Perturbative QCD prediction of the Λ EDM

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Outline

- Motivation
- Perturbative QCD prediction for Λ EDM
- Numerical estimation
- Summary

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■ The enigma of CP-violation

- CP-violation (CPV) in the standard model (SM)

  ✓ Incorporated in the CKM phase, which successfully explains CPV in hadron systems.

  ✓ However, insufficient to account for the observed baryon-antibaryon asymmetry of the Universe.

- Electric dipole moment (EDM) as a signature of CPV beyond the SM

  ✓ EDMs predicted by the SM are extremely small, making any observation a strong indicator of CPV interactions beyond the SM.

  ✓ EDMs of e^-, n have been extensively studied, while hyperon EDMs are scarce.

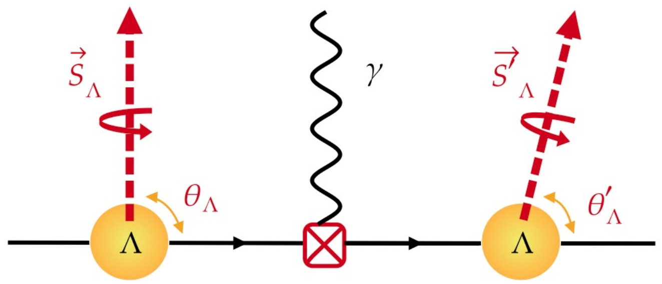
Λ hyperon EMD limit: $|d_\Lambda| < 1.5\times10^{-16} e$ cm.

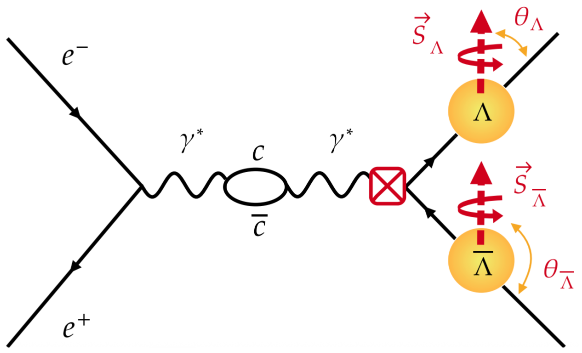
Obtained at Fermilab more than 40 years ago. *L. Pondrom et al., Phys. Rev. D 23, 814 (1981)*

Motivation

■ New Λ EDM limit from BESIII

BESIII's novel approach: entangled $\Lambda\bar{\Lambda}$ pair production through $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$





M. Ablikim et al., (BESIII Collaboration), arXiv:2506.19180

New bounds on Λ EDM obtained by BESIII:

$$-8.6\times10^{-19} < \mathrm{Re}(d_\Lambda) < 3.3\times10^{-19} e\ \mathrm{cm},$$
$$-2.5\times10^{-19} < \mathrm{Im}(d_\Lambda) < 7.2\times10^{-19} e\ \mathrm{cm}.$$

~ 3 orders of magnitude improvement

$$|d_\Lambda| < 6.5\times10^{-19}\ e\ \mathrm{cm} \quad (95\%\ CL)$$

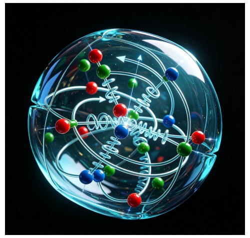
World's most precise measurement of Λ EDM! 🎉 🎉 🎉

Motivation

- ✓ EDM measurements for other hyperons (Σ^+, Σ^0, Ξ^-, Ξ^0, $\cdots$) are underway and are expected to achieve similar precision.
- ✓ With more data at BESIII and the planned Super Tau-Charm Factory and the electron-ion colliders, further significant improvements in hyperon EDM measurements are anticipated.

Key theoretical question:

How do CP-violating quark-gluon interactions generate a non-zero hyperon EDM?



Understanding this connection is crucial for constructing new physics models that can be tested experimentally.

