CP Violation in Hyperon Interactions

Xiao-Gang He

TDLI， SJTU

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Hyperons decays and their couplings to other particles contain a lot of information about weak interactions, P and CP violations. This talk will focuse on two subject related to hyperons

1. A new test of CP violation for Hyperon production

2. CP violation in two body weak decays of hyperons

3. Conclusions

1. A new test of CP violation for Hyperon production

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X-G He, J-P Ma, B. Mckellar, PRD 47(1993) 1744; X-G He and J-P Ma, PLB839(2023)137834
Yong Du, X-G He, J-P Ma, X-Y Du, arXiv: 2405.09625 (PRD accepted)

Testing of P and CP symmetries with $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$

$$\mathcal{A}^\mu = \bar{u}(k_1)\left[\gamma^\mu F_V + \frac{i}{2m_\Lambda}\sigma^{\mu\nu}q_\nu H_\sigma + \gamma^\mu\gamma_5 F_A + \sigma^{\mu\nu}q_\nu\gamma_5 H_T\right]v(k_2),$$

$$G_1^B = F_V^B + H_\sigma^B, \quad G_2^B = G_1^B - \frac{(k_1-k_2)^2}{4m_B^2}H_\sigma^B, \qquad H_T = \frac{2e}{3m_{J/\psi}^2}g_V d_\Lambda$$

$$\Lambda \to p + \pi \text{ or } \bar{\Lambda} \to \bar{p} + \pi$$

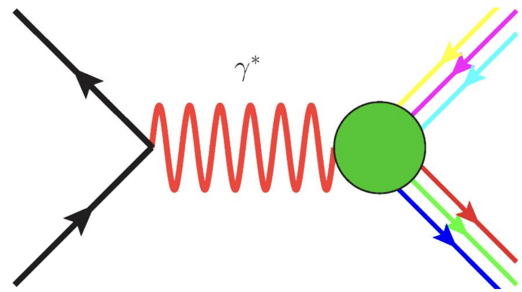
$\hat{l}_p$, $l_{\bar{p}}$ and $\hat{k}$ momentum directions of p, $\bar{p}$ and Λ.

Dipole moment contribution to H_T

H_T is flavor conserving CP violating. It is extremely small in the SM.

Beyond SM, it may be large. Consider now Λ edm contribution.

$$L_{edm} = -i\frac{d_\Lambda}{2}\Lambda\sigma_{\mu\nu}\gamma_5\Lambda F^{\mu\nu}$$



Excahnge a photon $$< 0|\bar{c}\gamma_\mu c|J/\Psi >= \epsilon^J_\mu g_V,\ g_V = 1.25GeV^2$$

We have $$H_T = \frac{2e}{3m^2_{J/\psi}} g_V d_\Lambda$$

The EDM of a fundamental particle

Classically a EDM $\vec{D} = \int d^3x \vec{x} \rho(\vec{x})$ interacts with an electric field $\vec{E}$

The interaction energy is given by $H = \vec{D} \cdot \vec{E}$, allowed by P and T symmetries.

Under P, $\vec{D} \to -\vec{D}$ and $\vec{E} \to -\vec{E}$, H conserves both P and T.

A fundamental particle, $\vec{D}$ is equal to $d\vec{S}$, $H_{edm} = d\vec{S} \cdot \vec{E}$.

Since under P, $\vec{S} \to \vec{S}$ and under T, $\vec{S} \to -\vec{S}$

Magnetic Dipole conserves P and T

$H_{mdm} = d_m \vec{S} \cdot \vec{B}$,

Under P: $\vec{B} \to \vec{B}$ and under T: $\vec{B} \to -\vec{B}$

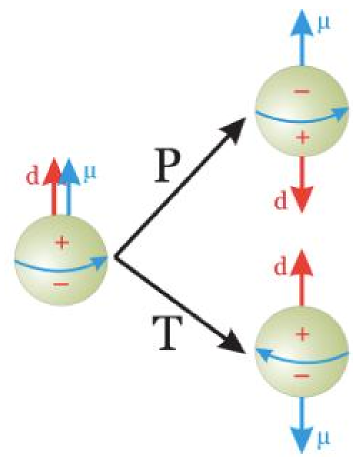
Relativistic expression: $d_m \bar{\psi} \sigma^{\mu\nu} \psi F_{\mu\nu}$.

H_{edm} violates both P and T, CPT is conserved, CP is also violated!

Quantum field theory, $H_{edm} = -i\frac{1}{2} d \bar{\psi} \sigma^{\mu\nu} \psi \tilde{F}_{mu\nu} = -i\frac{1}{2} d \bar{\psi} \sigma^{\mu\nu} \gamma_5 \psi F_{\mu\nu}$

In non-relativestic limit H_{edm} reduce to $d\frac{\vec{\sigma}}{2} \cdot \vec{E} = d\vec{S} \cdot \vec{E}$.

One easily sees that H_{edm} violates P and T, violates CP, but conserve CPT.



A non-zero fundamental particle EDM, violates P, T and CP!

First fundamental particle EMD measurement: neutron EDM in 1950 by Purcell and Ramsey. Landau first pointed out that EDM violates P and T symmetry.

No measurement of a fundamental particle EDM, yet!

Current 90% C.L. limits on EDM:

Proton $|d_p| < 2.1 \times 10^{-25}$ ecm,

Neutron $|d_n| < 1.8 \times 10^{-26}$ ecm,

Lambda $|d_\Lambda| < 1.5 \times 10^{-16}$ ecm,

Other hyperons, no measurements

electron $|d_e| < 1.1 \times 10^{-29}$ ecm

muon $|d_\mu| < 1.8 \times 10^{-19}$ ecm

tauon $\mathrm{Re}(d_\tau)$ −2.2 to 0.45 $\times 10^{-17}$ ecm

$\mathrm{Im}(d_\tau)$ −2.5 to 0.08 $\times 10^{-17}$ ecm

Measrements of Hyperon EDM from $J/\psi \to \Lambda\bar{\Lambda}$ is the value at $q^2 = m_{J/\psi}^2$

e+ e- -> J/Ψ   Density matrix

$$\mathcal{T} = \epsilon^\mu \mathcal{A}_\mu, \quad R(\hat{\boldsymbol{p}}, \hat{\boldsymbol{k}}, \boldsymbol{s}_1, \boldsymbol{s}_2) = \mathcal{T}\mathcal{T}^\dagger = \rho^{ij}\mathcal{M}^{ij},$$

$$\mathcal{M}^{ij} = \mathcal{A}^i \mathcal{A}^{*j}, \quad \rho^{ij} = \epsilon^i \epsilon^{*j}. \quad \rho^{ij}(\hat{\boldsymbol{p}}) = \frac{1}{3}\delta^{ij} - i d_J \epsilon^{ijk}\hat{p}^k - \frac{c_J}{2}\left(\hat{p}^i\hat{p}^j - \frac{1}{3}\delta^{ij}\right),$$

d_J induced by Z exchange in SM   e+ e- ->Z -> J/Ψ

$$d_J = \frac{3 - 8\sin^2\theta_W}{32\cos^2\theta_W \sin^2\theta_W}\frac{M^2_{J/\psi}}{M^2_Z} \approx 2.53 \times 10^{-4},$$

$$\hat{\boldsymbol{p}} = \frac{\boldsymbol{p}}{|\boldsymbol{p}|}, \quad \hat{\boldsymbol{k}} = \frac{\boldsymbol{k}}{|\boldsymbol{k}|}, \quad \hat{\boldsymbol{n}} = \frac{\boldsymbol{p}\times\boldsymbol{k}}{|\boldsymbol{p}\times\boldsymbol{k}|}, \quad \omega = \hat{\boldsymbol{p}}\cdot\hat{\boldsymbol{k}}.$$

$$R\left(\hat{\boldsymbol{p}}, \hat{\boldsymbol{k}}, \boldsymbol{s}_1, \boldsymbol{s}_2\right) = a(\omega) + \boldsymbol{s}_1 \cdot \boldsymbol{B}_1(\hat{\boldsymbol{p}}, \hat{\boldsymbol{k}}) + \boldsymbol{s}_2 \cdot \boldsymbol{B}_2(\hat{\boldsymbol{p}}, \hat{\boldsymbol{k}}) + s_1^i s_2^j C^{ij}(\hat{\boldsymbol{p}}, \hat{\boldsymbol{k}}).$$

a, B_1, B_2 and C^{ij} are functions of $F_{V,A}$, $H_{\sigma, T}$

$$\boldsymbol{B_1}(\hat{\boldsymbol{p}},\hat{\boldsymbol{k}}) = \hat{\boldsymbol{p}} b_{1p}(\omega) + \hat{\boldsymbol{k}} b_{1k}(\omega) + \hat{\boldsymbol{n}} b_{1n}(\omega), \quad \boldsymbol{B_2}(\hat{\boldsymbol{p}},\hat{\boldsymbol{k}}) = \hat{\boldsymbol{p}} b_{2p}(\omega) + \hat{\boldsymbol{k}} b_{2k}(\omega) + \hat{\boldsymbol{n}} b_{2n}(\omega),$$

