# Probing hyperon EDM at BESIII and STCF

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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

J. Fu *et al*. Phys.Rev.D108,L091301(2023)

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# Electric Dipole Moments

- Quantum system: ensemble of particles, $\Lambda$, $\Sigma$, $\Xi$…

$$\boldsymbol{\delta} = d\,\mu_B\,\frac{\mathbf{s}}{2} \qquad\qquad \boldsymbol{\mu} = g\,\mu_B\,\frac{\mathbf{s}}{2}$$

Spin polarization vector: $\boldsymbol{s} = \mathrm{Tr}\,[\rho\boldsymbol{\sigma}] = \frac{2}{\hbar}\langle\hat{\boldsymbol{S}}\rangle$

Magneton: $\mu_{\mathrm{B}}$

Gyro-electric(magnetic) factor: $d$ ( $g$ )

- Non relativistic Hamiltonian

$$\mathcal{H} = -\boldsymbol{\mu}\cdot\boldsymbol{B} - \boldsymbol{\delta}\cdot\boldsymbol{E}$$

$$\mathcal{H} \xrightarrow{\mathrm{P,T}} \mathcal{H} = -\boldsymbol{\mu}\cdot\boldsymbol{B} \boxed{+\boldsymbol{\delta}\cdot\boldsymbol{E}}$$

EDM violates P and T, thus CP through CPT theorem

# Why EDM

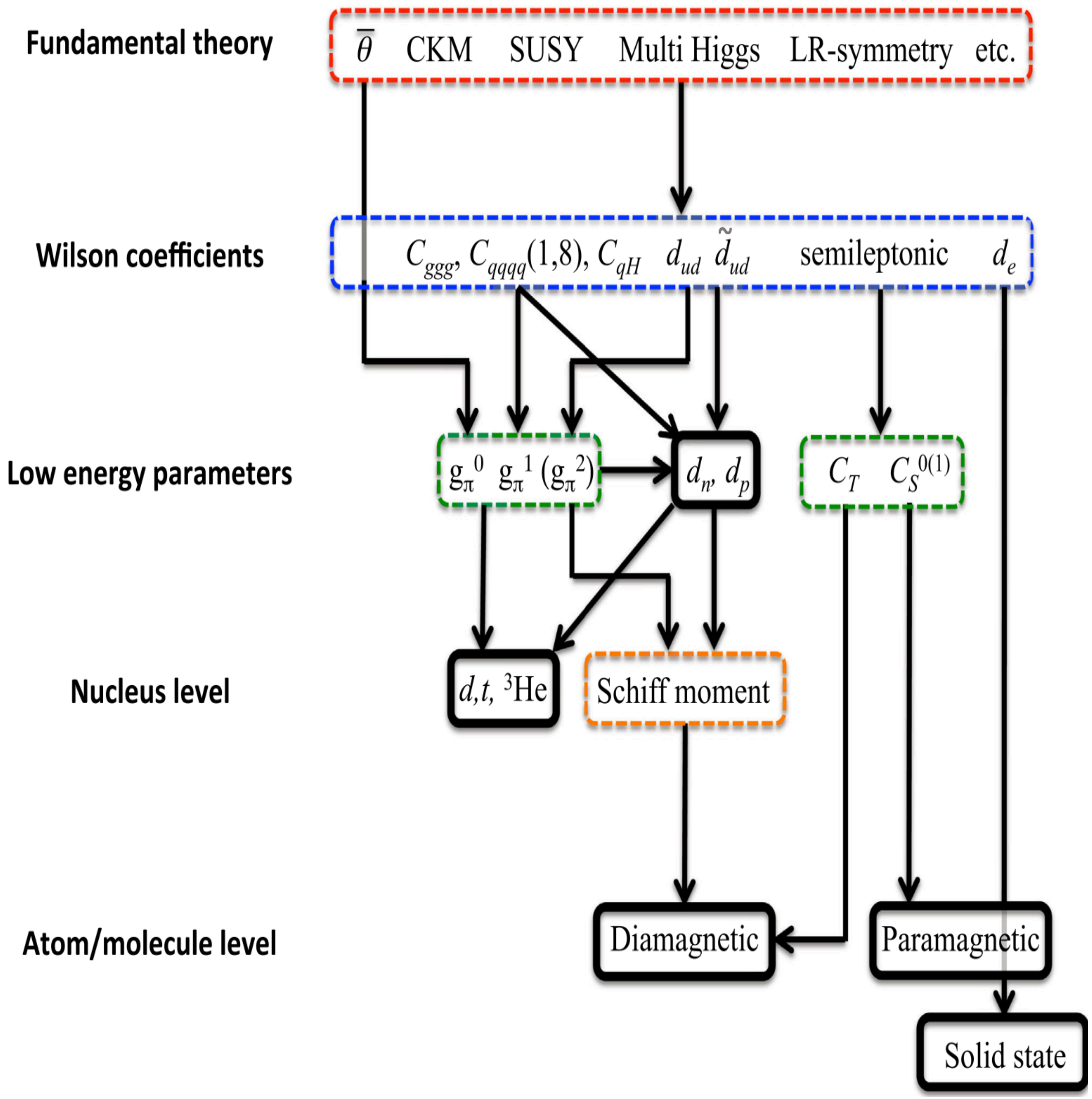
- CPV is a necessary condition to explain the matter dominated universe (Sakahrov condition), but CKM mechanism not sufficient and New Physics (NP) is required

- EDM is extremely small in SM. NP at the weak scale, TeV scale and beyond can also induce EDMs.

$$d \approx (10^{-16} e\,\mathrm{cm}) \left(\frac{v}{\Lambda}\right)^2 (\sin \phi_{\mathrm{CPV}})(y_f F)$$

- For hyperon, strange quark may have a special interaction with NP, resulting in large EDM effect

