Hyperon Electric Dipole Moment at BESIII and STCF

based on recent work arXiv:2307.04364

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Electric Dipole Moments

- Quantum system: ensemble of particles, Λ, Σ, Ξ…

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

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

Magneton: μ_{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, $\sim 10^8$

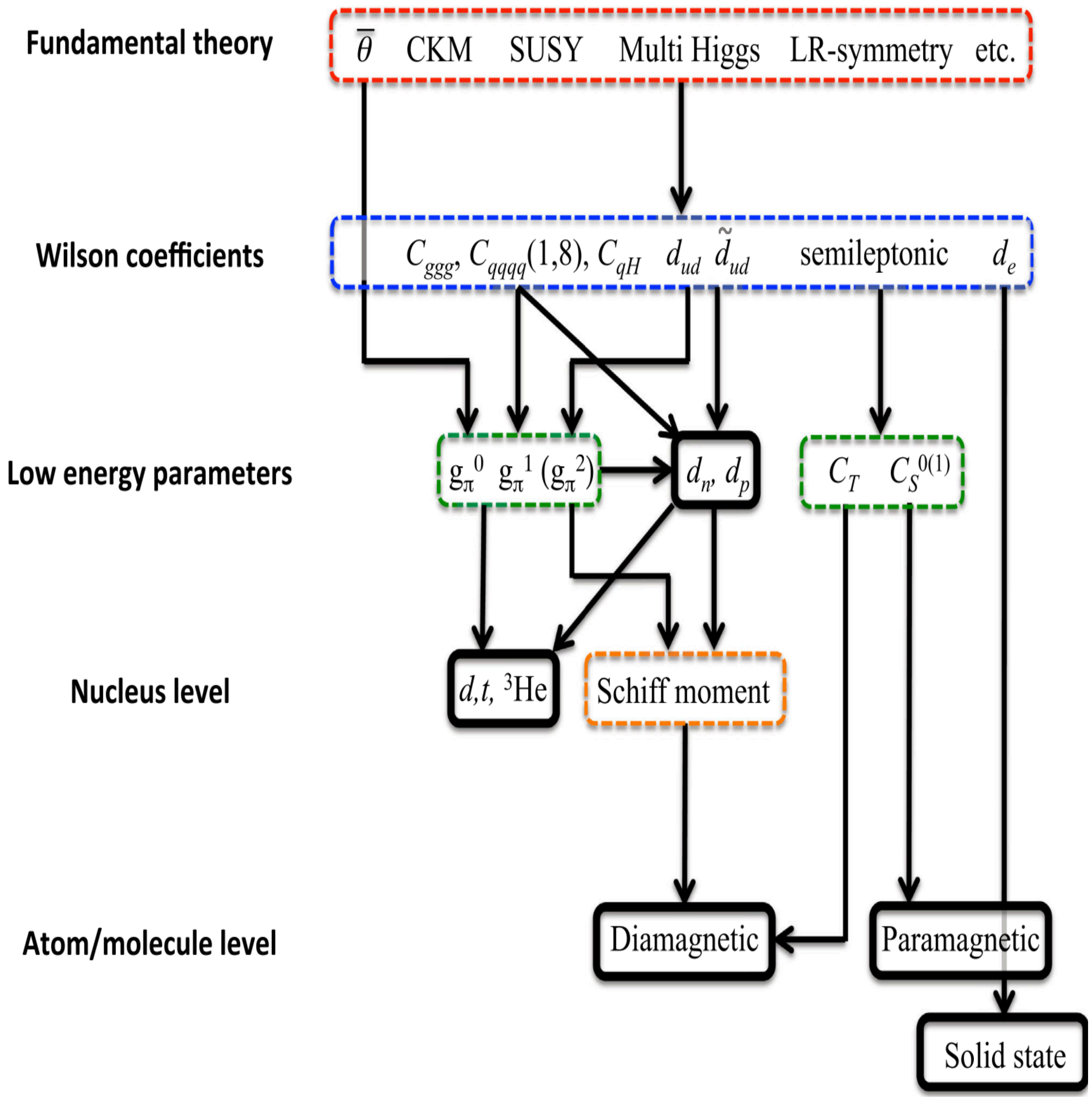
- EDM can access to new sources from flavour-diagonal CPV

- SM prediction extremely small, but can be largely enhance by new physics

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

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

Fundamental parameters and EDM



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

EFT

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

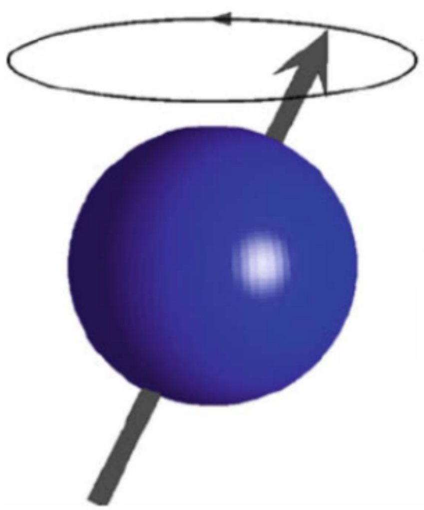
Hyperon system also required by a global analysis of EDMs