$$C^{ij}(\hat{\boldsymbol{p}},\hat{\boldsymbol{k}}) = \delta^{ij} c_0(\omega) + \epsilon^{ijk}\left(\hat{\boldsymbol{p}}^k c_1(\omega) + \hat{\boldsymbol{k}}^k c_2(\omega) + \hat{\boldsymbol{n}}^k c_3(\omega)\right) + \left(\hat{\boldsymbol{p}}^i\hat{\boldsymbol{p}}^j - \frac{1}{3}\delta^{ij}\right) c_4(\omega) + \left(\hat{\boldsymbol{k}}^i\hat{\boldsymbol{k}}^j - \frac{1}{3}\delta^{ij}\right) c_5(\omega)$$
$$+ \left(\hat{\boldsymbol{p}}^i\hat{\boldsymbol{k}}^j + \hat{\boldsymbol{k}}^i\hat{\boldsymbol{p}}^j - \frac{2}{3}\omega\delta^{ij}\right) c_6(\omega) + \left(\hat{\boldsymbol{p}}^i\hat{\boldsymbol{n}}^j + \hat{\boldsymbol{n}}^i\hat{\boldsymbol{p}}^j\right) c_7(\omega) + \left(\hat{\boldsymbol{k}}^i\hat{\boldsymbol{n}}^j + \hat{\boldsymbol{n}}^i\hat{\boldsymbol{k}}^j\right) c_8(\omega),$$

$$a(\omega) = E_c^2\left[|G_1|^2(1+\omega^2) + |G_2|^2 y_m^2(1-\omega^2)\right],$$
$$c_0(\omega) = \frac{1}{3}a(\omega),$$
$$c_1(\omega) = -4E_c^3\beta\omega\mathrm{Re}\left(H_T G_1^*\right),$$
$$c_2(\omega) = 4E_c^3 y_m\beta\left\{\mathrm{Re}\left(H_T G_2^*\right) + \omega^2\mathrm{Re}\left[H_T(G_1-G_2)^*\right]\right\},$$
$$c_3(\omega) = 0,$$
$$c_4(\omega) = 2E_c^2|G_1|^2,$$
$$c_5(\omega) = 2E_c^2\left[|G_1|^2 - y_m^2|G_2|^2 + |G_1 - y_m G_2|^2\omega^2\right],$$
$$c_6(\omega) = -2E_c^2\omega\left[|G_1|^2 - y_m\mathrm{Re}\left(G_1G_2^*\right)\right],$$
$$c_7(\omega) = 2E_c^2\beta\left|\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}\right|\mathrm{Im}\left(F_A G_1^*\right),$$

$$c_8(\omega) = 2E_c^2\left|\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}\right|\left\{2d_J y_m\mathrm{Im}\left(G_1G_2^*\right) - \beta\omega\mathrm{Im}\left[F_A\left(G_1 - y_m G_2\right)^*\right]\right\},$$
$$b_{1n}(\omega) = b_{2n}(\omega) = 2\left|\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}\right| E_c^2\omega y_m\mathrm{Im}\left(G_1G_2^*\right),$$
$$b_{1p}(\omega) = 2E_c^2\left\{2y_m d_J\mathrm{Re}\left(G_1G_2^*\right) + \beta\omega\left[y_m\mathrm{Re}\left(F_AG_2^*\right) + 2E_c\mathrm{Im}\left(H_TG_1^*\right)\right]\right\},$$
$$b_{2p}(\omega) = 2E_c^2\left\{2y_m d_J\mathrm{Re}\left(G_1G_2^*\right) + \beta\omega\left[y_m\mathrm{Re}\left(F_AG_2^*\right) - 2E_c\mathrm{Im}\left(H_TG_1^*\right)\right]\right\},$$
$$b_{1k}(\omega) = 2E_c^2\left\{2d_J\omega\left(|G_1|^2 - y_m\mathrm{Re}\left(G_1G_2^*\right)\right) + \beta\,\mathrm{Re}\left[F_A\left((1+\omega^2)G_1 - \omega^2 y_m G_2\right)^*\right]\right.$$
$$\left. -2E_c\beta\,\mathrm{Im}\left[H_T\left(\omega^2G_1 + (1-\omega^2)y_mG_2\right)^*\right]\right\},$$
$$b_{2k}(\omega) = 2E_c^2\left\{2d_J\omega\left(|G_1|^2 - y_m\mathrm{Re}\left(G_1G_2^*\right)\right) + \beta\,\mathrm{Re}\left[F_A\left((1+\omega^2)G_1 - \omega^2 y_m G_2\right)^*\right]\right.$$
$$\left. +2E_c\beta\,\mathrm{Im}\left[H_T\left(\omega^2G_1 + (1-\omega^2)y_mG_2\right)^*\right]\right\},$$

On-shell production of J/Ψ and observables

$$e^-(p_1) + e^+(p_2) \to J/\psi \to \Lambda(k_1, s_1) + \bar{\Lambda}(k_2, s_2),$$

$$p_1^\mu = (E_c, \boldsymbol{p}), \quad p_2^\mu = (E_c, -\boldsymbol{p}), \quad k_1^\mu = (k^0, \boldsymbol{k}), \quad k_2^\mu = (k^0, -\boldsymbol{k}).$$

$$\Lambda \to p + \pi \ \text{ or } \ \bar{\Lambda} \to \bar{p} + \pi$$

$$\frac{d\Gamma_\Lambda}{d\Omega_p}(\boldsymbol{s}_1, \hat{\boldsymbol{l}}_p) \propto 1 + \alpha \boldsymbol{s}_1 \cdot \hat{\boldsymbol{l}}_p, \quad \frac{d\Gamma_{\bar{\Lambda}}}{d\Omega_{\bar{p}}}(\boldsymbol{s}_2, \hat{\boldsymbol{l}}_{\bar{p}}) \propto 1 - \bar{\alpha} \boldsymbol{s}_2 \cdot \hat{\boldsymbol{l}}_{\bar{p}}$$

$\hat{\boldsymbol{l}}_p$ and $\hat{\boldsymbol{l}}_{\bar{p}}$ is the direction of the momentum of the proton or anti-proton in the rest frame of Λ or $\bar{\Lambda}$

$$\mathcal{A}(\mathcal{O}) = \frac{\mathcal{N}_{\text{event}}(\mathcal{O} > 0) - \mathcal{N}_{\text{event}}(\mathcal{O} < 0)}{\mathcal{N}_{\text{event}}(\mathcal{O} > 0) + \mathcal{N}_{\text{event}}(\mathcal{O} < 0)} = \frac{1}{\mathcal{N}} \int \frac{d\Omega_k d\Omega_p d\Omega_{\bar{p}}}{(4\pi)^3} \Big(\theta(\mathcal{O}) - \theta(-\mathcal{O}) \Big) \mathcal{W}(\Omega)$$

$$\langle \hat{\boldsymbol{l}}_b \cdot \hat{p} \rangle = \frac{4\alpha_B}{9\mathcal{N}} E_c^2 d_J \left(4y_m \mathrm{Re}\,(G_1 G_2^*) + |G_1|^2 \right),$$

$$\langle \hat{\boldsymbol{l}}_{\bar{b}} \cdot \hat{\boldsymbol{p}} \rangle = -\frac{4\bar{\alpha}_B}{9\mathcal{N}} E_c^2 d_J \left(4y_m \mathrm{Re}\,(G_1 G_2^*) + |G_1|^2 \right),$$

$$\langle \hat{\boldsymbol{l}}_b \cdot \hat{\boldsymbol{k}} \rangle = \frac{8\alpha_B \beta}{9\mathcal{N}} E_c^2 \left[\mathrm{Re}\,(F_A G_1^*) - E_c \mathrm{Im}\,(H_T G_1^* + y_m H_T G_2^*) \right],$$

$$\langle \hat{\boldsymbol{l}}_{\bar{b}} \cdot \hat{\boldsymbol{k}} \rangle = -\frac{8\bar{\alpha}_B \beta}{9\mathcal{N}} E_c^2 \left[\mathrm{Re}\,(F_A G_1^*) + E_c \mathrm{Im}\,(H_T G_1^* + y_m H_T G_2^*) \right],$$

$$\langle (\hat{\boldsymbol{l}}_b \times \hat{l}_{\bar{b}}) \cdot \hat{\boldsymbol{k}} \rangle = -\frac{16\alpha_B \bar{\alpha}_B}{27\mathcal{N}} \beta y_m E_c^3 \mathrm{Re}\,(H_T G_2^*),$$

$$\mathcal{N} = \frac{2}{3} E_c^2 \left(2\,|G_1|^2 + y_m^2\,|G_2|^2 \right)$$

P violating observable

$$\mathcal{A}(\hat{\boldsymbol{l}}_b \cdot \hat{\boldsymbol{p}} - \hat{\boldsymbol{l}}_{\bar{b}} \cdot \hat{\boldsymbol{p}}) \equiv A^{(1)}_{\rm PV} \simeq \frac{4\alpha_B}{3\mathcal{N}} E_c^2 d_J \left(4 y_m {\rm Re}\,(G_1 G_2^*) + |G_1|^2\right),$$

$$\mathcal{A}(\hat{\boldsymbol{l}}_b \cdot \hat{\boldsymbol{k}} - \hat{\boldsymbol{l}}_{\bar{b}} \cdot \hat{\boldsymbol{k}}) \equiv A^{(2)}_{\rm PV} \simeq \frac{8\alpha_B \beta}{3\mathcal{N}} E_c^2\, {\rm Re}\,(F_A G_1^*),$$

CP violating observable

$$\mathcal{A}(\hat{\boldsymbol{l}}_b \cdot \hat{\boldsymbol{k}} + \hat{\boldsymbol{l}}_{\bar{b}} \cdot \hat{\boldsymbol{k}}) \equiv A^{(1)}_{\rm CPV} \simeq -\frac{4\alpha_B \beta}{3\mathcal{N}} E_c^3\, {\rm Im}\,(H_T G_1^* + y_m H_T G_2^*),$$

$$\mathcal{A}((\hat{\boldsymbol{l}}_b \times \hat{\boldsymbol{l}}_{\bar{b}}) \cdot \hat{\boldsymbol{k}}) \equiv A^{(2)}_{\rm CPV} \simeq -\frac{8\alpha_B \bar{\alpha}}{9\mathcal{N}} \beta y_m E_c^3 {\rm Re}\,(H_T G_2^*),$$