# Fundamental parameters and EDM




$$\mathcal{L}_{\rm CPV} = \mathcal{L}_{\rm CKM} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\rm BSM}$$

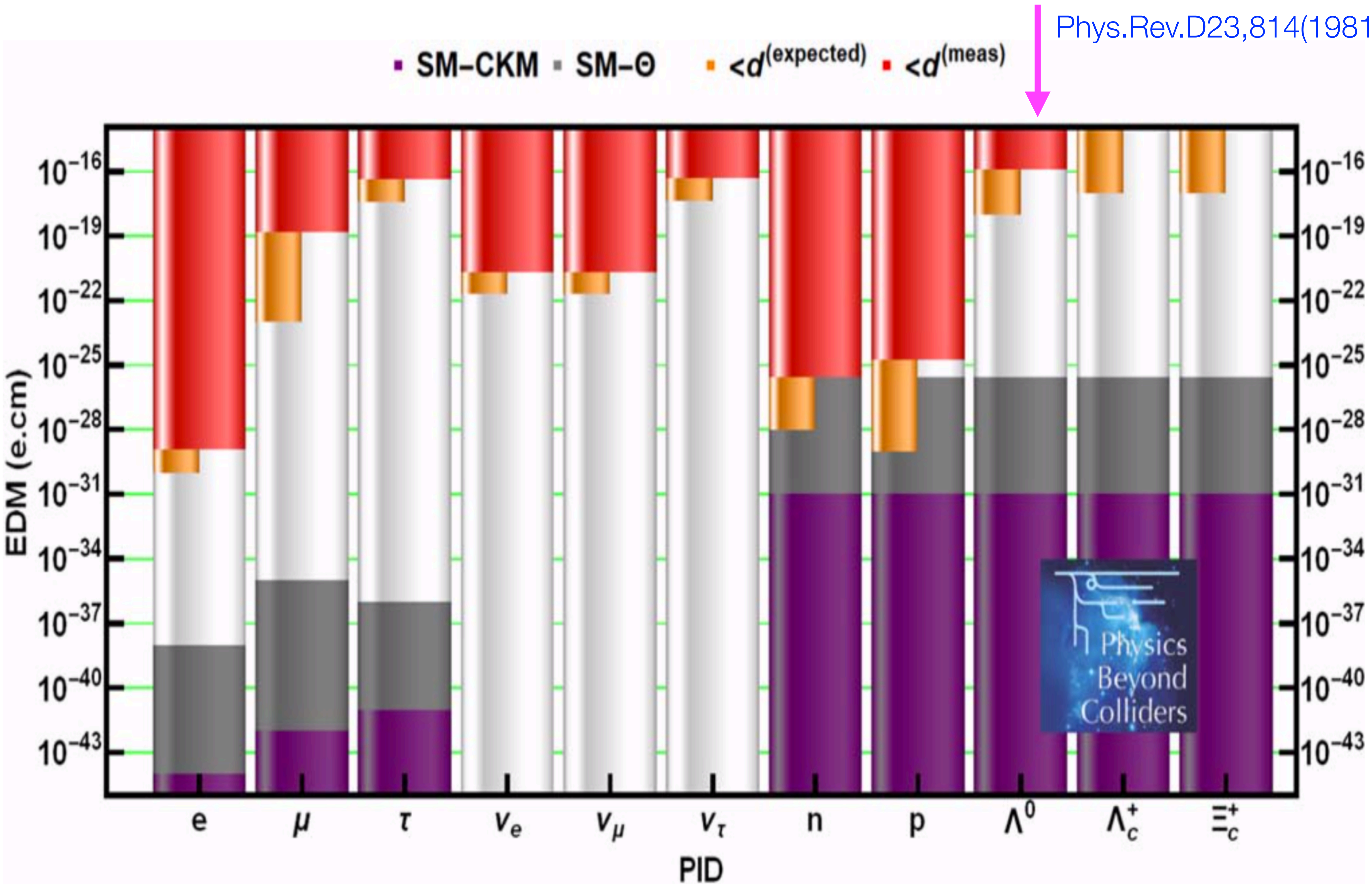
EFT

EDM measured in a low-energy system, i.e. **hyperon**

Hyperon system also required by a global analysis of EDMs

T.Chupp et al, Rev.Mod.Phys.91(2019)015001

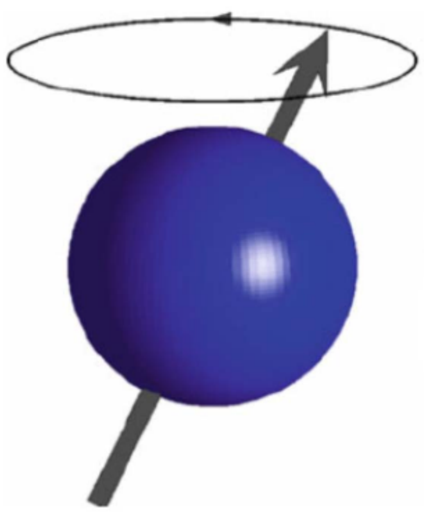
# Status of EDM measurements



# How to access EDM

- Direct approach — spin procession

$$\frac{d\mathbf{s}}{dt} = \mathbf{s} \times \boldsymbol{\Omega} \qquad \boldsymbol{\Omega} = \boldsymbol{\Omega}_{\mathrm{MDM}} + \boldsymbol{\Omega}_{\mathrm{EDM}} + \boldsymbol{\Omega}_{\mathrm{TH}}$$