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

How to access EDM

- Direct approach — spin procession

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

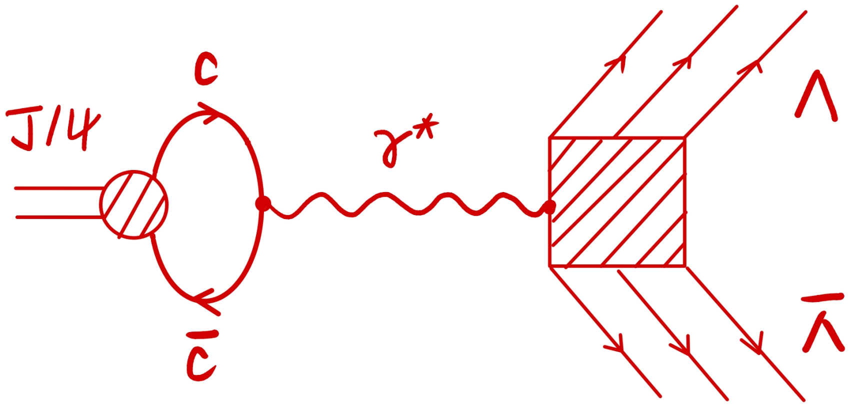


$$\boldsymbol{\Omega}_{\rm MDM} = \frac{g\mu_B}{\hbar}\left(\mathbf{B} - \frac{\gamma}{\gamma+1}(\boldsymbol{\beta}\cdot\mathbf{B})\boldsymbol{\beta} - \boldsymbol{\beta}\times\mathbf{E}\right)$$

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

Significant challenge for short-lived fermions

- Indirect approach

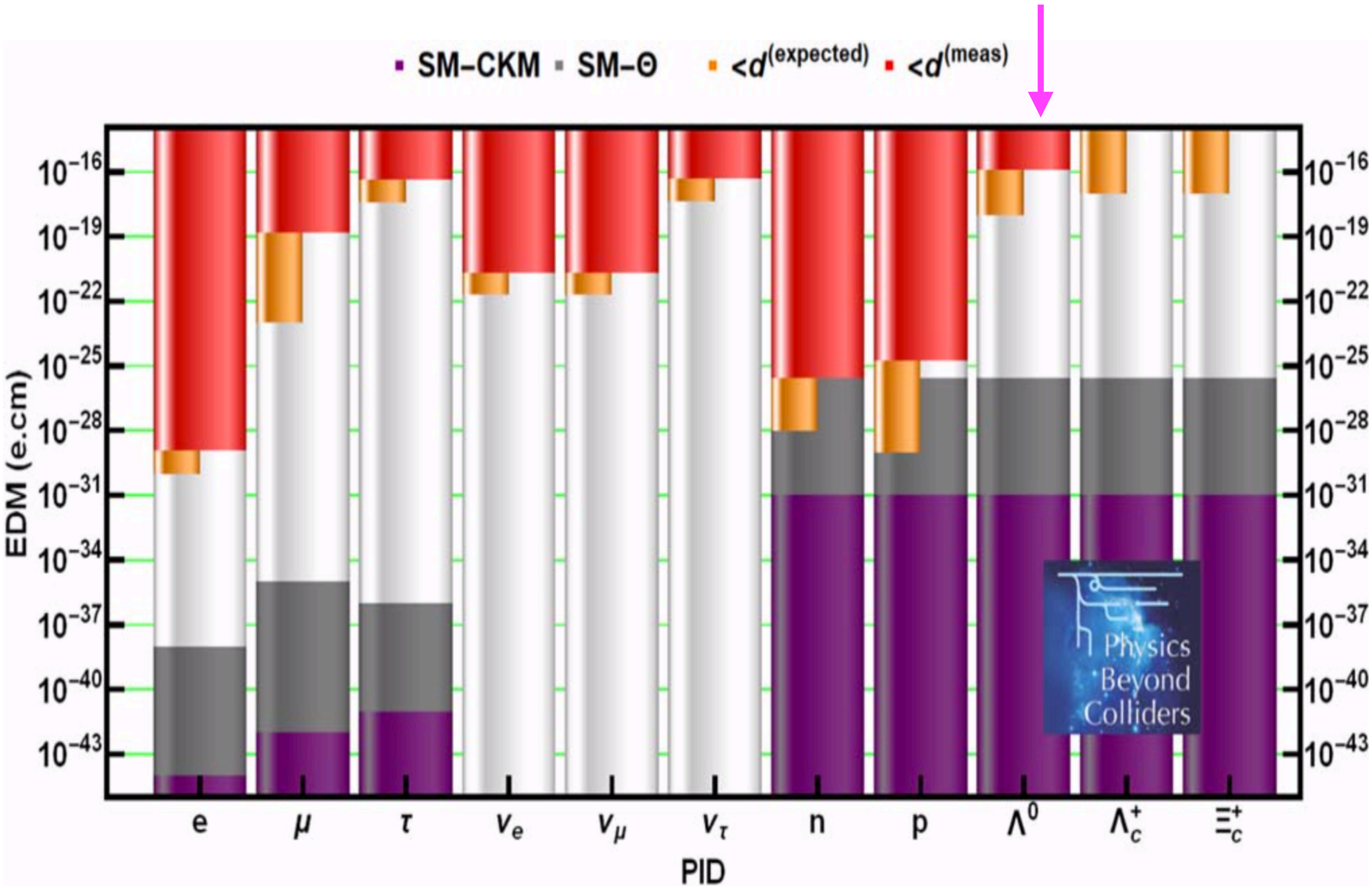


i.e. measure time-like electric dipole form factor ($q^2 \neq 0$)

