125, 052004(2020)



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

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

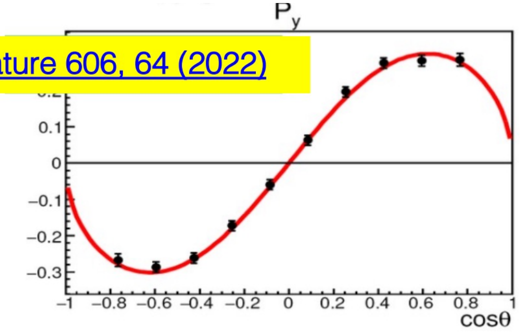
arXiv:2304.14655



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

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

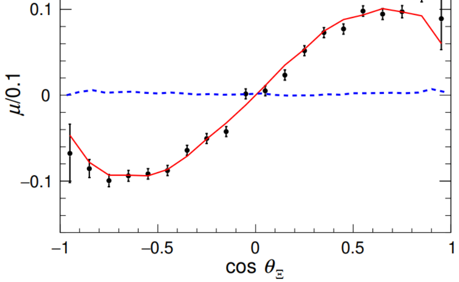
Nature 606, 64 (2022)



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

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

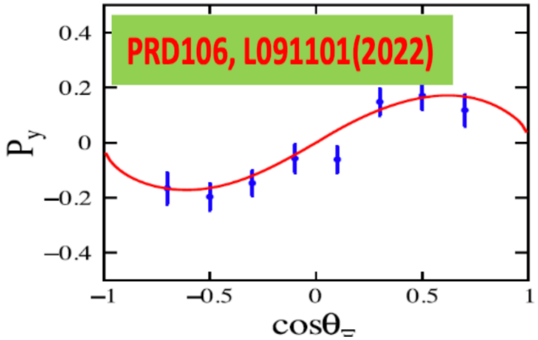
arXiv:2305.09218v1



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

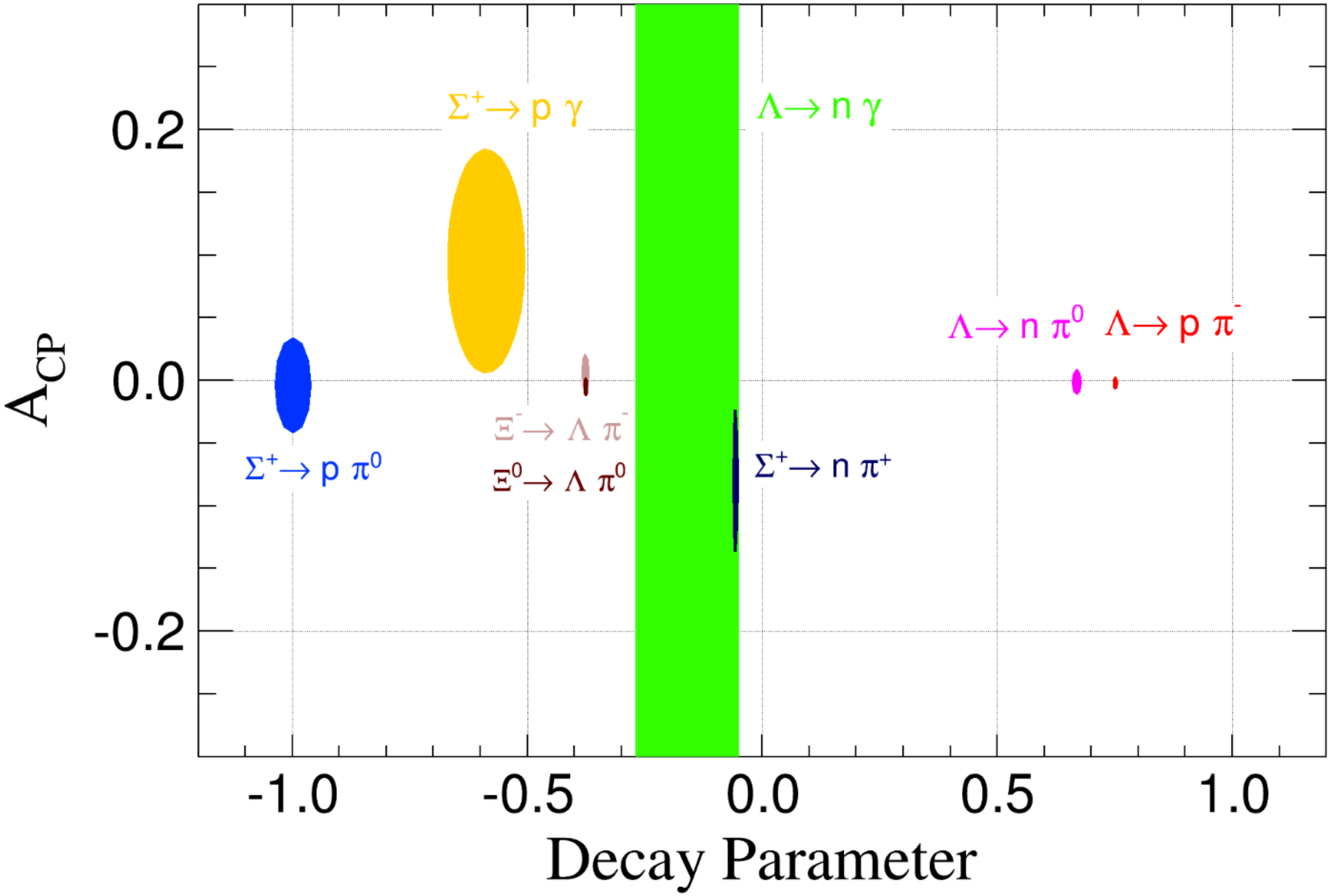
$\psi(2S) \to \Xi^-\bar{\Xi}^+$

PRD106, L091101(2022)