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

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

Sizable polarized particle source

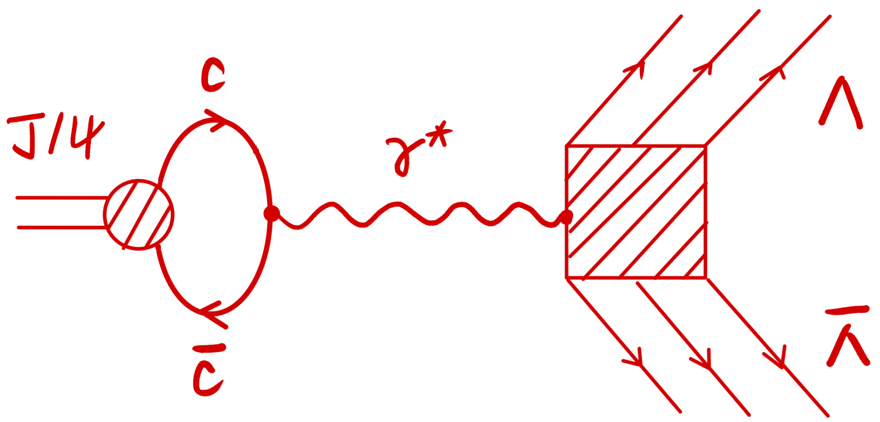
Enough lifetime to process

Significant challenge for short-lived fermions

# How to access EDM

- Indirect approach

  i.e. measure time-like dipole form factor ($q^2 \neq 0$)




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

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

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

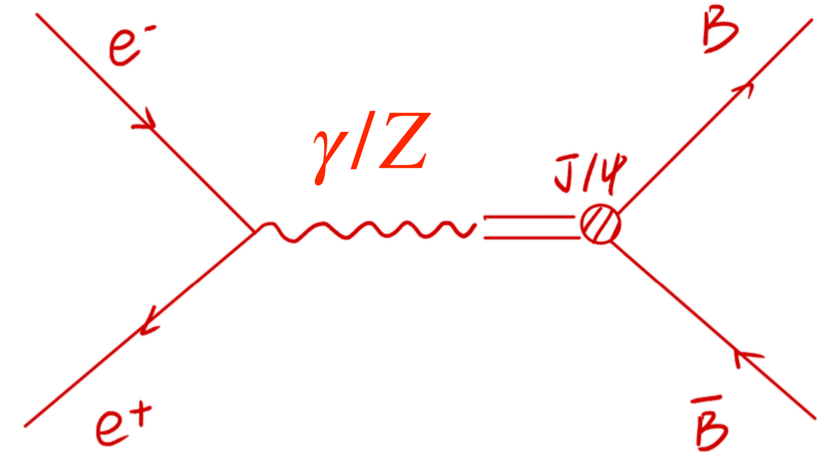
- Benefits from BESIII experiment

  $10^6$ hyperon anti-hyperon pairs reconstructed from $10^{10}$ $J/\psi$ decays

  Typically with a purity exceeding 95%

  The statistics increased by several orders of magnitude at future STCF

# $J/\psi$ production




- $J/\psi$ polarization with unpolarized beam

$P_L = (\rho_{++} - \rho_{--})/(\rho_{++} + \rho_{--})$ $\rho_{m,m'}$ spin density matrix for $J/\psi$

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

- With longitudinally polarized electron beam $P_e$ at STCF

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

dominated by $P_e$

provides a way for precise measurement of beam polarization

# Amplitude for $J/\psi$ decay to hyperon pair

- Polarization effects encoded in hyperon anti-hyperon pair ($\Lambda$,$\Sigma$,$\Xi$) spin density matrix

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

- Lorentz invariance introduces P and CP violating form factors in helicity amplitude

$$\mathcal{M}_{\lambda_1,\lambda_2} = \epsilon_\mu(\lambda_1-\lambda_2)\bar{u}(\lambda_1,p_1)(F_V\gamma^\mu + \frac{i}{2M_\Lambda}\sigma^{\mu\nu}q_\nu H_\sigma + \gamma^\mu\gamma^5 F_A + \sigma^{\mu\nu}\gamma^5 q_\nu H_T)v(\lambda_2,p_2).$$

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# Form factor $H_T$ and $F_A$

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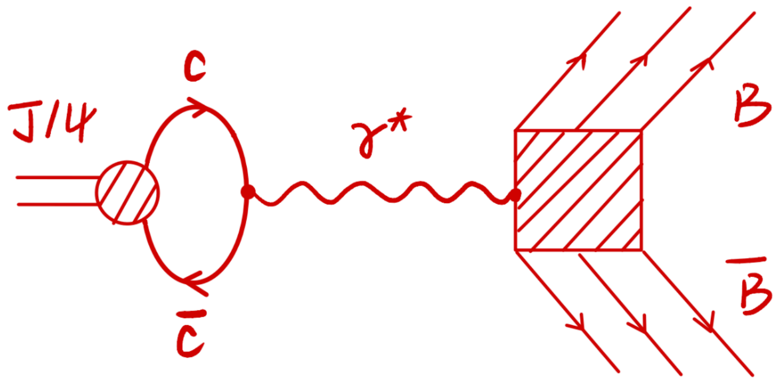
Phys.Lett.B 839(2023)137834

- Take hyperon EDM as the major source for $H_T$



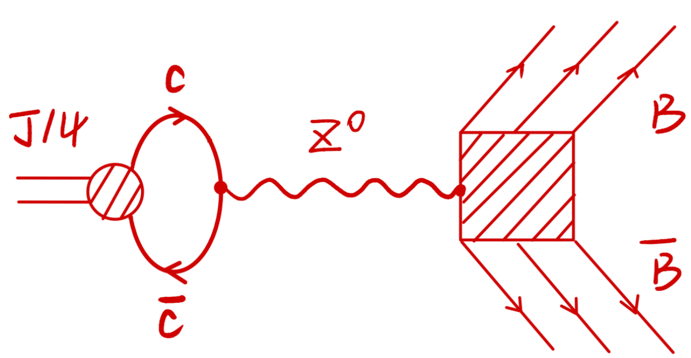

$$L_{\text{dipole}} = i\frac{d_\Lambda}{2}\bar{\Lambda}\sigma_{\mu\nu}\gamma_5\Lambda F^{\mu\nu}$$