J/ψ to Octet baryon pairs B anti-B

$$B = \begin{pmatrix} \Sigma^0/\sqrt{2} + \Lambda/\sqrt{6} & \Sigma^+ & p \\ \Sigma^- & -\Sigma^0/\sqrt{2} + \Lambda/\sqrt{6} & n \\ \Xi^- & \Xi^0 & -2\Lambda/\sqrt{6} \end{pmatrix}$$

$$H_T = \left| \frac{e \cdot Q_c \cdot g_V \cdot d_B}{m^2_{J/\psi}} \right.$$

d_B	QM	Reduced Results	d_B	NR QCD & QM	Reduced Results
d_p^{qEDM}	$\frac{1}{3}(4d_u - d_d)$	—	d_p^{qCDM}	$-\frac{1}{3}(4Q_d f_d - Q_u f_u)$	—
d_n^{qEDM}	$\frac{1}{3}(4d_d - d_u)$	—	d_p^{qCDM}	$-\frac{1}{3}(4Q_u f_u - Q_d f_d)$	—
$d_{\Sigma^+}^{\mathrm{qEDM}}$	$\frac{1}{3}(4d_u - d_s)$	$-\frac{1}{3}d_s$	d_p^{qCDM}	$-\frac{1}{3}(4Q_u f_u - Q_s f_s)$	$-\frac{1}{9}ef_s$
$d_{\Sigma^0}^{\mathrm{qEDM}}$	$\frac{1}{3}(2d_u + 2d_d - d_s)$	$-\frac{1}{3}d_s$	d_p^{qCDM}	$-\frac{1}{3}(2Q_u f_u + 2Q_d f_d - Q_s f_s)$	$-\frac{1}{9}ef_s$
$d_{\Sigma^-}^{\mathrm{qEDM}}$	$\frac{1}{3}(4d_d - d_s)$	$-\frac{1}{3}d_s$	d_p^{qCDM}	$-\frac{1}{3}(4Q_d f_d - Q_s f_s)$	$-\frac{1}{9}ef_s$
$d_{\Xi^0}^{\mathrm{qEDM}}$	$\frac{1}{3}(4d_s - d_u)$	$\frac{4}{3}d_s$	d_p^{qCDM}	$-\frac{1}{3}(4Q_s f_s - Q_u f_u)$	$\frac{4}{9}ef_s$
$d_{\Xi^-}^{\mathrm{qEDM}}$	$\frac{1}{3}(4d_s - d_d)$	$\frac{4}{3}d_s$	d_p^{qCDM}	$-\frac{1}{3}(4Q_s f_s - Q_d f_d)$	$\frac{4}{9}ef_s$
$d_{\Lambda^0}^{\mathrm{qEDM}}$	d_s	d_s	d_p^{qCDM}	$-Q_s f_s$	$\frac{1}{3}ef_s$

Known data and sensitivity to EDM

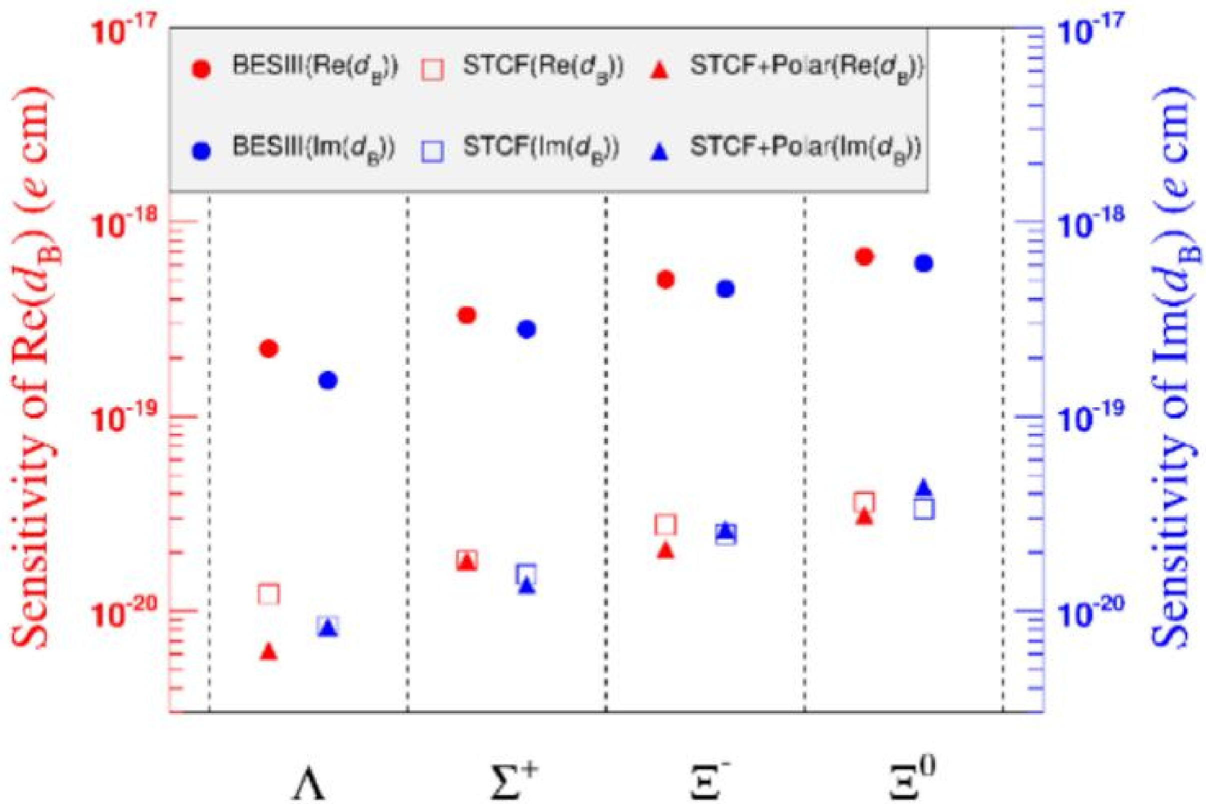
Parameters	$\Sigma^+\bar{\Sigma}^-$ [72]	$\Sigma^-\bar{\Sigma}^+$	$\Sigma^0\bar{\Sigma}^0$ [73]	$\Lambda\bar{\Lambda}$ [42]	$p\bar{p}$ [74]	$\Xi^0\bar{\Xi}^0$ [75, 76]	$\Xi^-\bar{\Xi}^+$ [40]
$\sqrt{s}$ (GeV)	2.9000	—	$m_{J/\psi}$	$m_{J/\psi}$	3.0800	$m_{J/\psi}$	$m_{J/\psi}$
$\alpha^B_{J/\psi}$	0.35 ± 0.23	—	-0.449 ± 0.022	0.4748 ± 0.0038	—	0.514 ± 0.016	0.586 ± 0.016
α_B	-0.982 ± 0.14	-0.068 ± 0.008	0.22 ± 0.31	0.7519 ± 0.0043	0.62 ± 0.11	-0.3750 ± 0.0038	-0.376 ± 0.008
$\bar{\alpha}_B$	-0.99 ± 0.04	—	—	0.7559 ± 0.0078	—	-0.3790 ± 0.0040	-0.371 ± 0.007
$\Delta\Phi$ (rad.)	1.3614 ± 0.4149	—	—	0.7521 ± 0.0066	—	1.168 ± 0.026	1.213 ± 0.049
$\lvert G_E/G_M \rvert \equiv$ R	0.85 ± 0.22	—	1.04 ± 0.37	0.96 ± 0.14	0.80 ± 0.15	1	1
$\lvert G_M \rvert$ $(\times 10^{-2})$	(derived)	—	0.71 ± 0.09	(derived)	3.47 ± 0.18	0.81 ± 0.21	1.14 ± 0.10

Best known hyperon EDM bound comes from $\Lambda < 1.6 \times 10^{-16}$ ecm

P/CP violation	$A^{(1)}_{\text{PV}}$ $(\times 10^{-4})$	$A^{(2)}_{\text{PV}}$ $(\times 10^{-4})$	$\sqrt{\epsilon \cdot t} \cdot d^{(1)}_B$ $(\times 10^{-18}\ e\,\text{cm})$		$\sqrt{\epsilon \cdot t} \cdot d^{(2)}_B$ $(\times 10^{-18}\ e\,\text{cm})$		$\sqrt{\epsilon \cdot t} \cdot \delta$ $(\times 10^{-4})$	
			BESIII	STCF	BESIII	STCF	BESIII	STCF
Λ $(\epsilon = 0.4)$	4.42	5.45	4.64	0.25	8.64	0.47	2.30	0.13
Σ^+ $(\epsilon = 0.2)$	-3.02	7.80	2.58	0.14	18.4	1.00	3.06	0.17
Ξ^0 $(\epsilon = 0.2)$	-1.55	-3.23	8.85	0.47	82.6	4.41	2.92	0.16
Ξ^- $(\epsilon = 0.2)$	-1.45	-2.55	8.93	0.48	95.9	5.20	3.21	0.17

TABLE IV: P violating asymmetries and baryon EDMs from current measurements summarized in table III. For the latter, $d^{(1)}_B$ ($d^{(2)}_B$) corresponds to the upper bounds at 95% CL resulted from $A^{(1)}_{\text{CPV}}$ ($A^{(2)}_{\text{CPV}}$), assuming statistics dominates the uncertainties at BESIII/STCFs. The last two columns show the statistical uncertainties δ with 10 billion events from a 12-year running time for BESIII and $t = 1$ for one-year data collection at STCF [50], assuming the systematical errors are well under control and a detector efficiency of ϵ indicated in the first column [81].