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

Summary of BESIII achievement on hyperon decay



Hyperon CP test in future plans

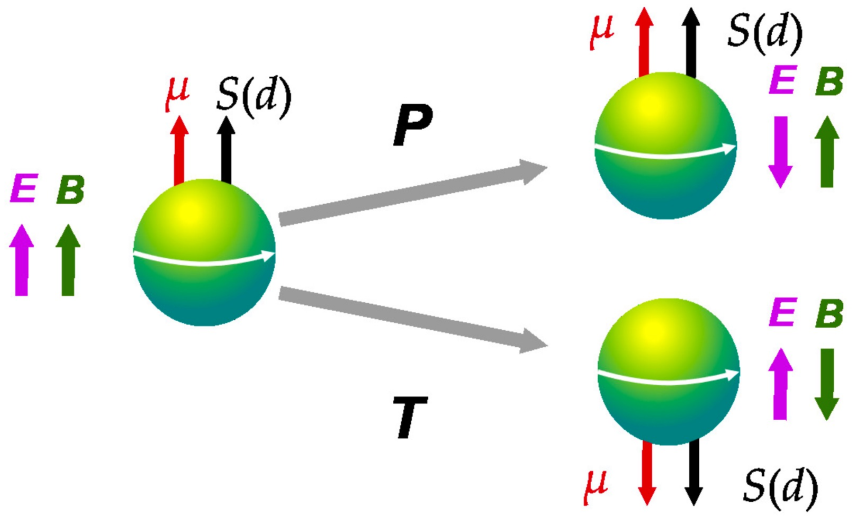
Electric Dipole Moment

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:

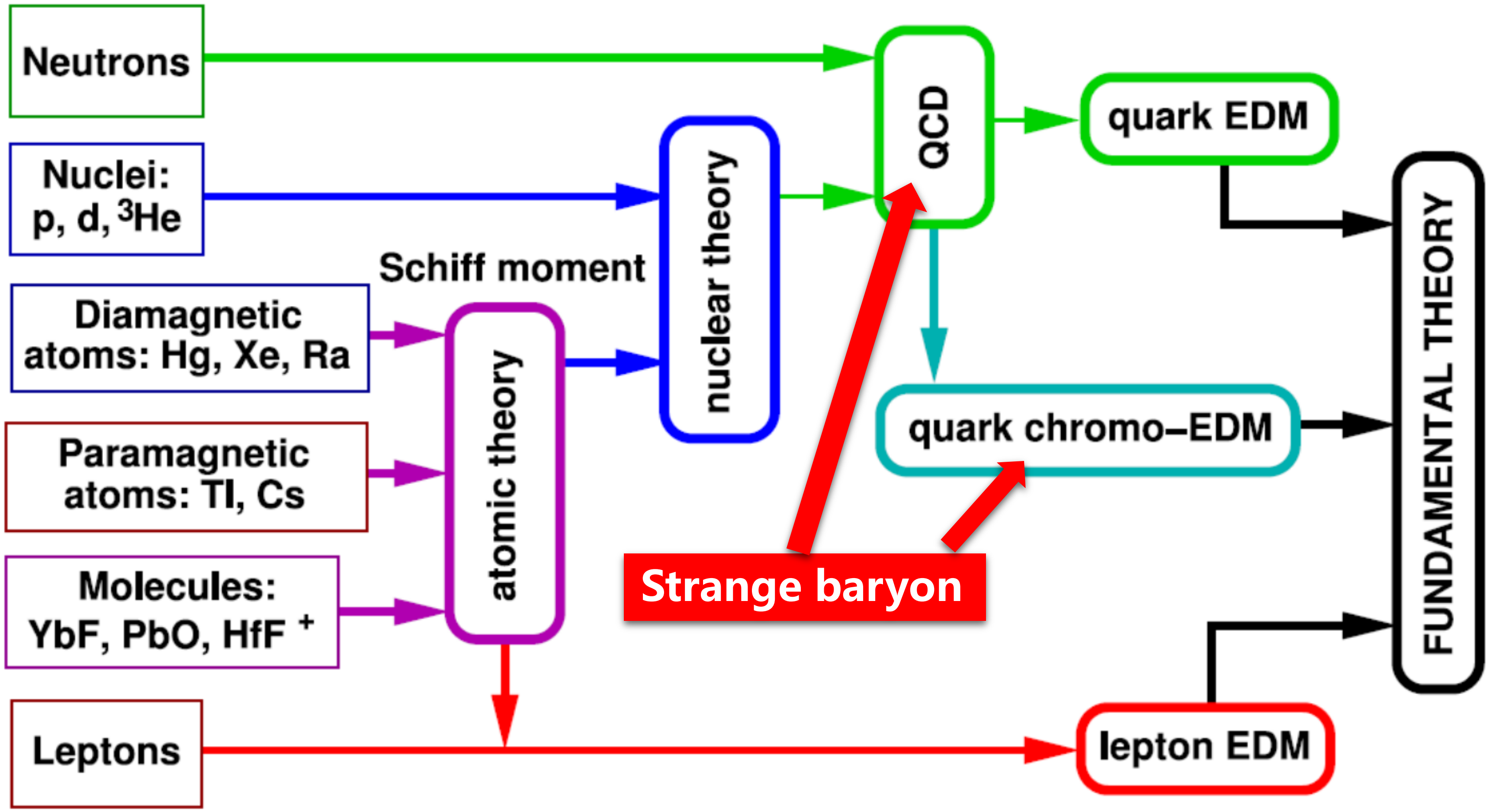
$$d_n < 1.6\times10^{-26}\ ecm$$

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

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

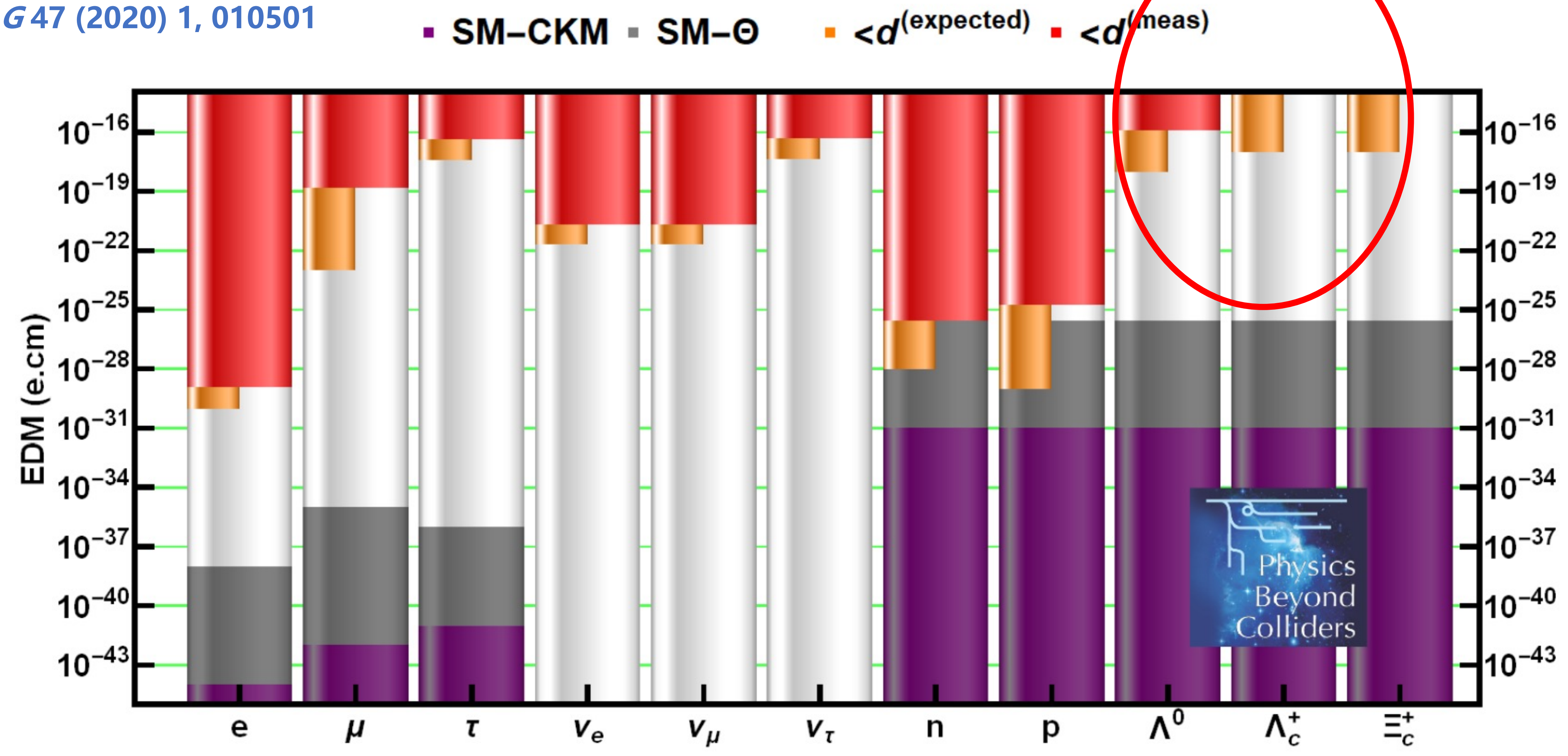


C. R. Physique 13 168 (2012)

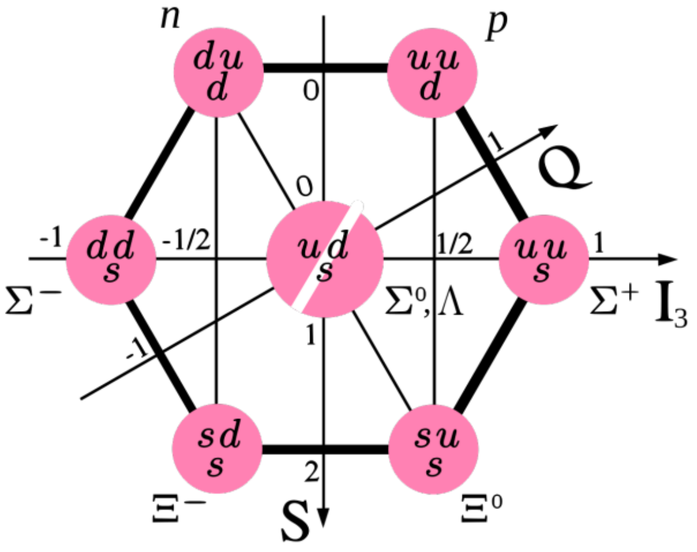