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

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

Neglect $q$ dependence, $d_B$ for hyperon EDM

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




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

# Form factor $F_V$ and $H_\sigma$

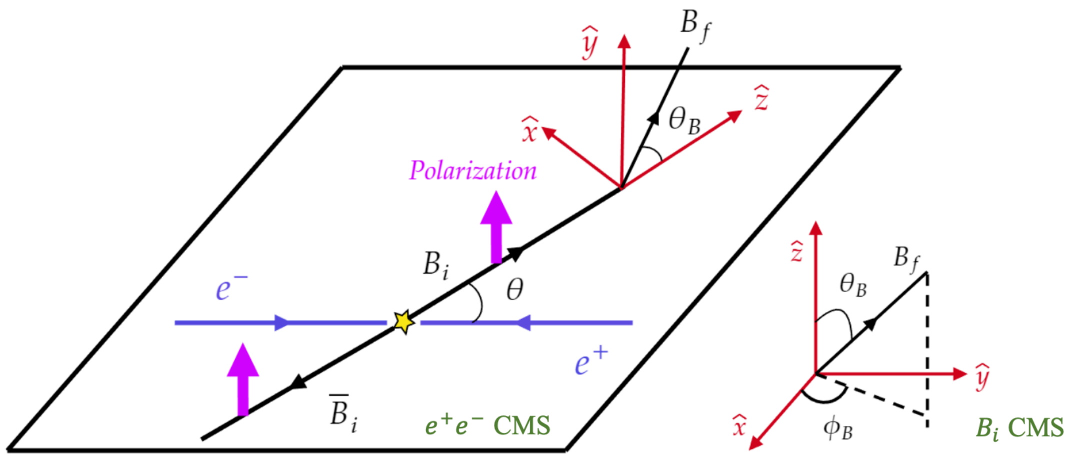
## Hyperon polarization parameters

$$F_V = G_1 - \frac{4M^2}{Q^2}(G_1 - G_2) \qquad H_\sigma = \frac{4M^2}{Q^2}(G_1 - G_2)$$

$$\alpha_{J/\psi} = \frac{s\left|G_1\right|^2 - 4m^2\left|G_2\right|^2}{s\left|G_1\right|^2 + 4m^2\left|G_2\right|^2} \qquad \frac{G_1}{G_2} = \left|\frac{G_1}{G_2}\right| e^{-i\Delta\Phi}$$

**Polarization:**

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




## $|G_1|$ can be extracted from the measurement of $\Gamma(J/\psi \to B\overline{B})$

# Angular distribution

$$\frac{d\sigma}{d\Omega} \propto \sum_{[\lambda]} R(\lambda_1, \lambda_2; \lambda_1', \lambda_2')$$

$$D^{*j=1/2}_{\lambda_1,\lambda_3}(\phi_1,\theta_1) D^{j=1/2}_{\lambda_1',\lambda_3'}(\phi_1,\theta_1) \mathcal{H}^*_{\lambda_3} \mathcal{H}_{\lambda_3'}$$

$$D^{*j=1/2}_{\lambda_2,\lambda_4}(\phi_2,\theta_2) D^{j=1/2}_{\lambda_2',\lambda_4'}(\phi_2,\theta_2) \bar{\mathcal{H}}^*_{\lambda_4} \bar{\mathcal{H}}_{\lambda_4'}$$

$$D^{*j=1/2}_{\lambda_3,\lambda_5}(\phi_3,\theta_3) D^{j=1/2}_{\lambda_3',\lambda_5}(\phi_3,\theta_3) \mathcal{F}^*_{\lambda_5} \mathcal{F}_{\lambda_5}$$

$$D^{*j=1/2}_{\lambda_4,\lambda_6}(\phi_4,\theta_4) D^{j=1/2}_{\lambda_4',\lambda_6}(\phi_4,\theta_4) \bar{\mathcal{F}}^*_{\lambda_6} \bar{\mathcal{F}}_{\lambda_6}$$

$\mathcal{H}$ and $\mathcal{F}$ parameterize dynamics of weak decay i.e. $\Xi \to \Lambda\pi$ and $\Lambda \to p\pi$