BES III and STCF sensitivities to Hyeron EDMs



Change hyperon to tauon, one can measure EDMs

2. CP violation in two body weak decays of hyperons

$$B = \begin{pmatrix} \Sigma^0/\sqrt{2} + \Lambda/\sqrt{6} & \Sigma^+ & p \\ \Sigma^- & -\Sigma^0/\sqrt{2} + \Lambda/\sqrt{6} & n \\ \Xi^- & \Xi^0 & -2\Lambda/\sqrt{6} \end{pmatrix}$$

$$F = \begin{pmatrix} \pi^0/\sqrt{2} + \eta/\sqrt{6} & \pi^- & K^- \\ \pi^+ & -\pi^0/\sqrt{2} + \eta/\sqrt{6} & \overline{K}^0 \\ K^+ & K^0 & -2\eta/\sqrt{6} \end{pmatrix}$$

$\Lambda^0 \to n\pi^0$
$\Lambda^0 \to p\pi^-$
$\Xi^0 \to \Lambda^0\pi^0$
$\Xi^- \to \Lambda^0\pi^-$
$\Sigma^- \to n\pi^-$
$\Sigma^+ \to p\pi^0$
$\Sigma^+ \to n\pi^+$

Observables

(Donoghue and Pakvasa, PRL55(1985)162, Donoghue, He and Pakvasa, PRD 34 (1986)833)

B -> F M

B initial baryon

F baryon in the final state

M meson in the final state

S p-parity violating

P p-parity conserving

$$\mathcal{A} = \bar{\mathcal{F}}(A_v + iA_c\gamma_5)\mathcal{B} = \mathcal{S} + \mathcal{P}\sigma\cdot\vec{p}_c$$

$$|\vec{p}_c| = \sqrt{E_{\mathcal{F}}^2 - m_{\mathcal{F}}^2}$$

$$\bar{\mathcal{A}} = -\bar{\mathcal{S}} + \bar{\mathcal{P}}\sigma\cdot\vec{p}_c$$

$$\mathcal{S} = A_v\sqrt{\frac{(m_{\mathcal{B}} + m_{\mathcal{F}})^2 - m_{\mathcal{M}}^2}{16\pi m_{\mathcal{B}}^2}}\,,\quad \mathcal{P} = A_c\sqrt{\frac{(m_{\mathcal{B}} - m_{\mathcal{F}})^2 - m_{\mathcal{M}}^2}{16\pi m_{\mathcal{B}}^2}}\,.$$

$$\frac{4\pi}{\Gamma}\frac{d\Gamma}{d\Omega} = 1 + \alpha\vec{s}_{\mathcal{B}}\cdot\vec{n} + \vec{s}_{\mathcal{F}}\cdot[(\alpha + \vec{s}_{\mathcal{B}}\cdot\vec{n})\vec{n} + \beta\vec{s}_{\mathcal{B}}\times\vec{n} + \gamma(\vec{n}\times(\vec{s}_{\mathcal{B}}\times\vec{n}))]$$

$\vec{s}_{\mathcal{B}}, \vec{s}_{\mathcal{F}}$ are the spins of initial b-baryon and final octet baryon.

$$\vec{n} = \vec{p_c}/|p_c|$$

$$\alpha = 2\,\mathrm{Re}S^*P/(|S|^2 + |P|^2),$$
$$\beta = 2\,\mathrm{Im}S^*P/(|S|^2 + |P|^2).$$

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

$$\bar{\alpha} = 2\,\mathrm{Re}\bar{S}^*\bar{P}/(|\bar{S}|^2 + |\bar{P}|^2),$$
$$\bar{\beta} = 2\,\mathrm{Im}\bar{S}^*\bar{P}/(|\bar{S}|^2 + |\bar{P}|^2),$$

$$\beta = (1-\alpha^2)^{\frac{1}{2}} sin\phi,\ \gamma = (1-\alpha^2)^{\frac{1}{2}} cos\phi,\ \phi = tan^{-1}(\beta/\gamma)$$

CPV observables

$$\Delta = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}, \qquad \Delta = -2\frac{\sum_{i>j}[S_iS_j\sin(\delta_i^S-\delta_j^S)\sin(\phi_i^S-\phi_j^S)+P_iP_j\sin(\delta_i^P-\delta_j^P)\sin(\phi_i^P-\phi_j^P)]}{\sum_i(S_i^2+P_i^2)+2\sum_{i>j}[S_iS_j\cos(\delta_i^S-\delta_j^S)+P_iP_j\cos(\delta_i^P-\delta_j^P)]},$$

$$A = \frac{\Gamma\alpha + \bar{\Gamma}\bar{\alpha}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}}, \qquad A = -\left(\frac{\beta}{\alpha}\right)_{CPC}\frac{\sum_{i,j}S_iP_j\sin(\delta_j^P-\delta_i^S)\sin(\phi_j^P-\phi_i^S)}{\sum_{i,j}S_iP_j\sin(\delta_j^P-\delta_i^S)},$$

$\delta_i^{S,P}$

–CP violating phase

$$B = \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\beta - \bar{\Gamma}\bar{\beta}}, \qquad B = \left(\frac{\alpha}{\beta}\right)_{CPC}\frac{\sum_{i,j}S_iP_j\cos(\delta_j^P-\delta_i^S)\sin(\phi_j^P-\phi_i^S)}{\sum_{i,j}S_iP_j\cos(\delta_j^P-\delta_i^S)},$$

$\phi_i^{S,P}$

– CP conserving phase

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

$$P = \sum_i P_i e^{i(\delta_i^P+\phi_i^P)}. \qquad \bar{P} = \sum_i P_i e^{i(\delta_i^P-\phi_i^P)}.$$

$$\left(\frac{\beta}{\alpha}\right)_{CPC} = \frac{\sum_{i,j}S_iP_j\sin(\delta_j^P-\delta_i^s)}{\sum_{i,j}S_iP_j\cos(\delta_j^P-\delta_i^S)}.$$

Great Job done at BESIII

	Δ	A	B
$\Lambda^0 \to p\pi^-$	-5.4×10^{-7}	-0.5×10^{-4}	3.0×10^{-3}
$\Xi^- \to \Lambda^0\pi^-$	0	-0.7×10^{-4}	8.4×10^{-4}
$\Sigma^- \to n\pi^-$	0	1.6×10^{-4}	-1.2×10^{-2}
$\Sigma^+ \to p\pi^0$	-6.2×10^{-7}	-3.2×10^{-7}	-4.2×10^{-4}
$\Sigma^+ \to n\pi^+$	6.0×10^{-7}	-1.6×10^{-4}	-8.4×10^{-7}

Signals of {CP} Nonconservation in Hyperon Decay
John F. Donoghue (Massachusetts U., Amherst), Sandip Pakvasa (Hawaii U.).
Published in **Phys.Rev.Lett. 55 (1985) 162**

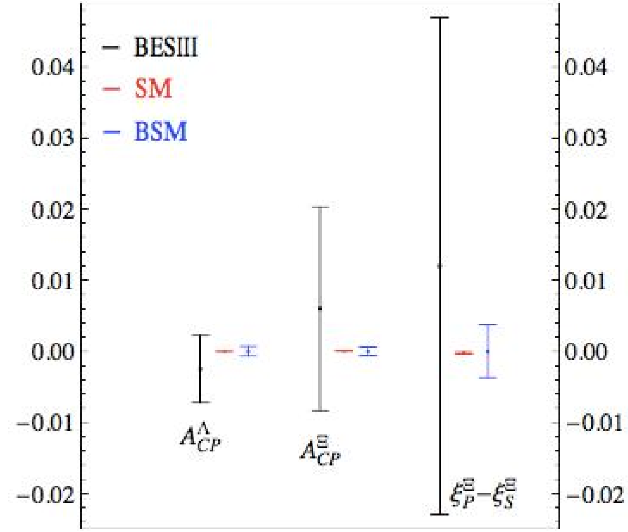
Hyperon decays and *CP* nonconservation

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)

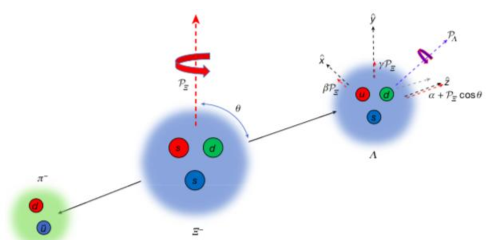
We study all modes of hyperon nonleptonic decay and consider the *CP*-odd observables which result. Explicit calculations are provided in the Kobayashi-Maskawa, Weinberg-Higgs, and left-right-symmetric models of *CP* nonconservation.



$A_{\Xi\Lambda}=A_\Xi + A_\Lambda$ HyperCP (Femilab E871): $A_{\Xi\Lambda} = [-6.0 \pm 2.1(\text{stat}) \pm 2.0(\text{syst})] \times 10^{-4}$

Recent measurement from BESIII
(Nature 606(2022)64)

$$A_{CP} = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}, \qquad B_{CP} = \frac{\beta + \overline{\beta}}{\alpha - \overline{\alpha}}$$



$$A_{CP}^{\Xi} = (6 \pm 13 \pm 6) \times 10^{-3},$$
$$B_{CP}^{\Xi} \simeq \xi_P^{\Xi} - \xi_S^{\Xi} = (1.2 \pm 3.4 \pm 0.8) \times 10^{-2},$$
$$A_{CP}^{\Lambda} = (-4 \pm 12 \pm 9) \times 10^{-3}$$

So far not CP violation effects have been established in baryon decay!.
Similar ideas can be used for c- and b-baryon decays.