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

Status of EDM measurements



Different proposals for hyperon EDM

- Utilizing spin precession induced:

  by dipole magnetic at LHCb for Λ Eur. Phys. J. C 77, 181 (2017)

  by bent crystal at fixed-target experiment for $\overline{\Xi}^+$ and $\overline{\Omega}^+$
  Eur. Phys. J C 77, 828 (2017)

- Triple-product moment for Λ, Σ^+, Ξ^- and Ξ^0

  Phys. Rev. D 47, R1744 (1993)
  Phys. Rev. D 49, 4548 (1993)
  Phys. Lett. B 681, 237 (2009)
  Chin. Phys. Lett. 27, 051101 (2010)
  Phys. Lett. B 839, 137834 (2023)

Indirect measurement using full angular analysis

- Based on our recent work on hyperon EDM measurement J. Fu et al, arXiv:2307.04364
- Inspired from a series work by Prof. Xiaogang He and Prof. Jianping Ma

X.G.He, J.P. Ma, Bruce McKellar, Phys.Rev.D47(1993)1744

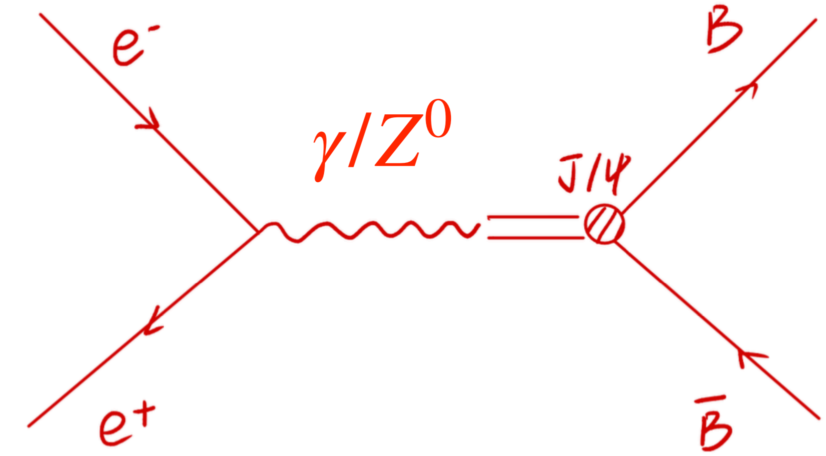
X.G.He, J.P. Ma, Phys.Lett.B 839(2023)137834

Type I	$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$	$\Lambda \to p\pi^-$
	$e^+e^- \to J/\psi \to \Sigma^+\bar{\Sigma}^-$	$\Sigma^+ \to p\pi^0$

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

Can be applied to $\psi(2S)$ decays

Polarization in J/ψ production



- J/ψ polarization with unpolarized beam (**BESIII**)

$$P_L = (\rho_{++} - \rho_{--})/(\rho_{++} + \rho_{--})$$

$\rho_{m,m'}$ spin density matrix for J/ψ

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

10^{-4} expected in SM

- With longitudinally polarized electron beam P_e (**STCF**)

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

dominated by P_e

provides a way for precise measurement of beam polarization

Spin density matrix for hyperon-antihyperon pair

- Polarization effects encoded in hyperon pair 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

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

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

Form factors G_1 and G_2

- Psionic form factors

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

- Hyperon polarization parameters

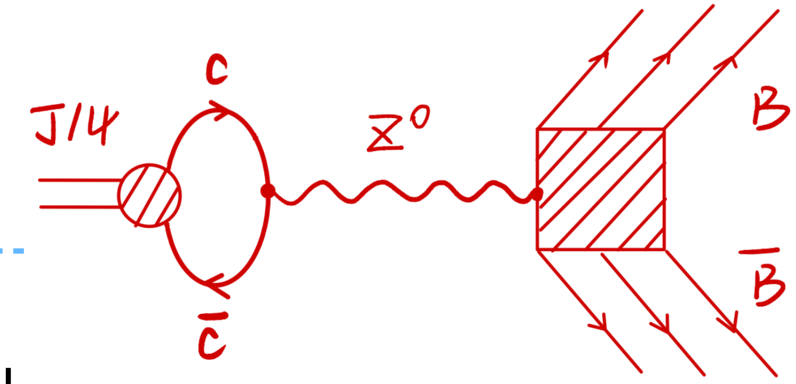
$$\alpha_{J/\psi} = \frac{s\left|G_1\right|^2 - 4m^2\left|G_2\right|^2}{s\left|G_1\right|^2 + 4m^2\left|G_2\right|^2} \qquad \frac{G_1}{G_2} = \left|\frac{G_1}{G_2}\right| e^{-i\Delta\Phi}$$