EDM Status

Only Λ hyperon has been measured with a large uncertainty!

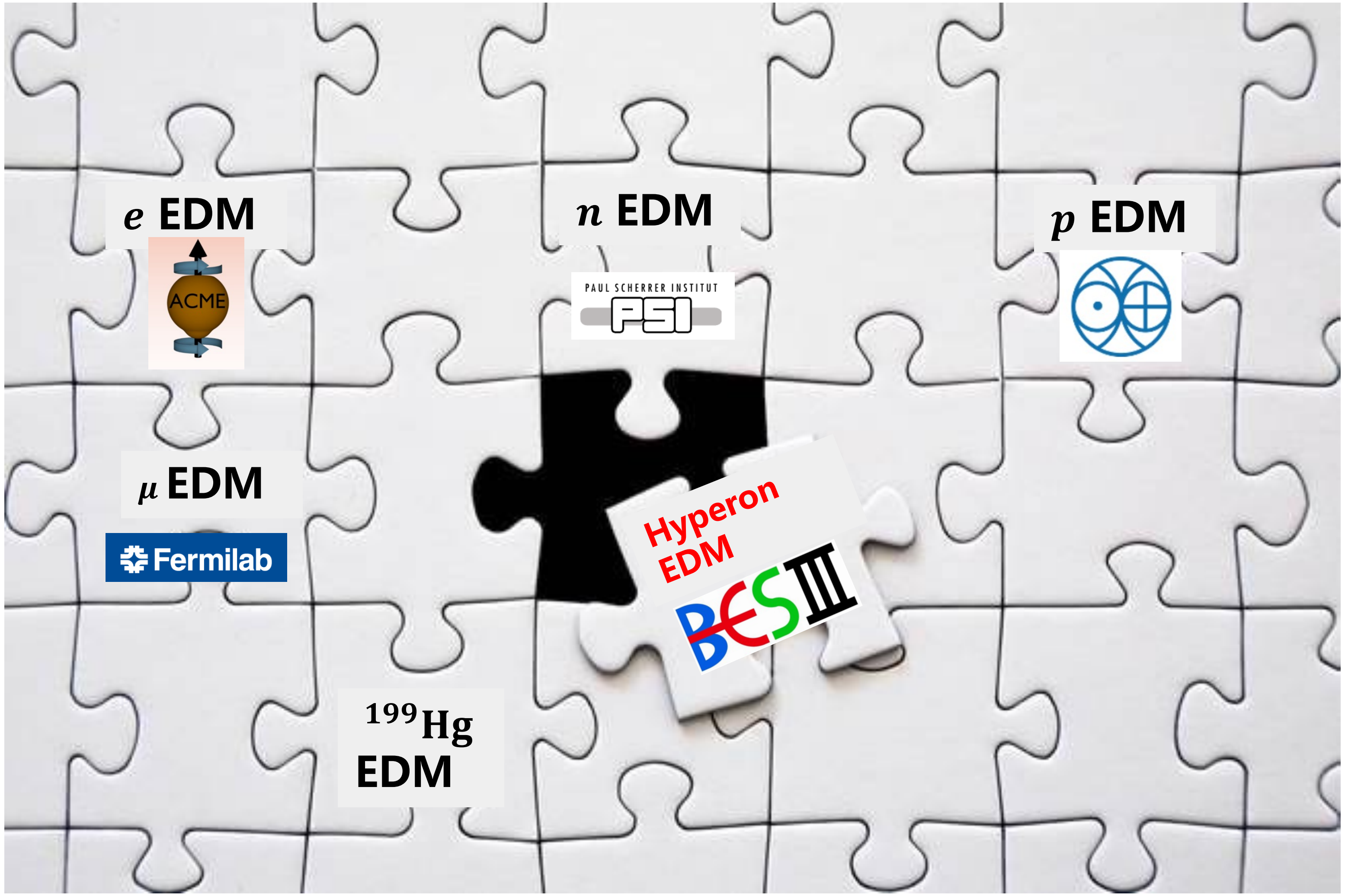
J.Phys.G 47 (2020) 1, 010501



What can BESIII / STCF do for EDM?



$+\ \Omega^-(sss)$ spin-$\frac{3}{2}$



What can BESIII / STCF do for EDM?