Theoretical understanding

Isospin decomposition of Hyperon decay amplitudes

$\Lambda^0 \to p\pi^-$

$$S(\Lambda^0_-) = -(\tfrac{2}{3})^{1/2} S_{11} e^{i(\delta_1+\phi_1^S)} + (\tfrac{1}{3})^{1/2} S_{33} e^{i(\delta_3+\phi_3^S)} ,$$

$$P(\Lambda^0_-) = -(\tfrac{2}{3})^{1/2} P_{11} e^{i(\delta_{11}+\phi_1^P)} + (\tfrac{1}{3})^{1/2} P_{33} e^{i(\delta_{11}+\phi_3^P)} ,$$

and for $\Lambda^0 \to n\pi^0$

$$S(\Lambda^0_0) = (\tfrac{1}{3})^{1/2} S_{11} e^{i(\delta_1+\phi_1^S)} + (\tfrac{2}{3})^{1/2} S_{33} e^{i(\delta_3+\phi_3^S)} ,$$

$$P(\Lambda^0_0) = (\tfrac{1}{3})^{1/2} P_{11} e^{i(\delta_{11}+\phi_1^P)} + (\tfrac{2}{3})^{1/2} P_{33} e^{i(\delta_{33}+\phi_3^P)} .$$

$$\Delta(\Lambda^0_0) = -\tfrac{1}{2}\Delta(\Lambda^0_-) ,$$

$$\Delta(\Lambda^0_0) = A(\Lambda^0_-) ,$$

$$A(\Lambda^0_0) = B(\Lambda^0_-) ,$$

for $\Xi^- \to \Lambda^0\pi^-$ are

$$S(\Xi^-_-) = S_{12} e^{i(\delta_2+\phi_{12}^S)} + \tfrac{1}{2} S_{32} e^{i(\delta_2+\phi_{32}^S)} ,$$

$$P(\Xi^-_-) = P_{12} e^{i(\delta_{21}+\phi_{12}^P)} + \tfrac{1}{2} P_{32} e^{i(\delta_{21}+\phi_{32}^S)} ,$$

$$\Delta(\Xi^0_0) = 0 , \quad A(\Xi^0_0) = A(\Xi^-_-) ,$$

while for $\Xi^0 \to \Lambda\pi^0$

$$S(\Xi^0_0) = \frac{1}{\sqrt{2}} (S_{12} e^{i(\delta_{21}+\phi_{12}^S)} - S_{32} e^{i(\delta_2+\phi_{32}^S)}) ,$$

$$P(\Xi^0_0) = \frac{1}{\sqrt{2}} (P_{12} e^{i(\delta_{21}+\phi_{12}^P)} - P_{32} e^{i(\delta_{21}+\phi_{32}^P)}) .$$

$$B(\Xi^0_0) \neq B(\Xi^-_-) ,$$

$\Sigma^- \to n\pi^-$,

$$S(\Sigma_-^-) = S_{13} e^{i(\delta_3 + \phi_{13}^S)} + (\tfrac{2}{3})^{1/2} S_{33} e^{i(\delta_3 + \phi_{33}^S)} ,$$

$$P(\Delta_-^-) = P_{13} e^{i(\delta_{31} + \phi_{13}^P)} + (\tfrac{2}{3})^{1/2} P_{33} e^{i(\delta_{31} + \phi_{33}^P)} ,$$

$$\Delta(\Sigma_-^-) = 0 ,$$

$$A(\Sigma_-^-) = -\tan(\delta_{31} - \delta_3) A ,$$

$$B(\Sigma_-^-) = \cot(\delta_{31} - \delta_3) A ,$$

$$A = \sin(\phi_{13}^P - \phi_{13}^S) \frac{\left[1 + \left[\frac{2}{5}\right]^{1/2} \frac{S_{33}}{S_{13}} \frac{\sin(\phi_{13}^P - \phi_{33}^S)}{\sin(\phi_{13}^P - \phi_{13}^S)} + \left[\frac{2}{5}\right]^{1/2} \frac{P_{33}}{P_{13}} \frac{\sin(\phi_{33}^P - \phi_{13}^S)}{\sin(\phi_{13}^P - \phi_{13}^S)} + \frac{2}{5} \frac{S_{33} P_{33}}{S_{13} P_{13}} \frac{\sin(\phi_{33}^P - \phi_{33}^S)}{\sin(\phi_{13}^P - \phi_{13}^S)} \right]}{\left[1 + \left[\frac{2}{5}\right]^{1/2} \frac{S_{33}}{S_{13}} + \left[\frac{2}{5}\right]^{1/2} \frac{P_{33}}{P_{13}} + \frac{2}{5} \frac{S_{33} P_{33}}{S_{13} P_{13}} \right]} .$$

while for $\Sigma^+ \to p\pi^0$,

$$S(\Sigma_0^+) = \frac{\sqrt{2}}{3} (S_{11} e^{i\phi_{11}^S} - \frac{1}{2} S_{31} e^{i\phi_{31}^S}) e^{i\delta_1} + \frac{\sqrt{2}}{3} [S_{13} e^{i\phi_{13}^S} - 2(\tfrac{2}{5})^{1/2} S_{33} e^{i\phi_{33}^S}] e^{i\delta_3} ,$$

$$P(\Sigma_0^+) = \frac{\sqrt{2}}{3} (P_{11} e^{i\phi_{11}^P} - \tfrac{1}{2} P_{31} e^{i\phi_{31}^P}) e^{i\delta_{11}} + \frac{\sqrt{2}}{3} [P_{13} e^{i\phi_{13}^P} - 2(\tfrac{2}{5})^{1/2} P_{33} e^{i\phi_{33}^S}] e^{i\delta_{31}} ,$$

$$\Delta(\Sigma_0^+) = -2 \left[\frac{\bar S_1 \bar S_3 \sin(\delta_1 - \delta_3) \sin(\bar\phi_1^S - \bar\phi_3^S) + \bar P_1 \bar P_3 \sin(\delta_{11} - \delta_{31}) \sin(\bar\phi_1^P - \bar\phi_3^P)}{\bar S_1^2 + \bar S_3^2 + \bar P_1^2 + \bar P_3^2 + 2\bar S_1 \bar S_3 \cos(\delta_1 - \delta_3) + 2\bar P_1 \bar P_3 \cos(\delta_{11} - \delta_{31})} \right] ,$$

$$A(\Sigma_0^+) = -\left[\frac{\beta}{\alpha}\right]_{CPC} (\Sigma_0^+) \left[\sin(\delta_{11} - \delta_1) \sin(\bar\phi_1^P - \bar\phi_1^S) + \frac{\bar P_3}{\bar P_1} \sin(\delta_{31} - \delta_1) \sin(\bar\phi_3^P - \bar\phi_1^S) + \frac{\bar S_3}{\bar S_1} \sin(\delta_{11} - \delta_3) \sin(\bar\phi_1^P - \bar\phi_3^S) + \frac{\bar S_3 \bar P_3}{\bar S_1 \bar P_1} \sin(\delta_{31} - \delta_3) \sin(\bar\phi_3^P - \bar\phi_3^S) \right] \Big/ \left[\sin(\delta_{11} - \delta_1) + \frac{\bar P_3}{\bar P_1} \sin(\delta_{31} - \delta_1) + \frac{\bar S_3}{\bar S_1} \sin(\delta_{11} - \delta_3) + \frac{\bar S_3 \bar P_3}{\bar S_1 \bar P_1} \sin(\delta_{31} - \delta_3) \right] ,$$

$$B(\Sigma_0^+) = \left[\frac{\alpha}{\beta}\right]_{CPC} (\Sigma_0^+) \left[\cos(\delta_{11} - \delta_1) \sin(\bar\phi_1^P - \bar\phi_1^S) + \frac{\bar P_3}{\bar P_1} \cos(\delta_{31} - \delta_1) \sin(\bar\phi_3^P - \bar\phi_1^S) + \frac{\bar S_3}{\bar S_1} \cos(\delta_{11} - \delta_3) \sin(\bar\phi_1^P - \bar\phi_3^S) + \frac{\bar S_3 \bar P_3}{\bar S_1 \bar P_1} \cos(\delta_{31} - \delta_3) \sin(\bar\phi_3^P - \bar\phi_3^S) \right] \Big/ \left[\cos(\delta_{11} - \delta_1) + \frac{\bar P_3}{\bar P_1} \cos(\delta_{31} - \delta_1) + \frac{\bar S_3}{\bar S_1} \cos(\delta_{11} - \delta_3) + \frac{\bar S_3 \bar P_3}{\bar S_1 \bar P_1} \cos(\delta_{31} - \delta_3) \right] ,$$

Quantities need to know

$\Lambda \to \pi$ N: $\delta_1 = 6.0^o$, $\delta_3 = -3.8^o$, $\delta_{11} = -1.1^o$, $\delta_{31} = -0.7^o$

$\Xi \to \pi\ \Lambda$: $\delta_2 = -18.7^o$, $\delta_{21} = -2.7^o$

Amplitudes known from Br

$\Sigma \to \pi$ N: $\delta_1 = 9.4^o$, $\delta_3 = -10.1^o$, $\delta_{11} = -1.8^o$, $\delta_{31} = -3.6^o$