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

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

Form factor F_A



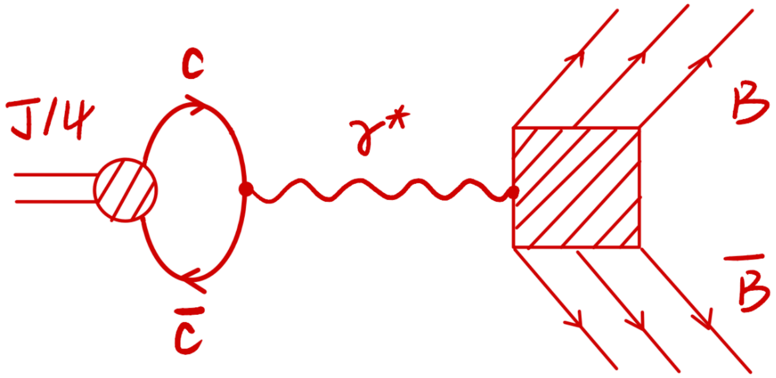
- Primarily from Z-boson exchange between $c\bar{c}$ and light quark pairs

- 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

Electric dipole 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

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 $\Lambda \to p\pi$

and construct Lee-Yang parameters for CPV in hyperon decays

$$A^Y_{CP} = (\alpha_Y + \bar{\alpha}_Y)/(\alpha_Y - \bar{\alpha}_Y)$$
$$\Delta\phi^Y_{CP} = (\phi_Y + \bar{\phi}_Y)/2$$

Sensitivity studies

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

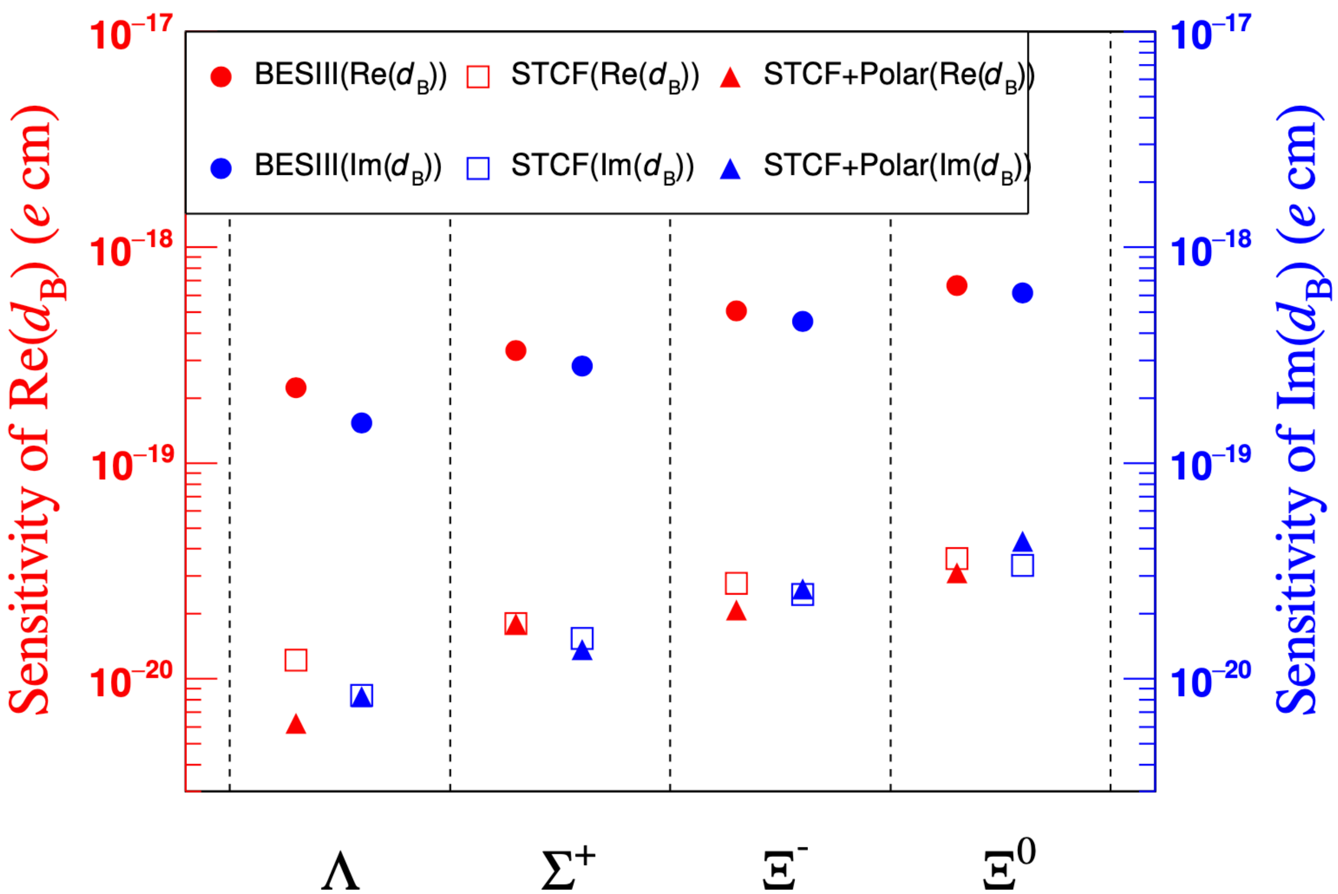
- Expected yields, Form Factors and decay parameters are fixed to known values for generation: G_1, $\alpha_{J/\psi}$, $\Delta\Phi$, F_A, H_T, α_B, $\alpha_{\overline{B}}$, ϕ_B and $\phi_{\overline{B}}$