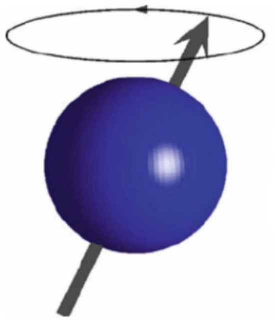
- Direct approach： spin procession 难以用来测量短寿命粒子的EDM

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

$$\boldsymbol{\Omega} = \boldsymbol{\Omega}_{\text{MDM}} + \boldsymbol{\Omega}_{\text{EDM}} + \boldsymbol{\Omega}_{\text{TH}}$$

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

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



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

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

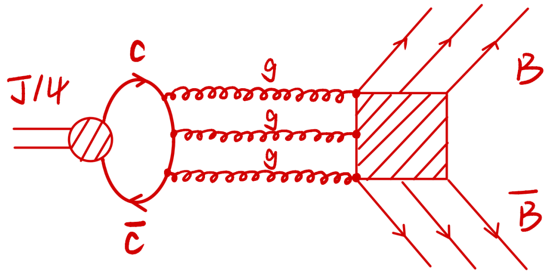
$$L_{c-\Lambda} = -\frac{2}{3M^2}ed_\Lambda(p_1^\mu - p_2^\mu)\bar{c}\gamma_\mu c\bar{\Lambda}i\gamma_5\Lambda$$

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

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

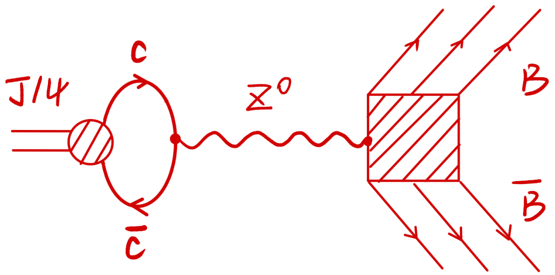
Detailed dynamics in J/ψ decay to hyperon pair, have been studied: X.G.He, J.P. Ma, Phys.Lett.B 839(2023)137834

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



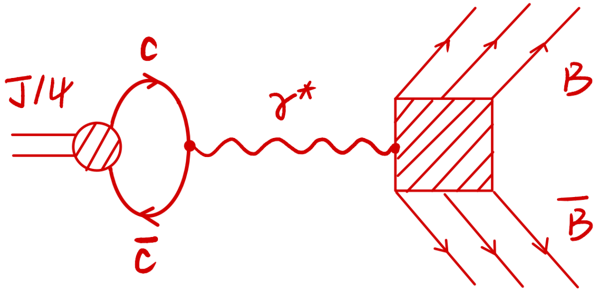
Dominant contribution
arXiv:hep-ph/0412158

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



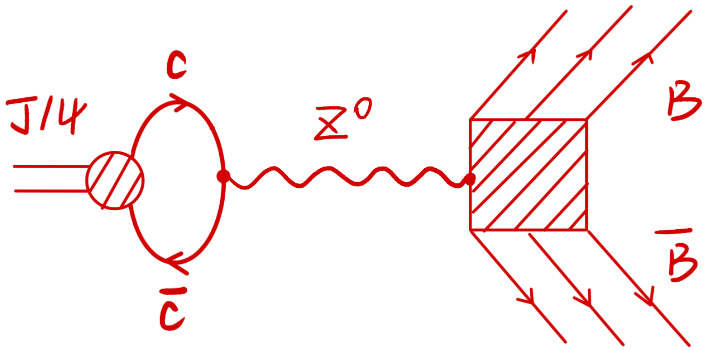
H_T: CP violation term

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

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

P violation form factor F_A



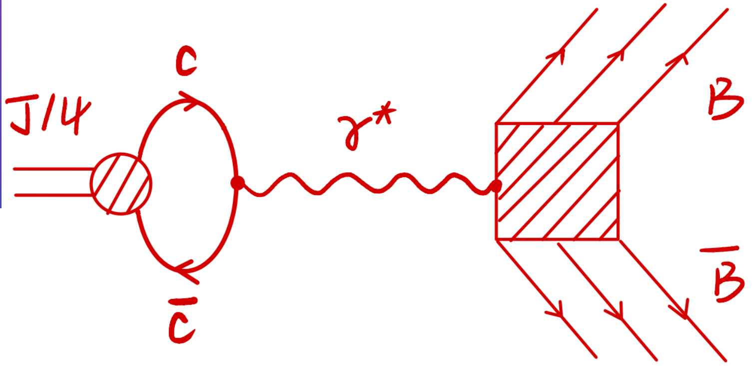
Primarily from Z-boson exchange between $c\bar{c}$ and light quark pairs

Related to weak mixing angle in SM

$$F_A \approx -\frac{1}{6} D g_V \frac{g^2}{4\cos^2\theta_W^{\text{eff}}} \frac{1 - 8\sin^2\theta_W^{\text{eff}}/3}{m_Z^2} \approx -1.07 \times 10^{-6}$$

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

CP violation form factor H_T



Several CPV sources contributed to H_T

Take hyperon EDM as the major source for H_T

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

Neglect q dependence, d_B for hyperon EDM

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

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:

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

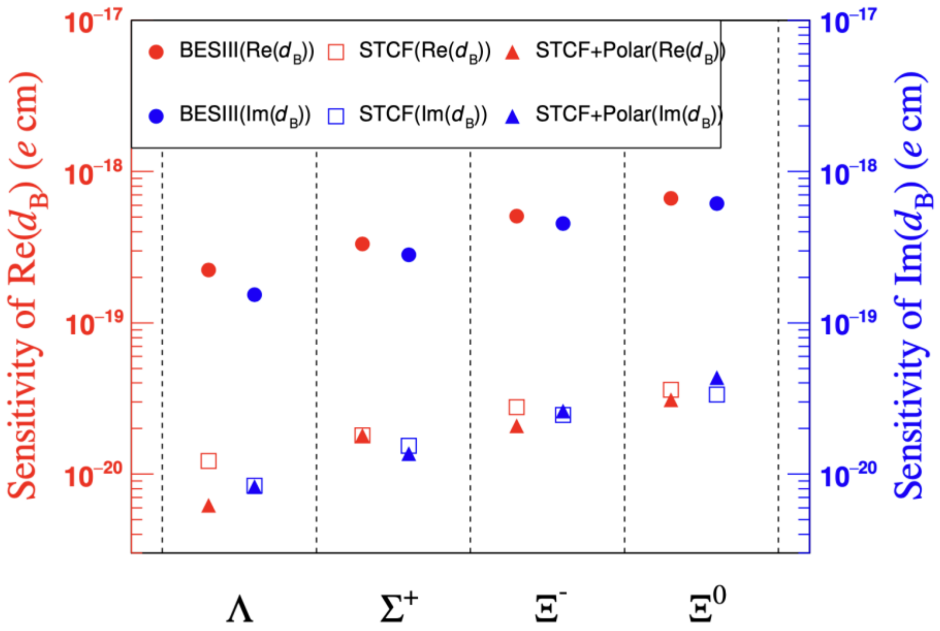
$$\frac{d\sigma}{d\Omega_k d\Omega_p d\Omega_{\bar{p}}} = N \sum_{[\lambda]} R(\lambda_1,\lambda_2;\lambda_1',\lambda_2') D^{j=1/2}_{\lambda_1,\lambda_p}(\theta_1,\phi_1) D^{*j=1/2}_{\lambda_1',\lambda_p}(\theta_1,\phi_1) \left|h_{\lambda_p}\right|^2 D^{j=1/2}_{\lambda_2,\lambda_{\bar{p}}}(\theta_2,\phi_2)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

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

$$\frac{d\sigma}{d\Omega_k d\Omega_\Lambda d\Omega_{\bar{\Lambda}} d\Omega_p d\Omega_{\bar{p}}} = N \sum_{[\lambda]} R(\lambda_1,\lambda_2;\lambda_1',\lambda_2') D^{*j=1/2}_{\lambda_1,\lambda_\Lambda}(\theta_1,\phi_1) D^{j=1/2}_{\lambda_1',\lambda'_\Lambda}(\theta_1,\phi_1) \mathcal{H}_{\lambda_\Lambda} \mathcal{H}^*_{\lambda_\Lambda'} D^{*j=1/2}_{\lambda_2,\lambda_{\bar{\Lambda}}}(\theta_2,\phi_2)$$
$$D^{j=1/2}_{\lambda_2',\lambda'_{\bar{\Lambda}}}(\theta_2,\phi_2) \mathcal{H}_{\lambda_{\bar{\Lambda}}} \mathcal{H}^*_{\lambda'_{\bar{\Lambda}}} D^{*j=1/2}_{\lambda_\Lambda,\lambda_p}(\theta_3,\phi_3) D^{*j=1/2}_{\lambda_\Lambda',\lambda_p}(\theta_3,\phi_3) \left|h_{\lambda_p}\right|^2 D^{*j=1/2}_{\lambda_{\bar{\Lambda}},\lambda_{\bar{p}}}(\theta_4,\phi_4) D^{j=1/2}_{\lambda_{\bar{\Lambda}}',\lambda_{\bar{p}}}(\theta_4,\phi_4) \left|h_{\lambda_{\bar{p}}}\right|^2$$

Sensitivity of hyperon EDM measurements

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



(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)

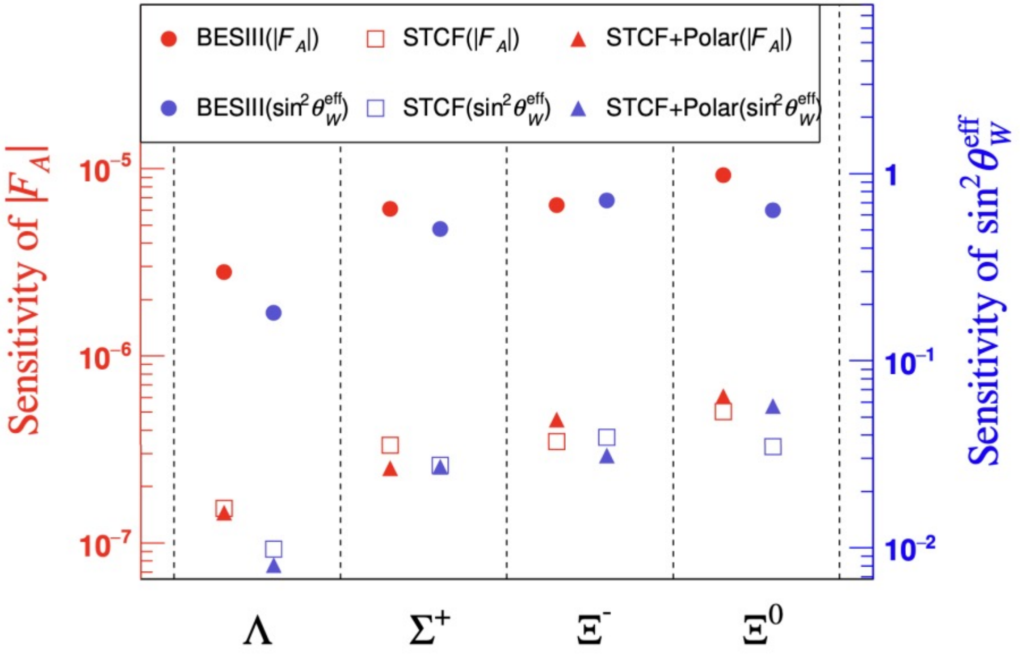
first achievement for Σ^+,Ξ^- and Ξ^0 at level of 10^{-19}e cm