Need to know weak phases $\phi^{S,P}_i$

	α	ϕ
$\Lambda^0 \to n\pi^0$	0.642 ± 0.013	$-6.5° \pm 3.5°$
$\Lambda^0 \to p\pi^-$	0.642 ± 0.013	$-6.5° \pm 3.5°$
$\Xi^0 \to \Lambda^0\pi^0$	-0.413 ± 0.022	$20.7° \pm 11.7°$
$\Xi^- \to \Lambda^0\pi^-$	-0.434 ± 0.015	$2.0° \pm 5.7°$
$\Sigma^- \to n\pi^-$	-0.0681 ± 0.0077	$10.3° \pm 4.6°$
$\Sigma^+ \to p\pi^0$	-0.979 ± 0.016	$35.8° \pm 33.7°$
$\Sigma^+ \to n\pi^+$	0.068 ± 0.013	$167.3° \pm 20.1°$

SM calculation for Weak phases $\phi^{S,P}_i$

Tree and penguin contributions

$$\mathcal{H}_{\rm eff}(\Delta S=1)=\frac{G_F}{\sqrt{2}}\, V_{us}^* V_{ud} \sum_{i=1}^{10} [z_i(\mu)+\tau\, y_i(\mu)] Q_i(\mu).$$

$$\tau = -\frac{V_{ts}^* V_{td}}{V_{us}^* V_{ud}}.$$

$$Q_1=(\bar{s}_i u_j)_{V-A}(\bar{u}_j d_i)_{V-A},$$

$$Q_2=(\bar{s}u)_{V-A}(\bar{u}d)_{V-A},$$

$$Q_3=(\bar{s}d)_{V-A}\sum_q (\bar{q}q)_{V-A},$$

$$Q_4=(\bar{s}_i d_j)_{V-A}\sum_q (\bar{q}_j q_i)_{V-A},$$

$$Q_5=(\bar{s}d)_{V-A}\sum_q (\bar{q}q)_{V+A},$$

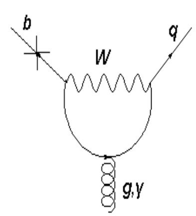
$$Q_6=(\bar{s}_i d_j)_{V-A}\sum_q (\bar{q}_j q_i)_{V+A}.$$

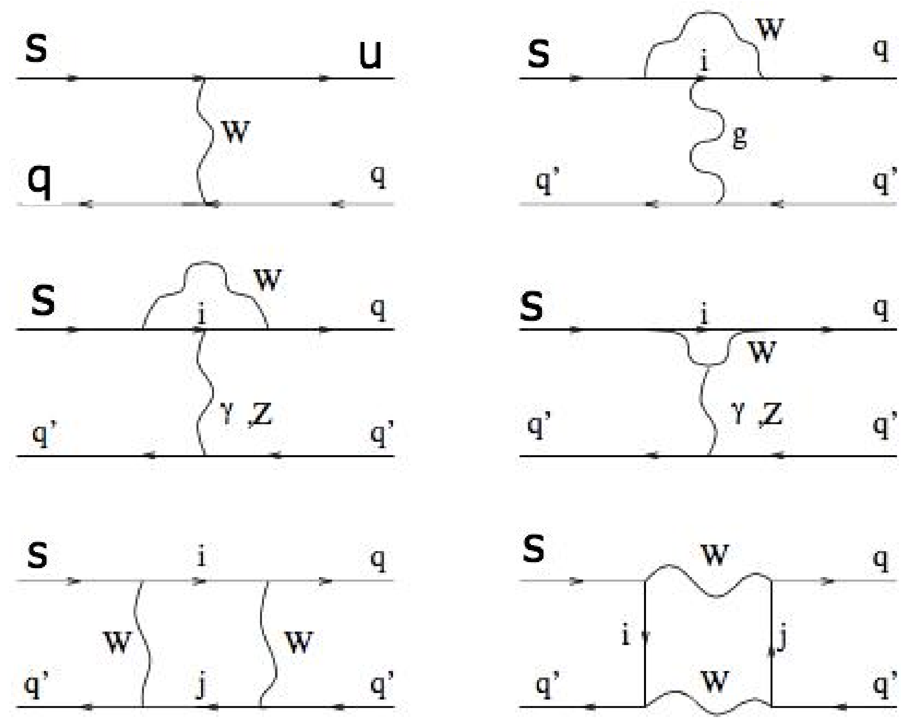
$$Q_7=\frac{3}{2}(\bar{s}d)_{V-A}\sum_q e_q(\bar{q}q)_{V+A},$$

$$Q_8=\frac{3}{2}(\bar{s}_i d_j)_{V-A}\sum_q e_q(\bar{q}_j q_i)_{V+A},$$

$$Q_9=\frac{3}{2}(\bar{s}d)_{V-A}\sum_q e_q(\bar{q}q)_{V-A},$$

$$Q_{10}=\frac{3}{2}(\bar{s}_i d_j)_{V-A}\sum_q e_q(\bar{q}_j q_i)_{V-A}.$$





ΔS=1 Wilson coefficients at μ=1 GeV for m_t=170 GeV. $y_1 = y_2 \equiv 0$.

	$\Lambda_{\overline{MS}}^{(4)}$=215 MeV			$\Lambda_{\overline{MS}}^{(4)}$=325 MeV			$\Lambda_{\overline{MS}}^{(4)}$=435 MeV		
Scheme	LO	NDR	HV	LO	NDR	HV	LO	NDR	HV
z_1	−0.607	−0.409	−0.494	−0.748	−0.509	−0.640	−0.907	−0.625	−0.841
z_2	1.333	1.212	1.267	1.433	1.278	1.371	1.552	1.361	1.525
z_3	0.003	0.008	0.004	0.004	0.013	0.007	0.006	0.023	0.015
z_4	−0.008	−0.022	−0.010	−0.012	−0.035	−0.017	−0.017	−0.058	−0.029
z_5	0.003	0.006	0.003	0.004	0.008	0.004	0.005	0.009	0.005
z_6	−0.009	−0.022	−0.009	−0.013	−0.035	−0.014	−0.018	−0.059	−0.025
z_7/α	0.004	0.003	−0.003	0.008	0.011	−0.002	0.011	0.021	−0.001
z_8/α	0	0.008	0.006	0.001	0.014	0.010	0.001	0.027	0.017
z_9/α	0.005	0.007	0	0.008	0.018	0.005	0.012	0.034	0.011
z_{10}/α	0	−0.005	−0.006	−0.001	−0.008	−0.010	−0.001	−0.014	−0.017
y_3	0.030	0.025	0.028	0.038	0.032	0.037	0.047	0.042	0.050
y_4	−0.052	−0.048	−0.050	−0.061	−0.058	−0.061	−0.071	−0.068	−0.074
y_5	0.012	0.005	0.013	0.013	−0.001	0.016	0.014	−0.013	0.021
y_6	−0.085	−0.078	−0.071	−0.113	−0.111	−0.097	−0.148	−0.169	−0.139
y_7/α	0.027	−0.033	−0.032	0.036	−0.032	−0.030	0.043	−0.031	−0.027
y_8/α	0.114	0.121	0.133	0.158	0.173	0.188	0.216	0.254	0.275
y_9/α	−1.491	−1.479	−1.480	−1.585	−1.576	−1.577	−1.700	−1.718	−1.722
y_{10}/α	0.650	0.540	0.547	0.800	0.690	0.699	0.968	0.892	0.906

$$S(\Lambda^0_-) = -(\tfrac{2}{3})^{1/2} S_{11} e^{i\phi_1^S} + (\tfrac{1}{3})^{1/2} S_{33} e^{i\phi_3^S}$$
$$= 32.8(1 - 0.42i\,\mathrm{Im}C_5) - 0.3\ ,$$

$$P(\Lambda^0_-) = -(\tfrac{2}{3})^{1/2} P_{11} e^{i\phi_1^P} + (\tfrac{1}{3})^{1/2} P_{33} e^{i\phi_3^P}$$
$$= 12.4(1 - 2.24i\,\mathrm{Im}C_5) - 0.06\ .$$

$$S(\Xi^-_-) = S_{12} e^{i\phi_{12}^S} + \tfrac{1}{2} S_{32} e^{i\phi_{32}^S}$$
$$= -46.2(1 - 0.29i\,\mathrm{Im}C_5) + 1.1\ ,$$

$$P(\Xi^-_-) = P_{12} e^{i\phi_{12}^P} + \tfrac{1}{2} P_{32} e^{i\phi_{32}^P}$$
$$= 10.2(1 + 0.92i\,\mathrm{Im}C_5) - 0.1\ .$$

$$S(\Sigma_0^+) = \frac{\sqrt{2}}{3} S_{13} e^{i\phi_{13}^S} - \frac{4}{3\sqrt{5}} S_{33} e^{i\phi_{33}^S} + \frac{\sqrt{2}}{3} \bar{S}_1 e^{i\bar{\phi}_1^S}$$
$$= -20.9(1 - 0.3i\,\mathrm{Im}C_5) - 1.5$$
$$- 10.3(1 - 0.3i\,\mathrm{Im}C_5)\ , \qquad (3.$$

$$P(\Sigma_0^+) = \frac{\sqrt{2}}{3} P_{13} e^{i\phi_{13}^P} - \frac{4}{3\sqrt{5}} P_{33} e^{i\phi_{33}^P} + \frac{\sqrt{2}}{3} \bar{P}_1 e^{i\bar{\phi}_1^P}$$
$$= -0.3(1 + 20.0i\,\mathrm{Im}C_5) - 1.9$$
$$+ 28.8(1 - 0.15i\,\mathrm{Im}C_5)\ . \qquad (3.$$