Our approach: Perturbative QCD analysis

To establish a QCD factorization framework linking the hyperon EDM form factor to fundamental quark CP-Violating dipole interactions and hyperon structure.

$$d_\Lambda \sim H(d_{q_i}, \tilde{d}_{q_i}, x_i \cdots) \otimes F_\Lambda(x_i, \cdots)$$

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Perturbative QCD prediction for Λ EDM

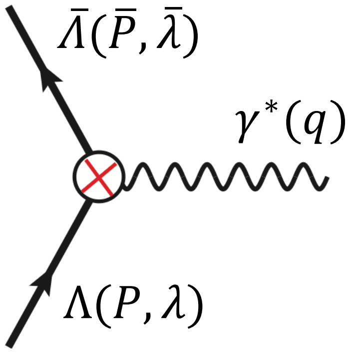
■ The definition and EDM form factor

- CP-violating effective Lagrangian:

$$\mathcal{L}_{CP} = \sum_q -\frac{i}{2} d_q \bar{q}\gamma_5\sigma_{\mu\nu} q F^{\mu\nu} - \frac{i}{2}\tilde{d}_q \bar{q}\gamma_5\sigma_{\mu\nu} q G^{\mu\nu}$$

Quark EDM (d_q) Quark CEDM (chromoelectric dipole moment) ($\tilde{d}_q$)

- The Λ EDM:



$$\langle 0|J^\mu|\Lambda(P,\lambda)\bar{\Lambda}(\bar{P},\bar{\lambda})\rangle = d_\Lambda(Q)\bar{V}(\bar{P},\bar{\lambda})\gamma_5\sigma^{\mu\nu}q_\nu U(P,\lambda) + \cdots$$

Λ EDM form factor Note: the static EDM is $d_\Lambda(0)$

The BESIII measurement corresponds to $d_\Lambda(Q = M_{J/\psi})$

Unlike static EDM at $Q = 0$, the large scale here calls for a factorization approach rather than low-energy effective theories or quark model.

Perturbative QCD prediction for Λ EDM

■ The framework

Collinear factorization for hard exclusive process

e.g., **hadronic form factors** ~ Hard coefficients ⨂ light-cone distribution amplitudes (LCDAs)

What's special for EDM calculation?

$$\langle 0|J^\mu|\Lambda(P,\lambda)\bar{\Lambda}(\bar{P},\bar{\lambda})\rangle = d_\Lambda(Q)\bar{V}(\bar{P},\bar{\lambda})\gamma_5\sigma^{\mu\nu}q_\nu U(P,\lambda) + \cdots$$

Helicity-flip

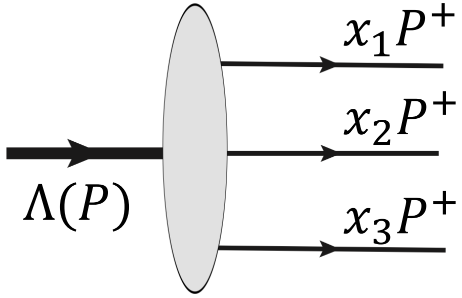
QCD conserves quark helicity, helicity-flip matrix element calls for higher twist effects.

$$\mathcal{L}_{CP} = \sum_q -\frac{i}{2}d_q\bar{q}\gamma_5\sigma_{\mu\nu}qF^{\mu\nu} - \frac{i}{2}\tilde{d}_q\bar{q}\gamma_5\sigma_{\mu\nu}qG^{\mu\nu}$$

The dipole interactions in $\mathcal{L}_{CP}$ already flip quark helicities, d_Λ has leading twist contribution.

Perturbative QCD prediction for Λ EDM

- Leading twist Λ LCDAs



$$4\epsilon^{abc}\int\frac{d\lambda_1 d\lambda_2 d\lambda_3}{(2\pi)^3}e^{iP^+(\lambda_1 x_1+\lambda_2 x_2+\lambda_3 x_3)}\langle 0|u_\alpha^a(\lambda_3 n)d_\beta^b(\lambda_2 n)s_\gamma^c(\lambda_1 n)|\Lambda(P)\rangle$$

$$=\mathcal{V}_\Lambda([x])(\gamma\cdot\hat{P}C)_{\alpha\beta}(\gamma_5 U)_\gamma+\mathcal{A}_\Lambda([x])(\gamma\cdot\hat{P}\gamma_5 C)_{\alpha\beta}U_\gamma+\mathcal{T}_\Lambda([x])(\hat{P}^\nu i\sigma_{\mu\nu}C)_{\alpha\beta}(\gamma^\mu\gamma_5 U)_\gamma+\cdots$$