Type I decay obtained by retaining only $\theta_{1,2}$ and $\phi_{1,2}$

**Type I**

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

$e^+e^- \to J/\psi \to \Sigma^+\overline{\Sigma}^-$  $\Sigma^+ \to p\pi^0$

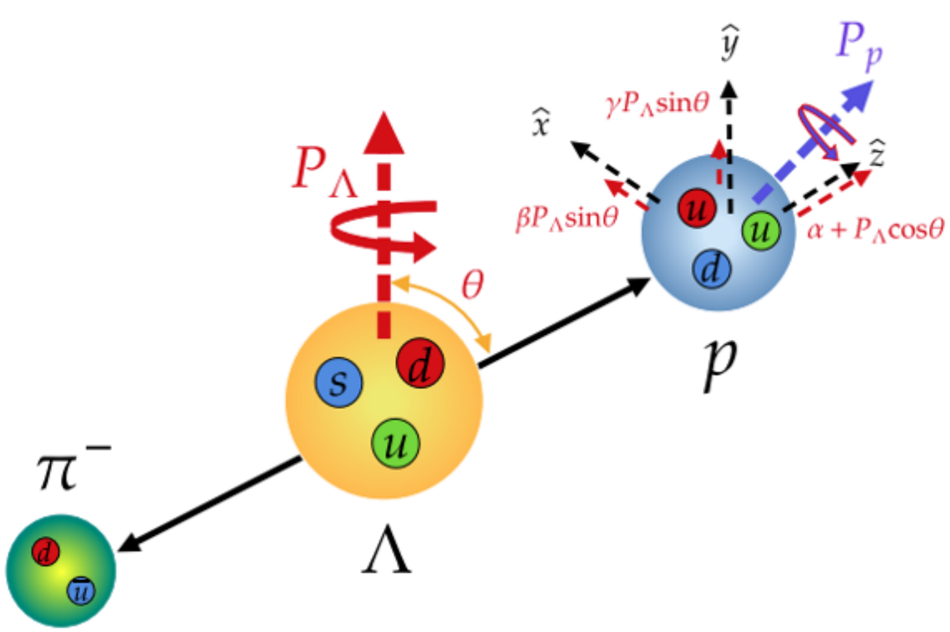
**Type II**

$e^+e^- \to J/\psi \to \Xi^-\overline{\Xi}^+$  $\Xi^- \to \Lambda\pi^-$

$e^+e^- \to J/\psi \to \Xi^0\overline{\Xi}^0$  $\Xi^0 \to \Lambda\pi^0$

# CPV in hyperon decay

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




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

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

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

$$\beta_Y = \sqrt{1 - \alpha_Y^2}\,\sin\phi_Y$$

$$\gamma_Y = \sqrt{1 - \alpha_Y^2}\,\cos\phi_Y$$

CPV observables

$$A_{CP}^Y = (\alpha_Y + \bar{\alpha}_Y)/(\alpha_Y - \bar{\alpha}_Y)$$

$$\Delta\phi_{CP}^Y = (\phi_Y + \bar{\phi}_Y)/2$$

# Sensitivity studies

- Sensitivity assessed from 500 psudoexperiments generated and fitted by using a probability density function based on the full angular distribution

- Expected yields, Form Factors and decay parameters are fixed to known values for generation: $G_1$, $\alpha_{J/\psi}$, $\Delta\Phi$, $F_A$, $H_T$, $\alpha_B$, $\alpha_{\overline{B}}$, $\phi_B$ and $\phi_{\overline{B}}$

- $P_L \sim 10^{-4}$ (80%) for unpolarized (longitudinally polarized) electron beam

| Decay Channel | $J/\psi \to \Lambda\bar{\Lambda}$ | $J/\psi \to \Sigma^+\bar{\Sigma}^-$ | $J/\psi \to \Xi^-\bar{\Xi}^+$ | $J/\psi \to \Xi^0\bar{\Xi}^0$ |
|---|---|---|---|---|
| $B_{tag}/(\times 10^{-4})$ [29] | 7.77 | 2.78 | 3.98 | 4.65 |
| $\epsilon_{tag}/\%$ [22, 28, 30, 31] | 40 | 25 | 15 | 7 |
| $N^{evt}_{tag}/(\times 10^5)$(BESIII) | 31.3 | 7.0 | 6.0 | 3.3 |
| $N^{evt}_{tag}/(\times 10^8)$(STCF) [17] | 10.6 | 2.4 | 2.0 | 1.1 |

# Sensitivity for EDM

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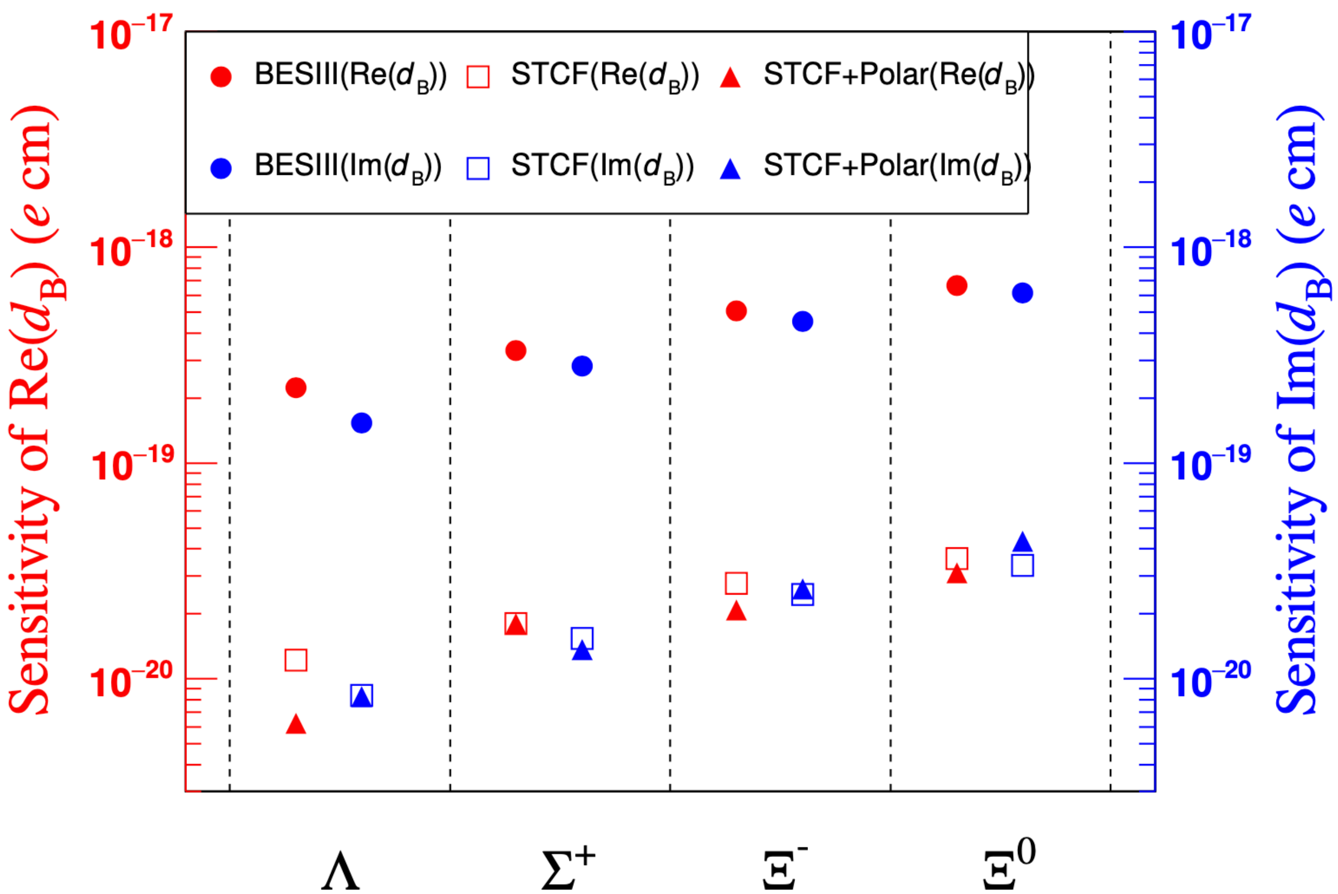
reminder: $H_T = \frac{2e}{3M_{J/\psi}^2} g_V d_B$