- $P_L \sim 10^{-4}$ (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
$N_{tag}^{evt}/(\times 10^5)$(BESIII)	31.3	7.0	6.0	3.3
$N_{tag}^{evt}/(\times 10^8)$(STCF) [17]	10.6	2.4	2.0	1.1

Sensitivity for EDM

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 for CPV in hyperon decays

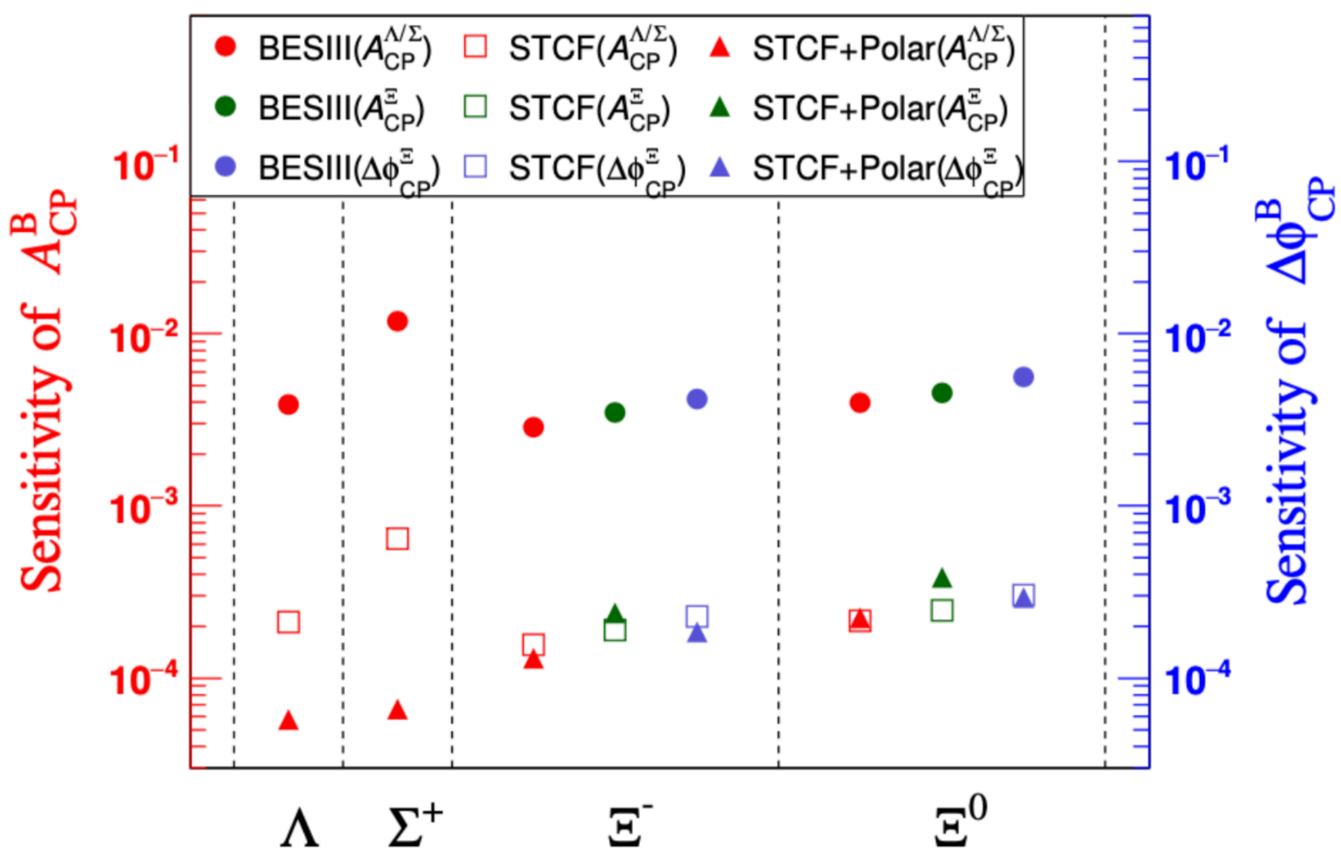
N.G.Deshpande et al, PLB326(1994)307