Λ LCDAs

V. M. Braun et al., Nucl. Phys. B553, 355 (1999)

$\hat{P}^\mu=(P^+,0,0,0)$

$[x]=x_1,x_2,x_3$

Properties under $x_2\leftrightarrow x_3$

$$\mathcal{V}_\Lambda(x_1,x_2,x_3)=-\mathcal{V}_\Lambda(x_1,x_3,x_2)$$

$$\mathcal{A}_\Lambda(x_1,x_2,x_3)=\mathcal{A}_\Lambda(x_1,x_3,x_2)$$

$$\mathcal{T}_\Lambda(x_1,x_2,x_3)=-\mathcal{T}_\Lambda(x_1,x_3,x_2)$$

In the helicity basis:

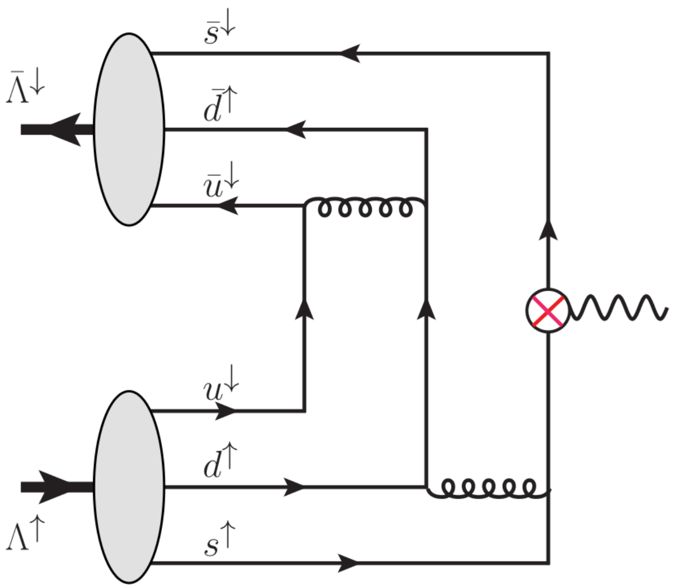
$$|\Lambda^\uparrow\rangle=\int\frac{[d^3x]}{4\sqrt{6}}\{[\mathcal{V}_\Lambda([x])-\mathcal{A}_\Lambda([x])]|u^\uparrow d^\downarrow s^\uparrow\rangle+[\mathcal{V}_\Lambda([x])+\mathcal{A}_\Lambda([x])]|u^\downarrow d^\uparrow s^\uparrow\rangle-2\mathcal{T}_\Lambda([x])|u^\uparrow d^\uparrow s^\downarrow\rangle\}$$