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

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

BESIII: milestone for hyperon EDM measurement

$\Lambda$ $10^{-19}$e cm ( FermiLab $10^{-16}$ e cm)

first achievement for $\Sigma^+$,$\Xi^-$ and $\Xi^0$ at level of $10^{-19}$e cm

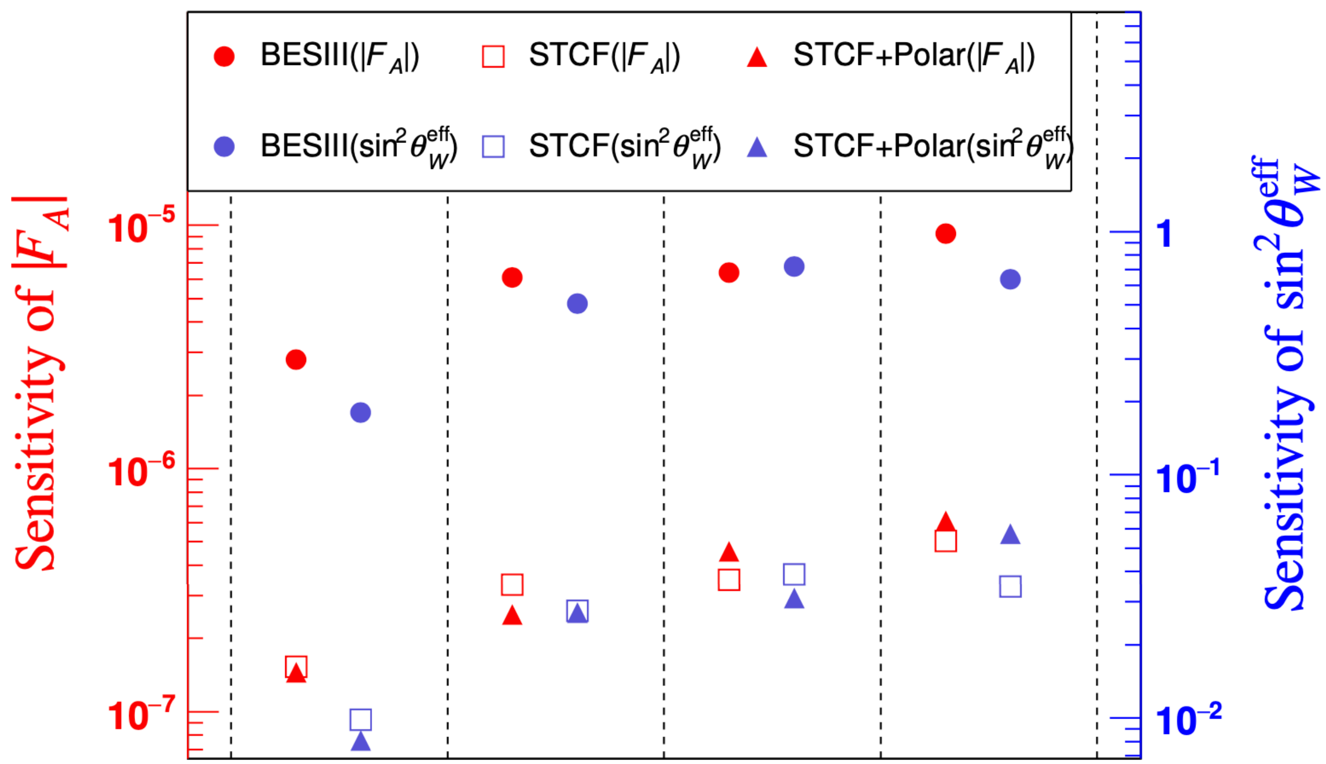
a litmus test for new physics

STCF: improved by 2 order of magnitude

# Sensitivity for $F_A$ and $\sin^2\theta_W^{\text{eff}}$

Phys.Rev.D108,L091301(2023)