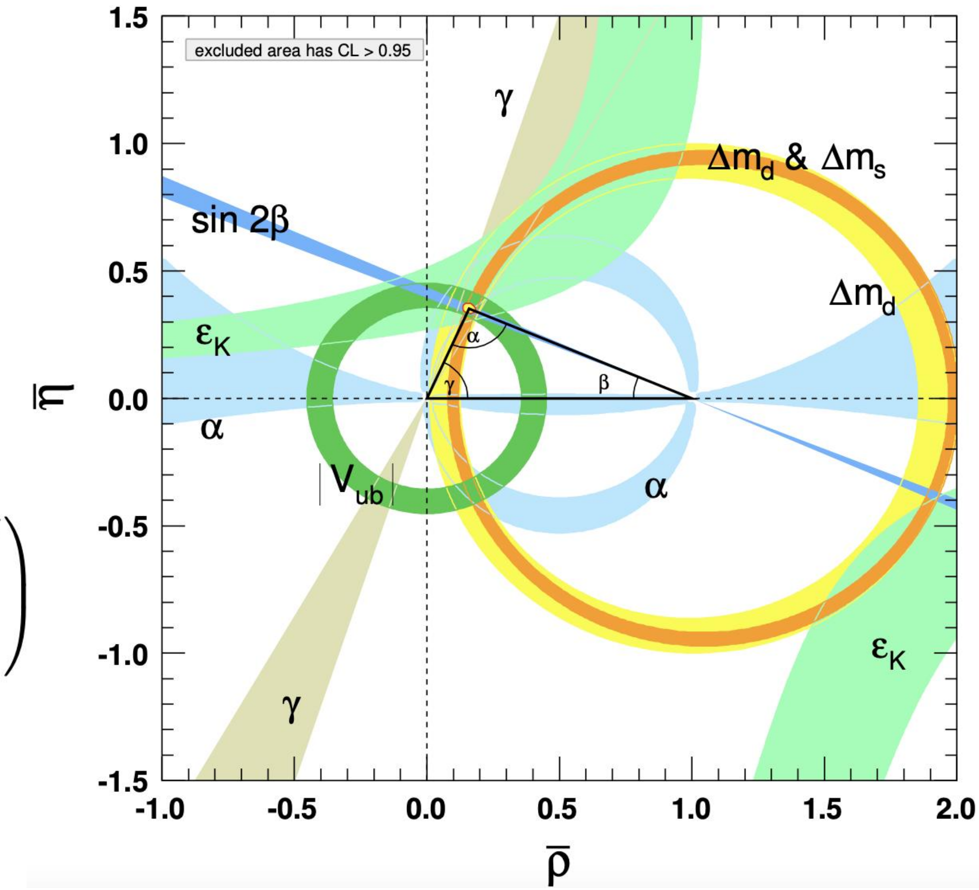
$\mathrm{Im}C_5 = \mathrm{Im}(-V_{td}^* V_{ts} / V_{ud}^* V_{us})\ Y_6$

Weak phase induced by KM matrix

$ImC_5=Im(-V_{td}^*V_{ts}/V_{ud}^*V_{us})\ Y_6$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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



$$\sin\theta_{12} = 0.22501 \pm 0.00068\,, \qquad \sin\theta_{13} = 0.003732^{+0.000090}_{-0.000085}\,,$$

$$\sin\theta_{23} = 0.04183^{+0.00079}_{-0.00069}\,, \qquad \delta = 1.147 \pm 0.026\,.$$

SM for CPV in Hyperon Decays

	Δ	A	B
$\Lambda^0 \to p\pi^-$	-5.4×10^{-7}	-0.5×10^{-4}	3.0×10^{-3}
$\Xi^- \to \Lambda^0\pi^-$	0	-0.7×10^{-4}	8.4×10^{-4}
$\Sigma^- \to n\pi^-$	0	1.6×10^{-4}	-1.2×10^{-2}
$\Sigma^+ \to p\pi^0$	-6.2×10^{-7}	-3.2×10^{-7}	-4.2×10^{-4}
$\Sigma^+ \to n\pi^+$	6.0×10^{-7}	-1.6×10^{-4}	-8.4×10^{-7}

$$A_{\Lambda\Xi} \equiv \frac{\alpha_\Lambda\alpha_\Xi - \alpha_{\bar\Lambda}\alpha_{\bar\Xi}}{\alpha_\Lambda\alpha_\Xi + \alpha_{\bar\Lambda}\alpha_{\bar\Xi}}$$

$$-3\times10^{-5} \le A_\Lambda \le 4\times10^{-5}\,, \qquad -2\times10^{-5} \le A_\Xi \le 1\times10^{-5}\,,$$

$$-5\times10^{-5} \le A_{\Xi\Lambda} \le 5\times10^{-5}\,.$$

J. Tandean and G. Valencia, Phys. Rev. D 67, 056001 (2003) [hep-ph/0211165].

J. Tandean, PRD 70, 076005 (2004).J. Tandean and G. Valencia, PLB 451, 382 (1999)

$\Omega \to \Lambda K \to p\pi K$; $\qquad \Omega^- \to \Xi\pi.$

$$A_{\Omega\Lambda} = \frac{\alpha_\Omega\alpha_\Lambda - \alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}}}{\alpha_\Omega\alpha_\Lambda + \alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}}} \simeq A_\Omega + A_\Lambda\,,$$

$$-4\times10^{-5} \le A_{\Omega\Lambda} \le 4\times10^{-5}$$

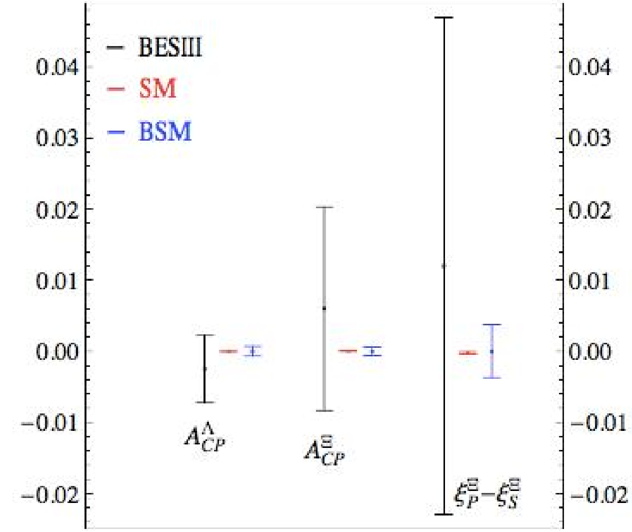
$$A_\Omega \equiv \frac{\alpha_\Omega + \alpha_{\overline{\Omega}}}{\alpha_\Omega - \alpha_{\overline{\Omega}}}\,, \qquad A_\Lambda \equiv \frac{\alpha_\Lambda + \alpha_{\overline{\Lambda}}}{\alpha_\Lambda - \alpha_{\overline{\Lambda}}}$$

Rate asymmetry 2×10^{-5}

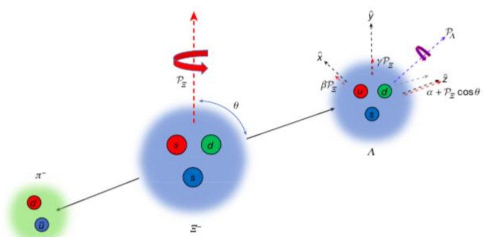
Great Job done at BESIII, STCF will do better!

$A_{\Xi\Lambda}=A_{\Xi} + A_{\Lambda}$ HyperCP (Femilab E871):

$$A_{\Xi\Lambda} = [-6.0 \pm 2.1(\text{stat}) \pm 2.0(\text{syst})] \times 10^{-4},$$



Recent measurement from BESIII
(Nature 606(2022)64)



$$A^{\Xi}_{CP} = (6 \pm 13 \pm 6) \times 10^{-3},$$
$$B^{\Xi}_{CP} \simeq \xi^{\Xi}_{P} - \xi^{\Xi}_{S} = (1.2 \pm 3.4 \pm 0.8) \times 10^{-2},$$
$$A^{\Lambda}_{CP} = (-4 \pm 12 \pm 9) \times 10^{-3}$$

So far not CP violation effects have been established in baryon decay!.
Similar ideas can be used for c- and b-baryon decays.