V. L. Chernyak et al., Z. Phys. C 42, 569 (1989)

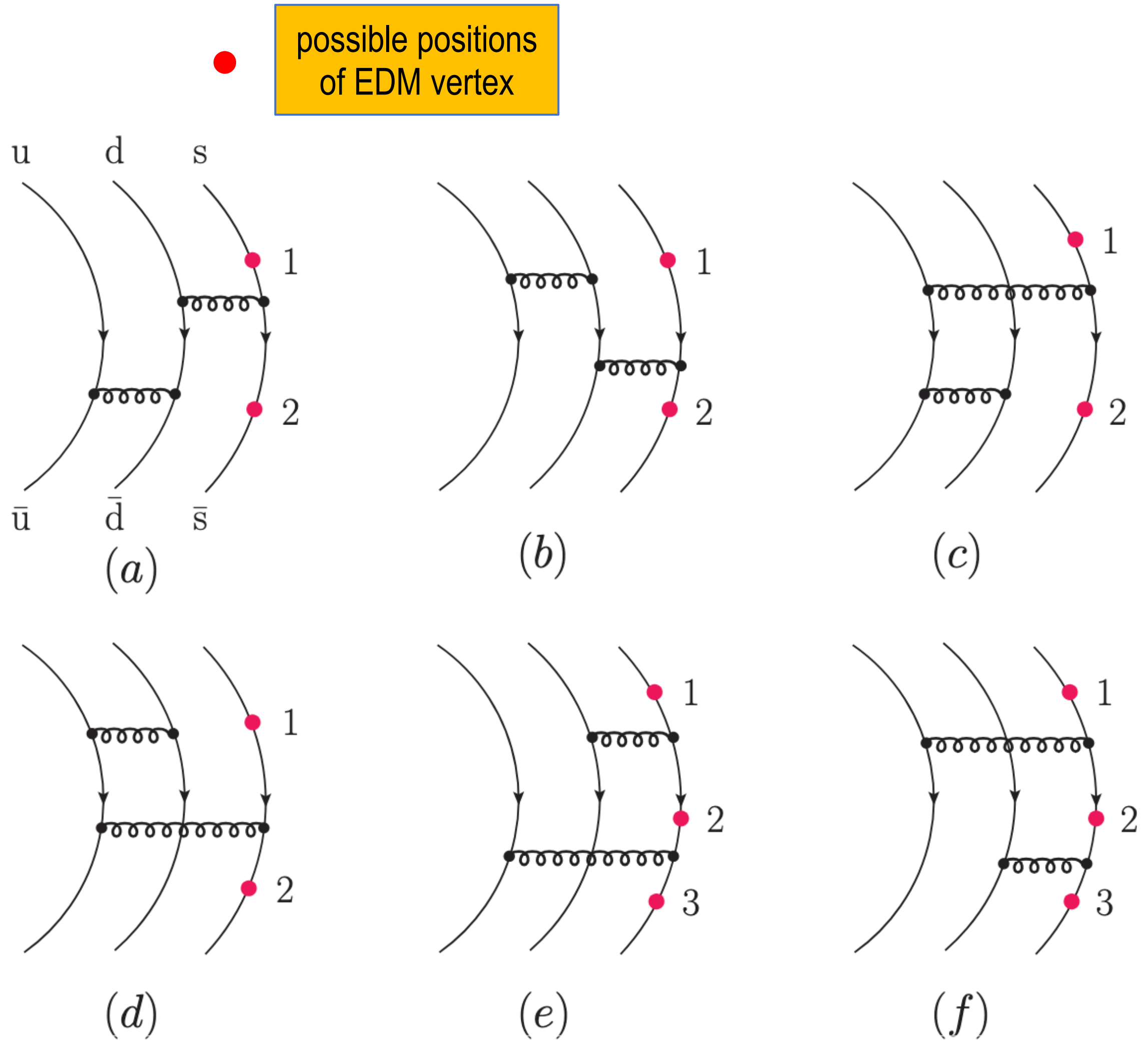
Perturbative QCD prediction for Λ EDM

■ Perturbative calculation

- Quark EDM contribution



A typical diagram for the s quark EDM contribution



14 diagrams for each quark EDM contribution, 42 diagrams in total

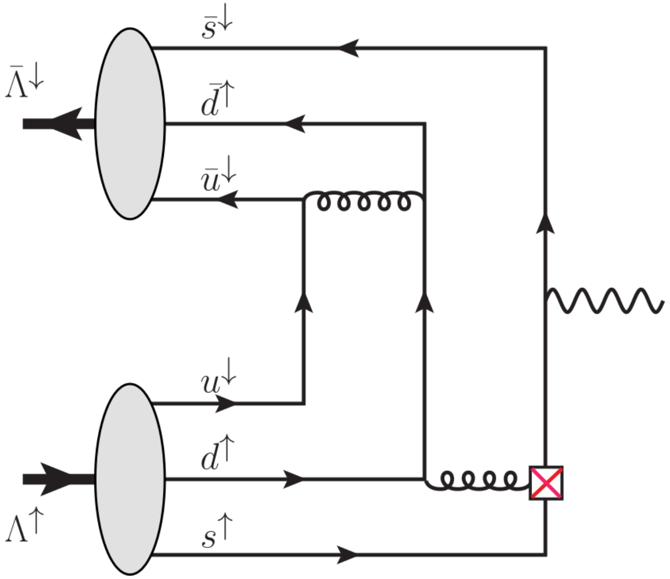
Perturbative QCD prediction for Λ EDM

■ Perturbative calculation

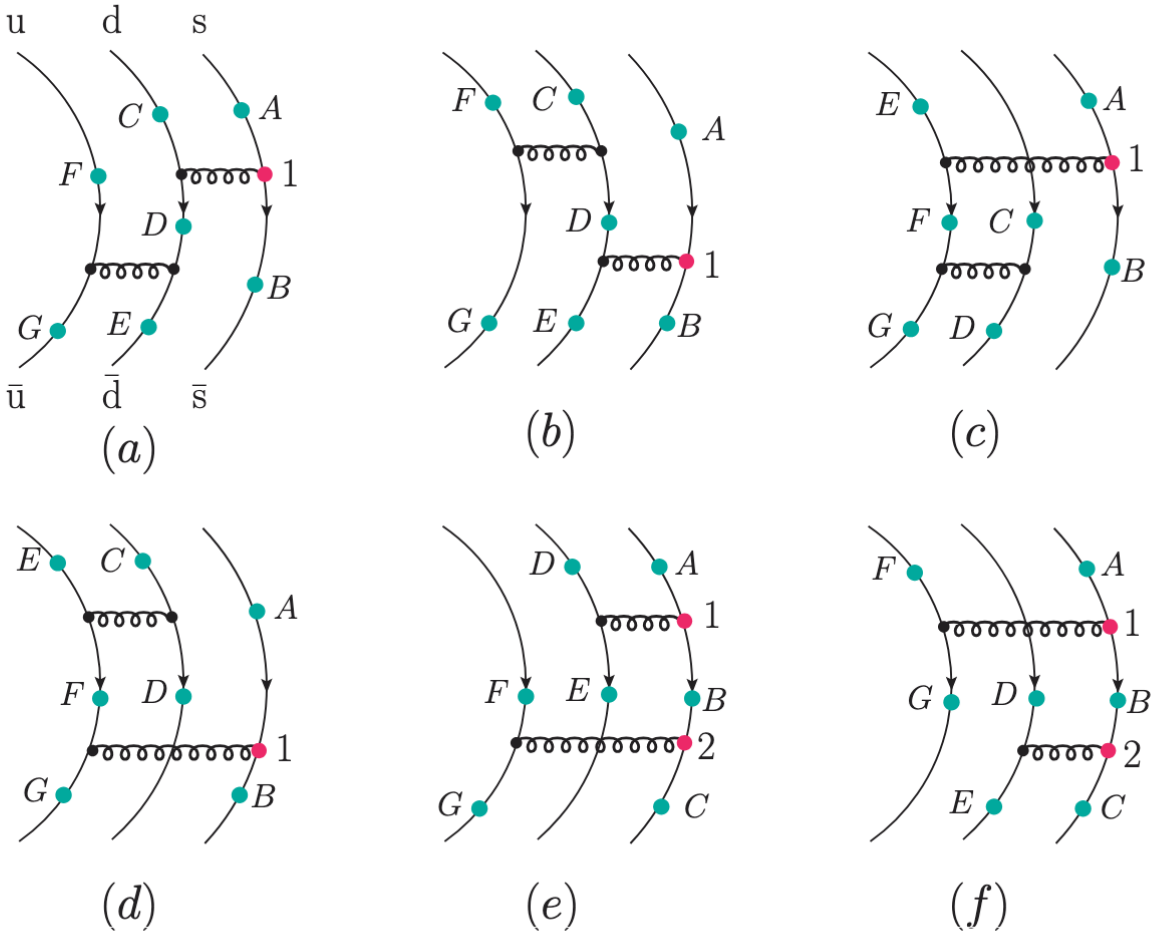
- Quark CEDM contribution

● possible positions of CEDM vertex

● possible positions of QED vertex



A typical diagram for the s quark CEDM contribution



56 diagrams for each quark CEDM contribution, 168 diagrams in total

Analytic results

$$d_\Lambda(Q)\Big|_{\mathrm{EDMs}} = C_B \frac{(4\pi\alpha_s)^2}{Q^4}\int [d^3x][d^3y]\Big\{d_s\Big[\big(\mathcal{V}_\Lambda([x])\mathcal{V}_{\bar\Lambda}([y]) - \mathcal{A}_\Lambda([x])\mathcal{A}_{\bar\Lambda}([y])\big)\mathcal{H}_s([x],[y]) + \big(\mathcal{V}_\Lambda([x])\mathcal{A}_{\bar\Lambda}([y]) - \mathcal{A}_\Lambda([x])\mathcal{V}_{\bar\Lambda}([y])\big)\mathcal{C}_s([x],[y])\Big] + (d_d + d_u)\big(\mathcal{V}_\Lambda([x]) + \mathcal{A}_\Lambda([x])\big)\mathcal{T}_{\bar\Lambda}([y])\mathcal{H}_q([x],[y])\Big\}$$

$$C_B = 2/27$$

$$[d^3x] = dx_1 dx_2 dx_3$$

$$d_\Lambda(Q)\Big|_{\mathrm{CEDMs}} = e g_s C_B \frac{4\pi\alpha_s}{Q^4}\int [d^3x][d^3y]\Big\{\tilde d_s \tilde{\mathcal{H}}_s([x],[y])\big[\mathcal{V}_\Lambda([x])\mathcal{V}_{\bar\Lambda}([y]) - \mathcal{A}_\Lambda([x])\mathcal{A}_{\bar\Lambda}([y])\big] + \big[\tilde d_d \tilde{\mathcal{H}}_d([x],[y]) + \tilde d_u \tilde{\mathcal{H}}_u([x],[y])\big]\big[\mathcal{V}_\Lambda([x]) + \mathcal{A}_\Lambda([x])\big]\mathcal{T}_{\bar\Lambda}([y])\Big\}$$

$$d_\Lambda(Q) \propto 1/Q^4$$

Hard coefficients:

$$\mathcal{H}_s([x],[y]) = \frac{-2}{\bar x_1^2 \bar y_1^2 x_3 y_3} - \frac{1}{2x_2x_3y_2y_3}\left(\frac{1}{\bar x_3\bar y_2} - \frac{1}{\bar x_1\bar y_2} - \frac{1}{\bar x_2\bar y_1}\right)$$

$$\mathcal{C}_s([x],[y]) = \frac{-1}{2x_2x_3y_2y_3}\left(\frac{1}{\bar x_3\bar y_2} - \frac{1}{\bar x_1\bar y_2} + \frac{1}{\bar x_2\bar y_1}\right)$$

$$\mathcal{H}_q([x],[y]) = \frac{-1}{x_1x_3y_1y_3}\left(\frac{1}{\bar x_2\bar y_3} - \frac{1}{\bar x_1\bar y_3} + \frac{1}{\bar x_1\bar y_2}\right) + \frac{2}{\bar x_2^2\bar y_2^2}\left(\frac{1}{x_3y_3} + \frac{1}{x_1y_1}\right)$$

$$\tilde{\mathcal{H}}_s([x],[y]) = Q_s\left[\frac{1}{\bar x_1\bar y_1}\left(\frac{1}{x_3y_3} + \frac{1}{x_2y_2}\right) + \frac{2}{x_2x_3y_2y_3}\right] + Q_d\left[\frac{1}{x_1y_1}\left(\frac{1}{x_3y_3} + \frac{1}{\bar x_2\bar y_2}\right) + \frac{2}{x_3y_3\bar x_2\bar y_2}\right] + Q_u\left[\frac{1}{x_1y_1}\left(\frac{1}{\bar x_3\bar y_3} + \frac{1}{x_2y_2}\right) + \frac{2}{x_2y_2\bar x_3\bar y_3}\right]$$