a litmus test for new physics

STCF: improved by 2 order of magnitude

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 $\sin^2\theta_W^{\rm eff}$ by simultaneous fit

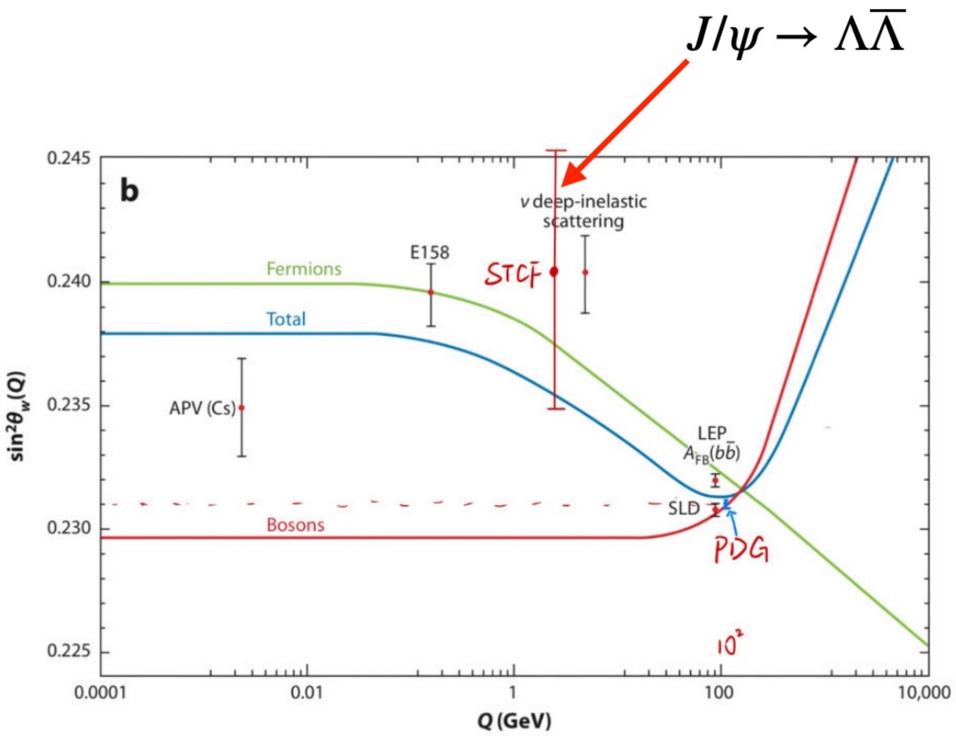


Figure 1

(*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}

Summary and Outlooks

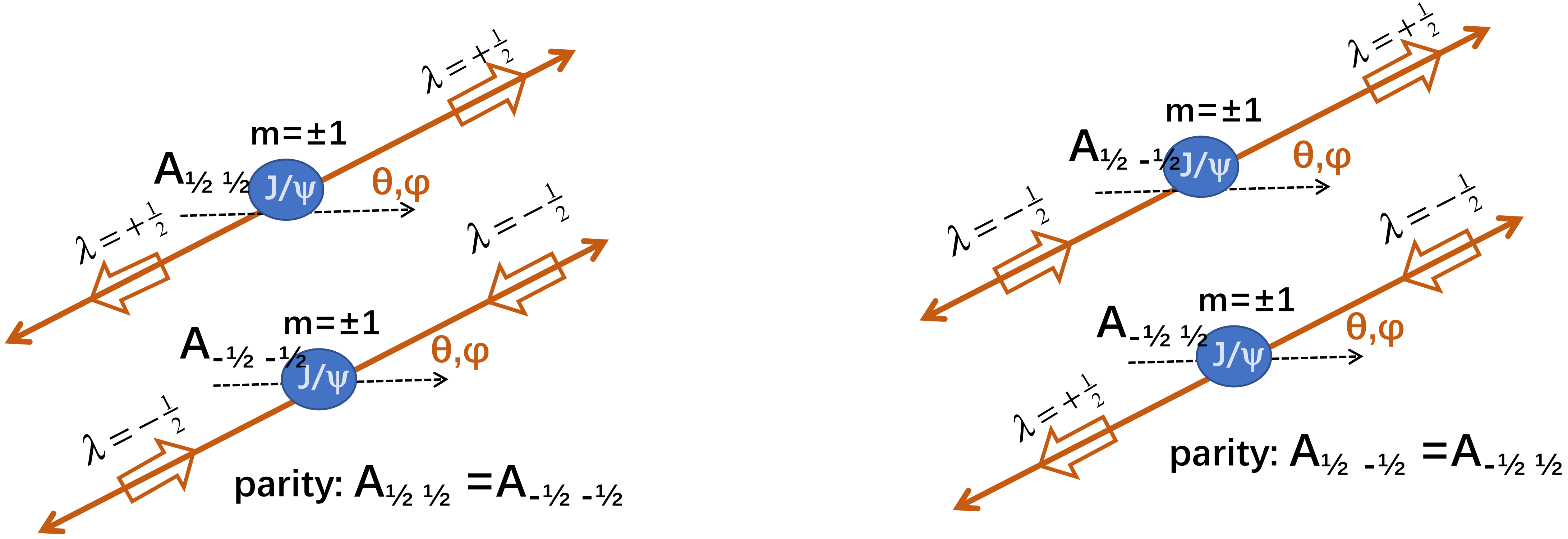
- **Polarization plays an important role in hyperon physics (at BESIII):**
  - **Precision measurements of hyperon decay parameters, polarization and CP:**
    - complementary to CPV studies with Kaons
    - BESIII has already rewritten the PDG book for Λ and Ξ decays
    - results of $\Sigma^{\pm}, \Xi$ 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 $\Sigma^{+}, \Xi^{-}, \Xi^{0}$ 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 $\Xi^- \rightarrow \Lambda\pi$ decay

decay rate difference

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

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