M. He, X-G He and G.N. Li PRD92(2015)036010

Constraining BSM

Example: Supersymmetric Model

He, Murayama, Pakvasa, Valencia, PRD61(2000)071701(R)

Exchange gluino can induce gluonic color dipole interaction

$$\mathcal{H}_{eff}=C_g\frac{g_s}{16\pi^2}m_s\bar{d}\sigma_{\mu\nu}G_a^{\mu\nu}t^a(1+\gamma_5)s$$

$$+\tilde{C}_g\frac{g_s}{16\pi^2}m_s\bar{d}\sigma_{\mu\nu}G_a^{\mu\nu}t^a(1-\gamma_5)s \quad + \quad \text{H.c.},$$

$$C_g=(\delta_{12}^d)_{LR}\frac{\alpha_s\pi}{m_{\tilde{g}}m_s}G_0(x), \quad \tilde{C}_g=(\delta_{12}^d)_{RL}\frac{\alpha_s\pi}{m_{\tilde{g}}m_s}G_0(x).$$

$$\eta=\left(\frac{\alpha_s(m_{\tilde{g}})}{\alpha_s(m_t)}\right)^{2/21}\left(\frac{\alpha_s(m_t)}{\alpha_s(m_b)}\right)^{2/23}\left(\frac{\alpha_s(m_b)}{\alpha_s(m_c)}\right)^{2/25}.$$

$$G_0(x)=x\frac{22-20x-2x^2+(16x-x^2+9)\log x}{3(x-1)^4}.$$

$$A(\Lambda_-^0)_{SUSY}=\left(\frac{\alpha_s(m_{\tilde{g}})}{\alpha_s(500\ \text{GeV})}\right)^{23/21}\left(\frac{500\ \text{GeV}}{m_{\tilde{g}}}\right)\frac{G_0(x)}{G_0(1)}$$

$$\times[(2.0B_p-1.7B_s)\text{Im}(\delta_{12}^d)_{LR}$$

$$+(2.0B_p+1.7B_s)\text{Im}(\delta_{12}^d)_{RL}].$$

$$\phi_s=-2.9\times10^7\ \text{GeV}$$

$$\times\frac{\alpha_s}{32\pi}\frac{\eta}{m_{\tilde{g}}}G_0(x)\text{Im}[(\delta_{12}^d)_{LR}-(\delta_{12}^d)_{RL}]B_s$$

$$\phi_p=-3.4\times10^7\ \text{GeV}$$

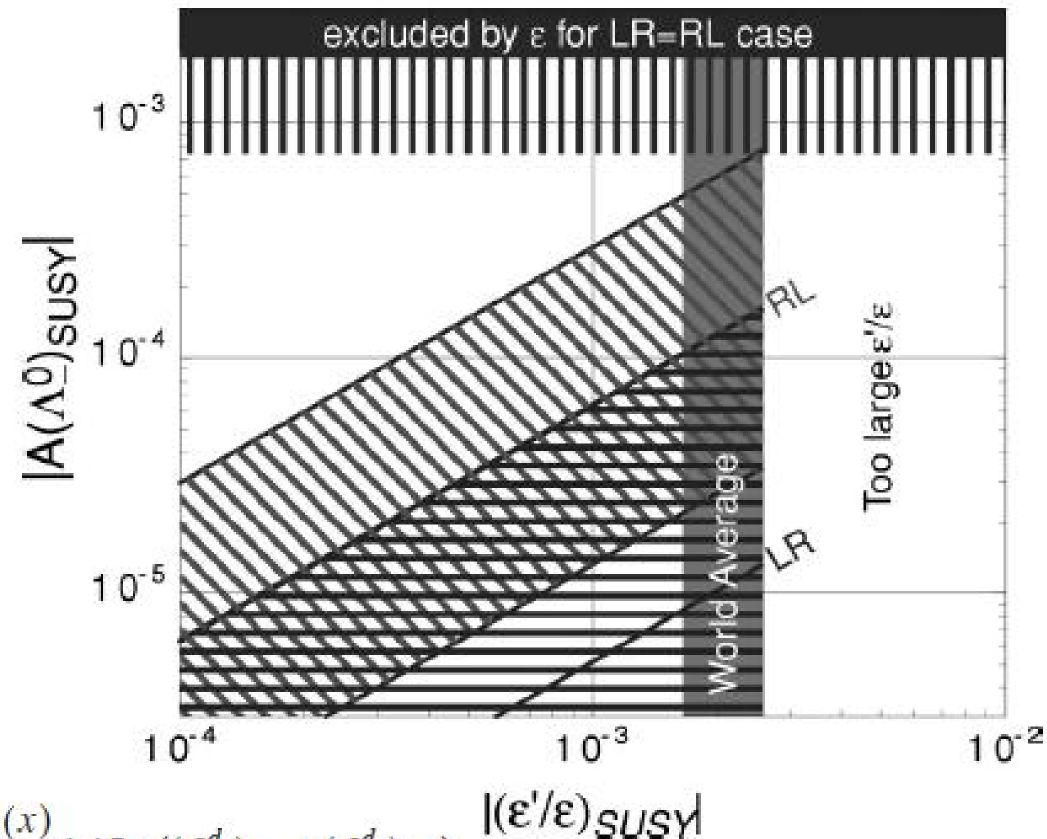
$$\times\frac{\alpha_s}{32\pi}\frac{\eta}{m_{\tilde{g}}}G_0(x)\text{Im}[(\delta_{12}^d)_{LR}+(\delta_{12}^d)_{RL}]B_p$$

$0.5<B_s<2.0$, $\quad 0.7B_s < B_p < 1.3\ B_s$

$$\left(\frac{\epsilon'}{\epsilon}\right)_{SUSY} = \left(\frac{\alpha_s(m_{\tilde{g}})}{\alpha_s(500\ \mathrm{GeV})}\right)^{23/21} \left(\frac{500\ \mathrm{GeV}}{m_{\tilde{g}}}\right) \frac{G_0(x)}{G_0(1)} B_G \left(\frac{158\ \mathrm{MeV}}{m_s(m_c)+m_d(m_c)}\right) 58\,\mathrm{Im}[(\delta^d_{12})_{LR} - (\delta^d_{12})_{RL}].$$

$0.5 < B_G < 2$

A(Λ) constrained, but can be as large as a few x10^{-4} .



$$(\epsilon)_{SUSY} = \left(\frac{\alpha_s(m_{\tilde{g}})}{\alpha_s(500\ \mathrm{GeV})}\right)^{23/21} \left(\frac{500\ \mathrm{GeV}}{m_{\tilde{g}}}\right) \frac{\kappa}{0.2} \frac{G_0(x)}{G_0(1)} 6.4\,\mathrm{Im}((\delta^d_{12})_{LR} + (\delta^d_{12})_{RL}),$$

$B \to K+$ invisible, dark matter, and CP violation in hyperon decays

Xiao-Gang He,[1,2,a] Xiao-Dong Ma,[3,4,b] Jusak Tandean,[5,c] and German Valencia[6,d]

arXiv: 2502.09603

A two Higgs + darkon model (dark matter scalar) explain Bell II B -> K invisible, Dark matter relic density, yet satisfy direct dark matter search limit, can have large CP violation in hyperon decays

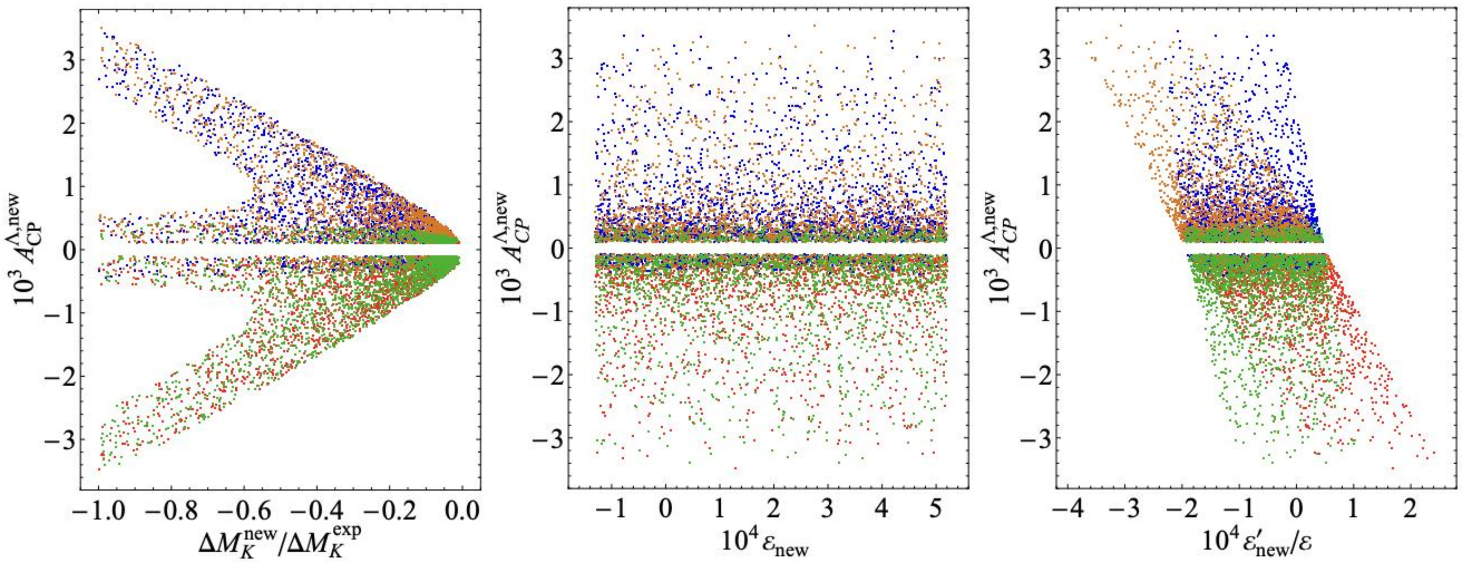


FIG. 7. Distributions of $A_{CP}^{\Lambda,\mathrm{new}}$ versus $\Delta M_K^{\mathrm{new}}/\Delta M_K^{\mathrm{exp}}$ (left), $\varepsilon_{\mathrm{new}}$ (middle), and $\varepsilon'_{\mathrm{new}}/\varepsilon$ (right), from the allowed Yukawa couplings.

3. Conclusions

New methods proposed. BESIII can improve Λ edm by about 2 orders of magnitude from J/ψ decays into Λ-pair. STCF will be able to improve another two orders of magnitude. Can do measurement of EDM for other hyperons too!

CP violation effect exist in hyperon decays.

Correlated ploarization measurement for the quantity A(B) from hyperon decays reaching 10^{-5} sensitivity will test the SM to a good precision. With a few 10^{-4} sensitivity will rule out some theoretical models beyond the SM.

STCF can reach SM predicted range.