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




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

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

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

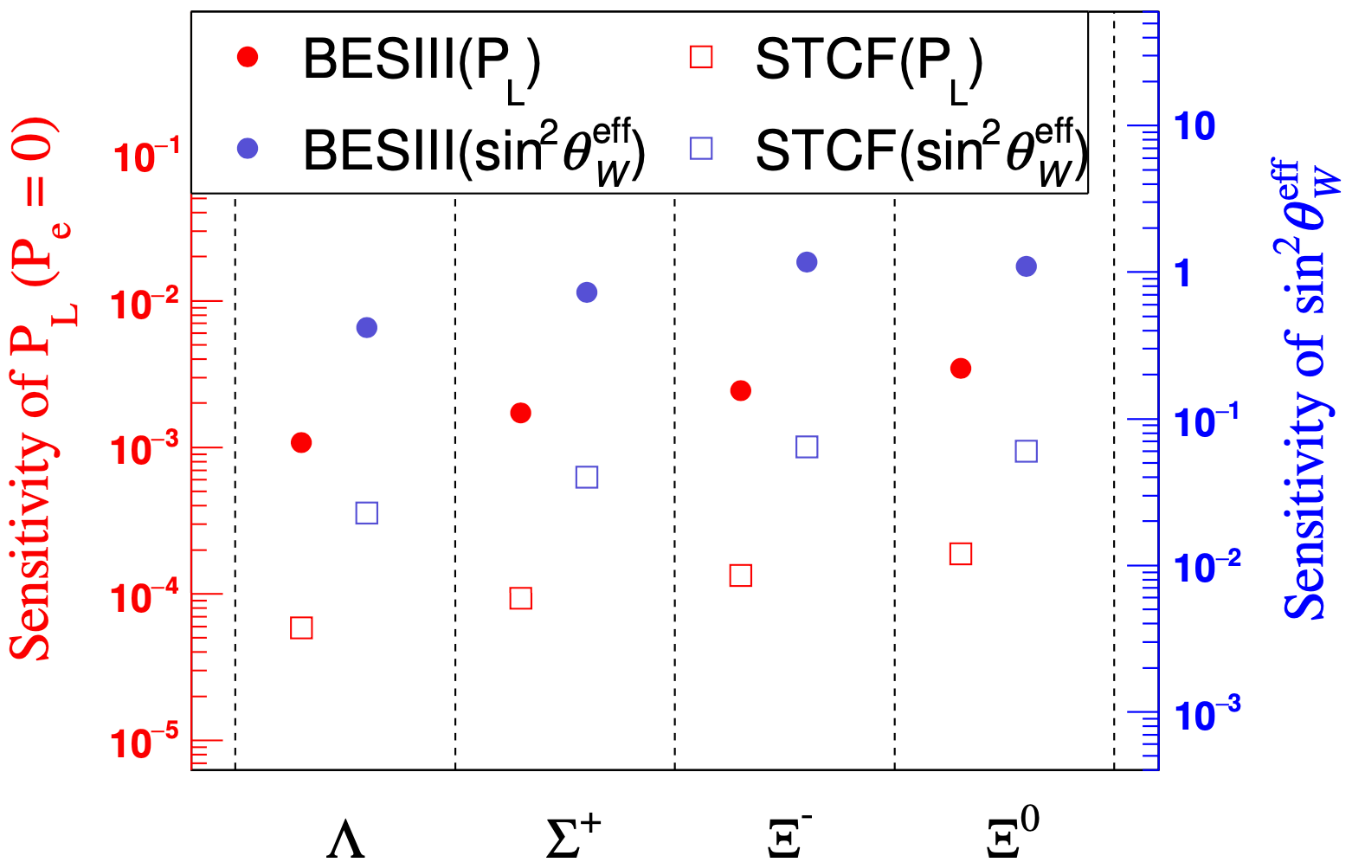
STCF:

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

# Sensitivity for $P_L$ and $\sin^2\theta_W^{\text{eff}}$

Phys.Rev.D108,L091301(2023)