decay asymmetry difference

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

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

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

final-state polarization difference

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

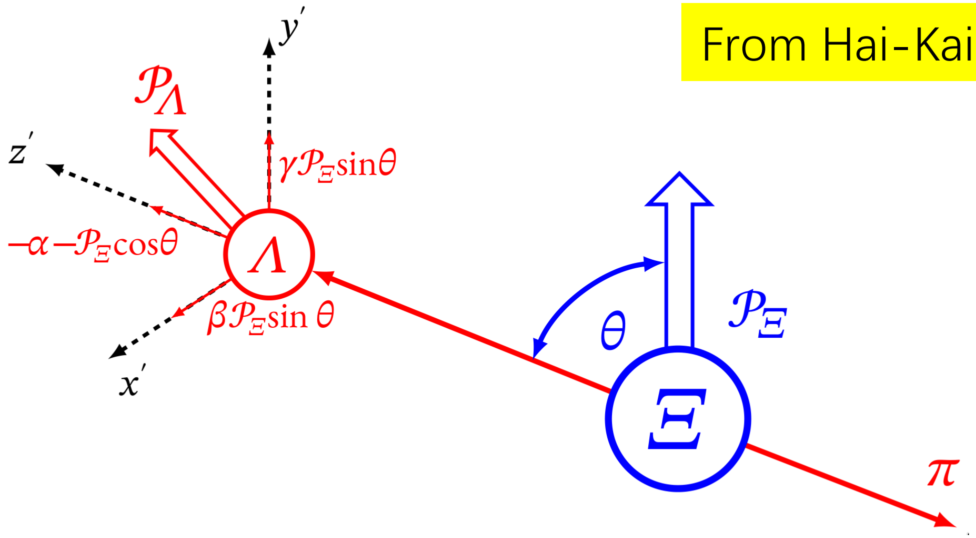
$$\frac{\beta_- + \beta_+}{\alpha_- - \alpha_+} = \frac{\cos\Delta_S \sin\phi_{CP}}{\cos\Delta_S \cos\phi_{CP}} = \tan\phi_{CP}$$

← 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

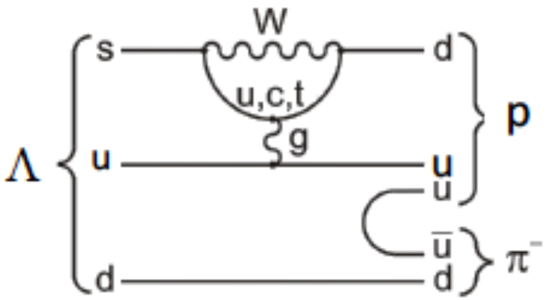
X.G. He

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

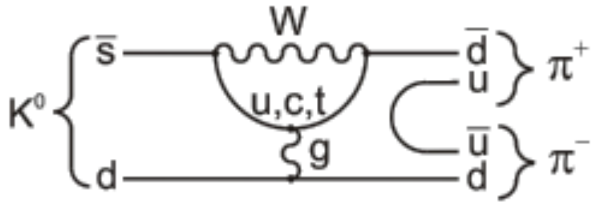


S- and P-waves
(parity violating
& conserving)

$\Lambda \to p\pi^-$	A_{NP}	
S-wave	$<6\times10^{-5}$	parity violating
P-wave	$<3\times10^{-4}$	parity conserving

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

$Re(\varepsilon'/\varepsilon)=(1.6+0.3)\times10^{-3}$



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.