J.Tandean et al, PRD67(2003)056001

J.F.Donoghue et al, PRD34(1986)833

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

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



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

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

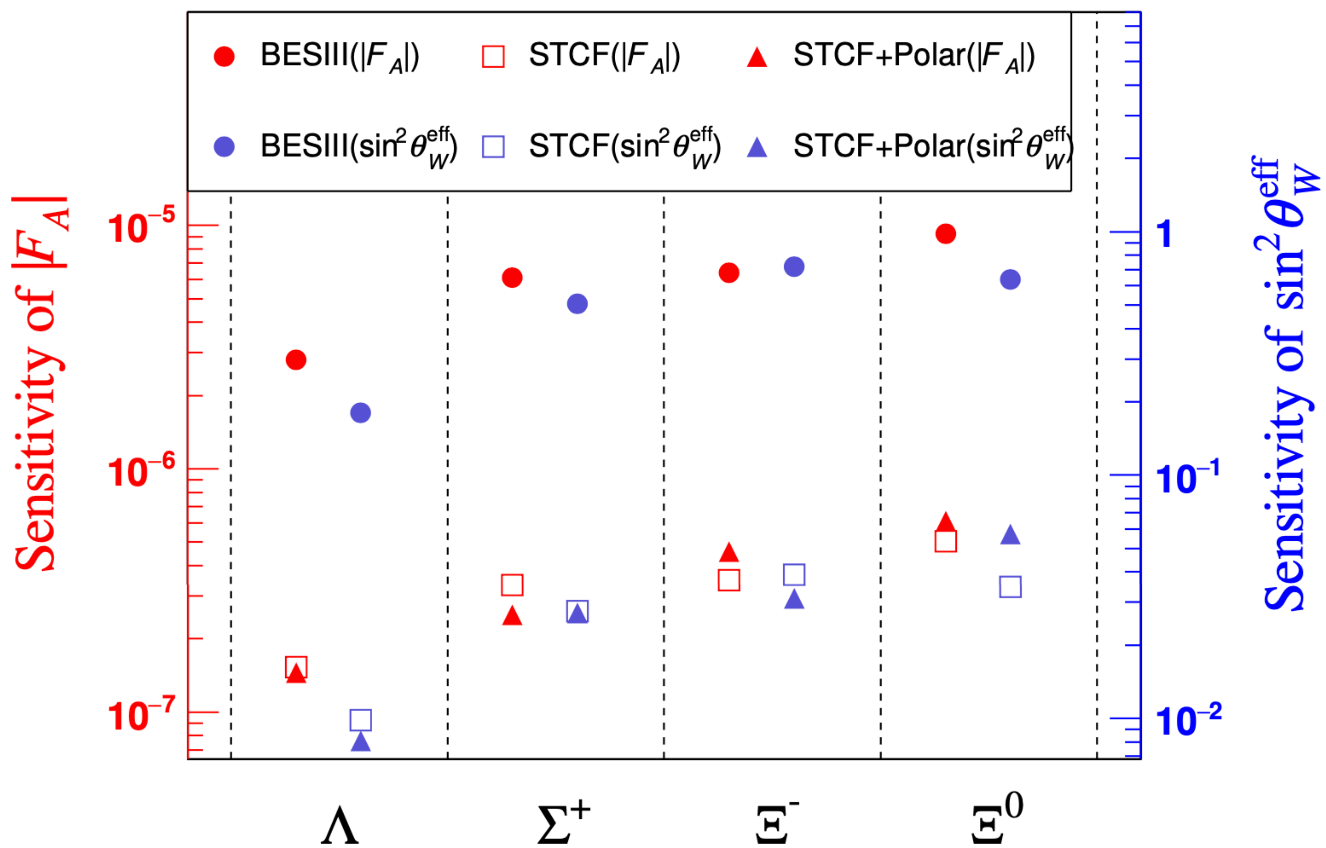
BESIII: 10^{-3}

STCF:

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

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

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



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

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

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

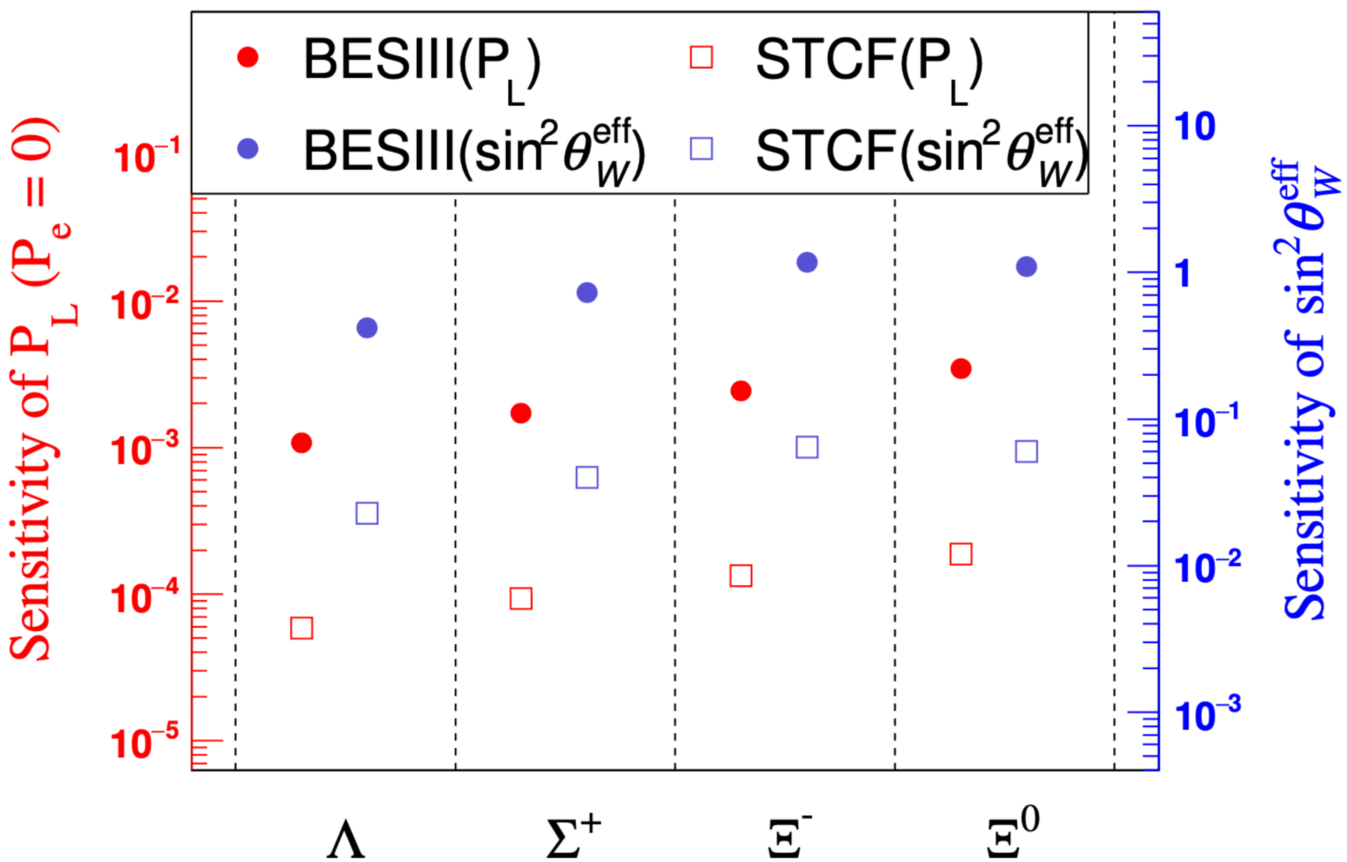
STCF:

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

BESIII: ~ 0.1

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

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



(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}

BESIII: ~ 0.3

Improved sensitivity for $\sin^2\theta_W^{\text{eff}}$

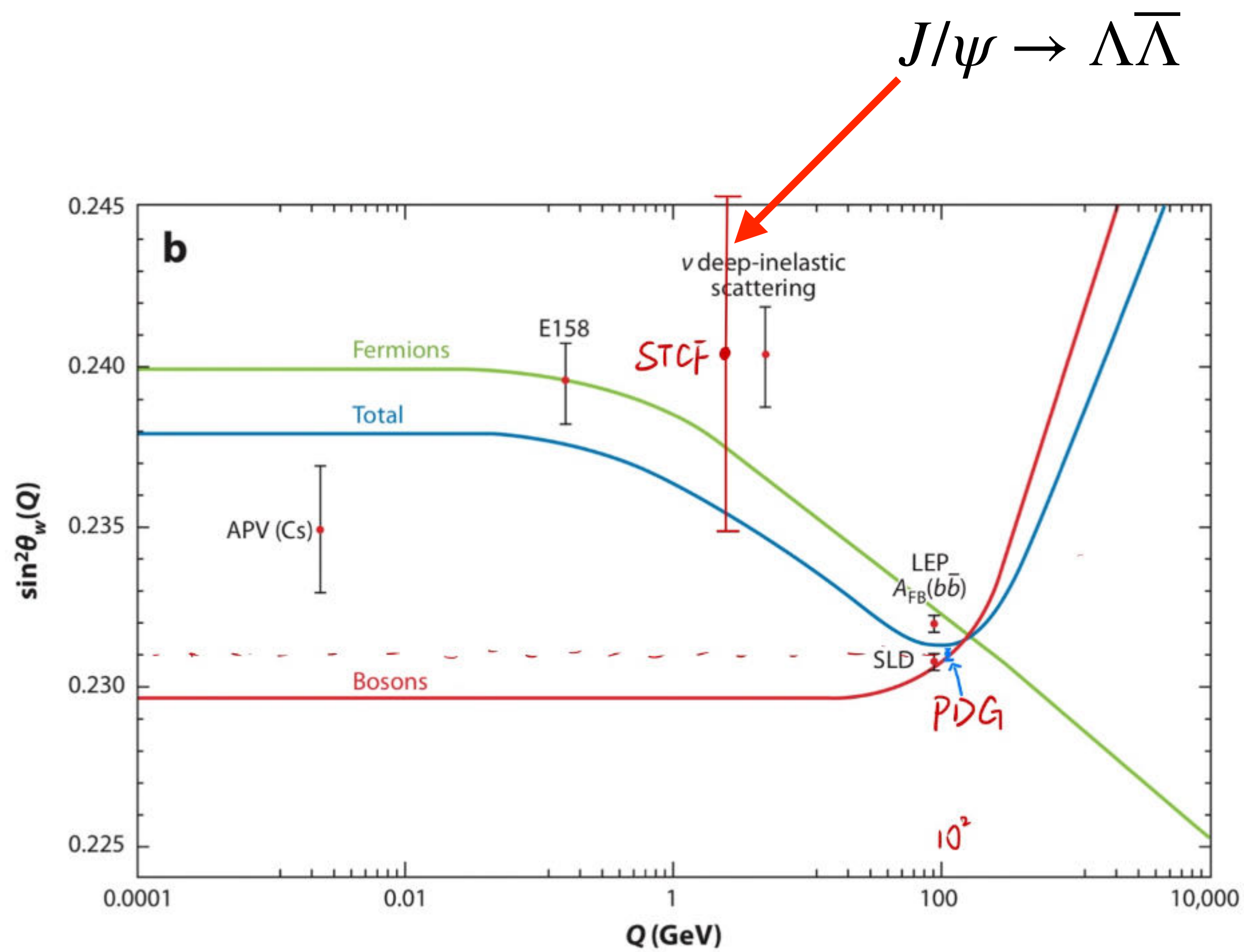


Figure 1

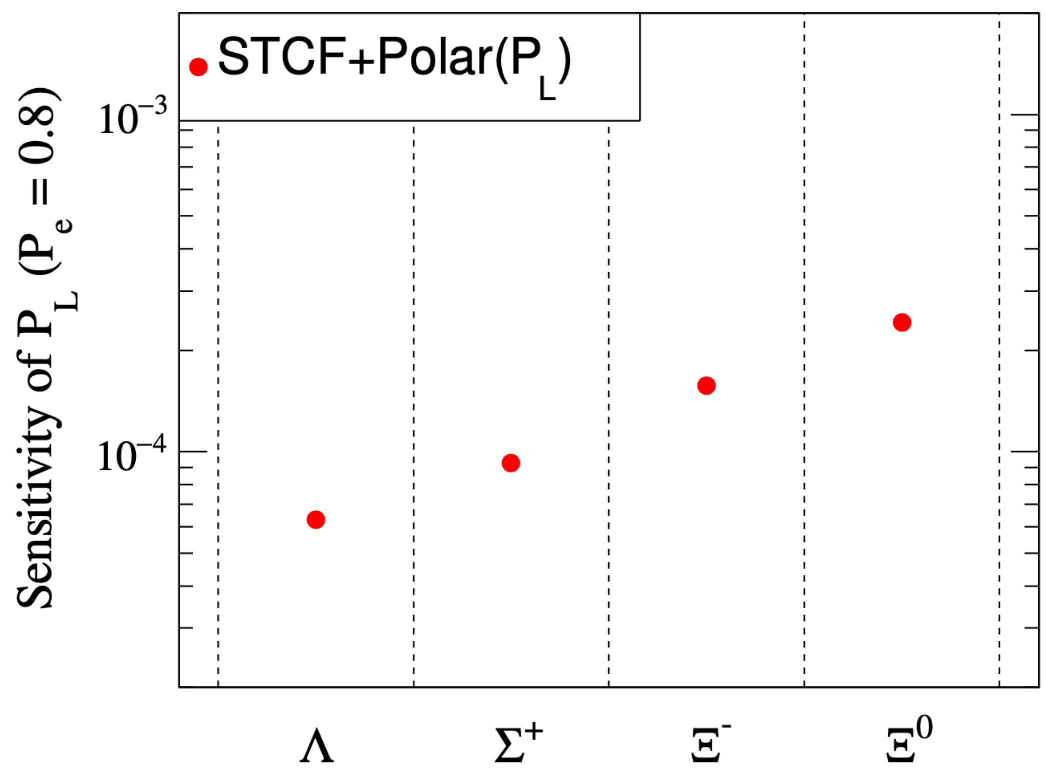
(*a*) $\sin^2\theta_W(\mu)_{\overline{MS}}$ (29) with an updated atomic parity violation (APV) result. (*b*) $\sin^2\theta_W(Q^2)$, a one-loop calculation dominated by $\gamma - Z^0$ mixing (52). The red and green curves represent the boson and fermion contributions, respectively.

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 for beam polarization



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

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

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

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

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

analysis Bhabha scattering events

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

Summary

- Proposed indirect measurement of hyperon EDM at BESIII/STCF using full angular analysis J. Fu et al, arXiv:2307.04364

  statistical sensitivity estimated:

  BESIII: Λ EDM 10^{-19} *e* cm

  first achievement Σ^+, Ξ^- and Ξ^0 EDM ~ 10^{-19} *e* cm

  STFC: further improved by 2 order of magnitude

- CPV in hyperon decays and weak mixing angle can be determined, simultaneously, which are also indirect approach to new physics

Thank you!