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




(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 $2 \times 10^{-2}$

# Improved sensitivity for $\sin^2\theta_W^{\text{eff}}$ Phys.Rev.D108,L091301(2023)

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

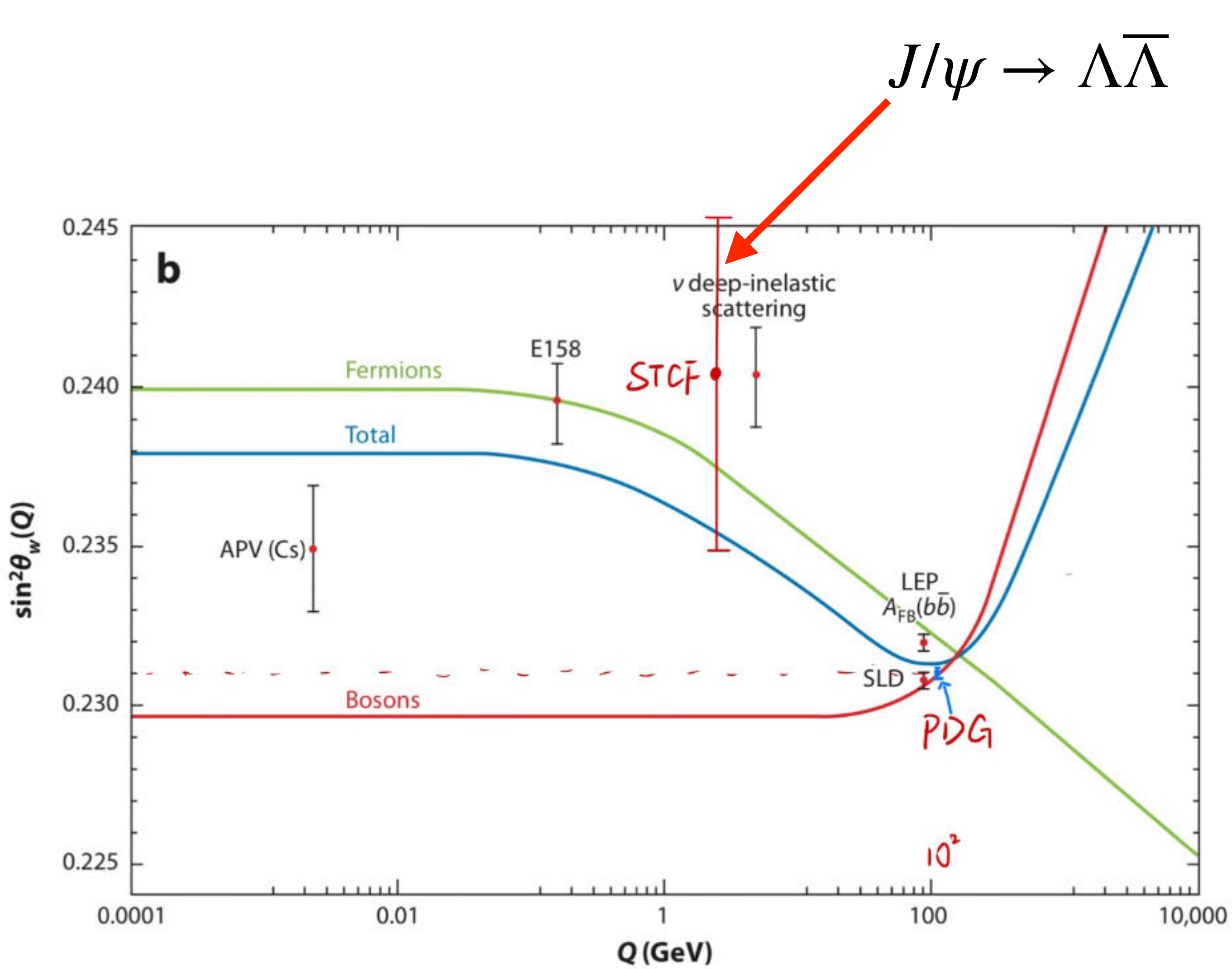



**Figure 1**

(*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 $5 \times 10^{-3}$

# Sensitivity for CPV in hyperon decays

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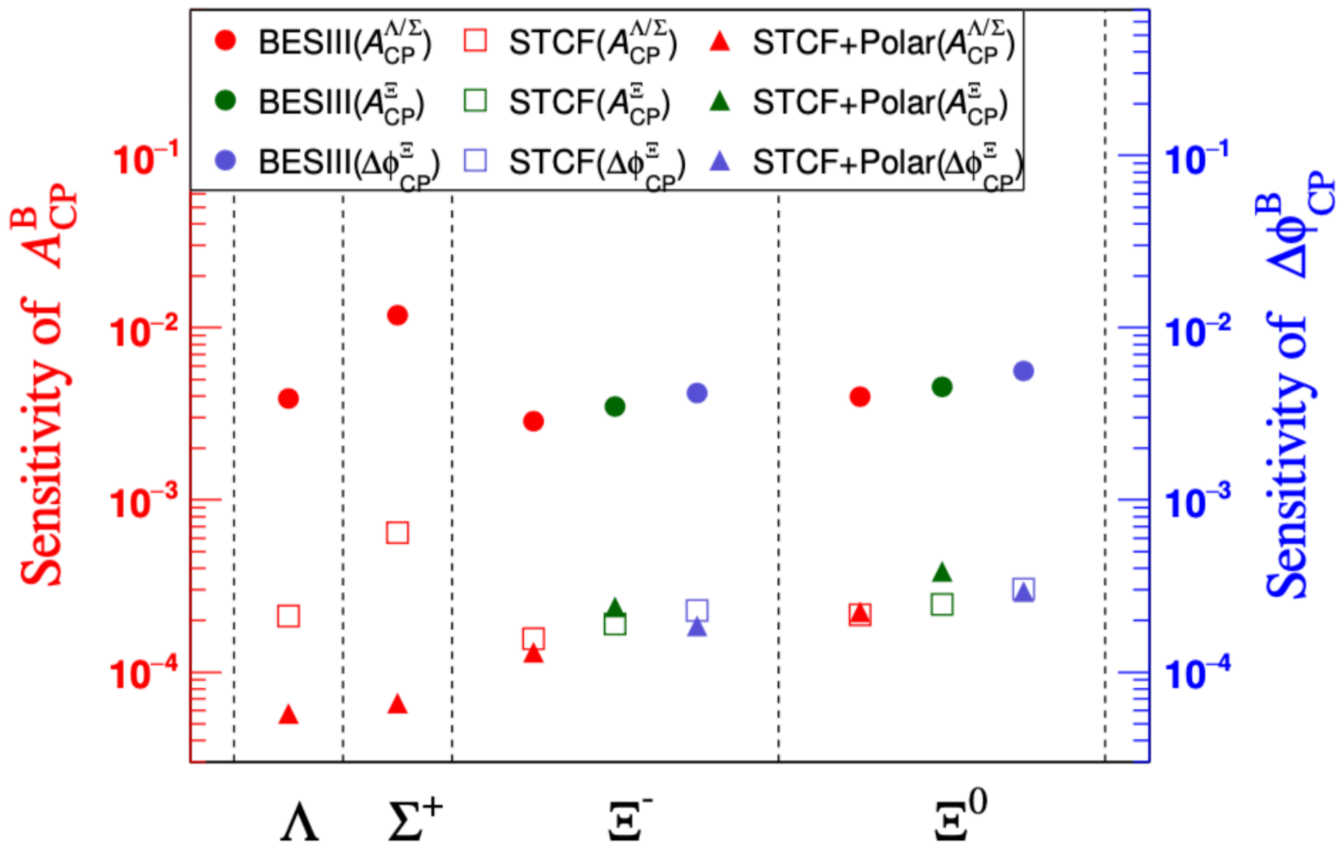
reminder:
$$A_{CP}^{B} = (\alpha_B + \bar{\alpha}_B)/(\alpha_B - \bar{\alpha}_B)$$
$$\Delta\phi_{CP}^{B} = (\phi_B + \bar{\phi}_B)/2$$




(b)Sensitivity of $A_{CP}^{B}$ and $\Delta\phi_{CP}^{B}$

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

STCF:

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

# Summary

- Develop a full angular analysis to probe hyperon EDMs systematically

  $10^{-19}$ *e* cm @ BESIII

  $10^{-21} \sim 10^{-20}$ *e* cm @ STCF

- Test CPV in hyperon decay at the level of $10^{-5} \sim 10^{-4}$ at STCF

- Weak mixing angle $\sin^2\theta_W^{\text{eff}}$ at $q = M_{J/\psi}$ can be determined at STCF

*Thank you!*