$$\tilde{\mathcal{H}}_d([x],[y]) = -Q_s\left[\frac{2}{x_2y_2}\left(\frac{1}{x_3y_3} + \frac{1}{\bar x_1\bar y_1}\right) + \frac{4}{x_3y_3\bar x_1\bar y_1}\right] - Q_d\left[\frac{2}{\bar x_2\bar y_2}\left(\frac{1}{x_3y_3} + \frac{1}{x_1y_1}\right) + \frac{4}{x_1x_3y_1y_3}\right] - Q_u\left[\frac{2}{x_2y_2}\left(\frac{1}{\bar x_3\bar y_3} + \frac{1}{x_1y_1}\right) + \frac{4}{x_1y_1\bar x_3\bar y_3}\right]$$

$$\tilde{\mathcal{H}}_u = \tilde{\mathcal{H}}_d(Q_u \leftrightarrow Q_d)$$

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Inputs for Λ LCDAs

LCDAs are non-perturbative, often extracted via QCD sum rules or lattice calculations.

- Asymptotic form (the first term of conformal partial wave expansion of LCDAs):

V. M. Braun et al., Nucl. Phys. B807, 89 (2009)

$$\mathcal{A}_\Lambda([x]) = f_\Lambda f_{\mathrm{as}}([x]) = 120 f_\Lambda x_1 x_2 x_3, \quad \mathcal{V}_\Lambda([x]) = \mathcal{T}_\Lambda([x]) = 0, \quad f_\Lambda \approx 6\times10^{-3}\mathrm{GeV}^2$$

➡ Only s quark contribute: $d_\Lambda = 1.72\times10^{-4} d_s + 2.06\times10^{-5} e\tilde{d}_s$

Valid at $Q \to \infty$, inconsistent for $Q \sim M_{J/\psi}$.

- Including the next term:

G. S. Bali et al., JHEP 02 (2016) 070

$$\mathcal{T}_\Lambda([x],\mu) = 7\sqrt{3/2}\, f_{\mathrm{as}}([x])(x_3 - x_2)\pi_{10}(\mu)$$
$$\mathcal{V}_\Lambda([x],\mu) = -\frac{7}{2}\sqrt{3/2}\, f_{\mathrm{as}}([x])(x_3 - x_2)[\varphi_{10}(\mu) - 3\varphi_{11}(\mu)]$$
$$\mathcal{A}_\Lambda([x],\mu) = \frac{1}{2}\sqrt{3/2}\, f_{\mathrm{as}}([x])[-2\varphi_{00}(\mu) + 7(x_3 + x_2 - 2x_1)(\varphi_{10}(\mu) + \varphi_{11}(\mu))]$$

shape parameters: $\varphi_{00}, \varphi_{10}, \varphi_{11}, \pi_{10}$

Numerical estimation

- Shape parameters from lattice

G. S. Bali et al., (RQCD Collaboration) JHEP 08 (2019) 065
G. S. Bali et al., (RQCD Collaboration) PRD 111, 094517 (2025)

$$\varphi_{00}(\mu_0) = 4.75\ \times 10^{-3}\ \mathrm{GeV}^2 \qquad \varphi_{11}(\mu_0) = 0.242\times 10^{-3}\ \mathrm{GeV}^2$$

$$\varphi_{10}(\mu_0) = 0.563\times 10^{-3}\ \mathrm{GeV}^2 \qquad \pi_{10}(\mu_0) = 0.237\times 10^{-3}\ \mathrm{GeV}^2$$

$$\mu_0 = 2\ \mathrm{GeV}$$

Scale evolution: $\varphi_{nk}(\mu) = \varphi_{nk}(\mu_0)\left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right)^{\gamma_{nk}/\beta_0}, \quad \pi_{nk}(\mu) = \pi_{nk}(\mu_0)\left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right)^{\gamma_{nk}/\beta_0}$

$$\gamma_{00} = 2/3,\ \gamma_{11} = 10/3,\ \gamma_{10} = 26/9,\ \beta_0 = 11 - 2N_f/3.$$

G. S. Bali et al., JHEP 02 (2016) 070

$$\Rightarrow\ d_\Lambda(M_{J/\psi}) = 5.29\times 10^{-4} d_s + 4.61\times 10^{-5}(d_u + d_d) + 6.21\times 10^{-5} e\tilde{d}_s + 1.98\times 10^{-5} e\tilde{d}_d - 2.14\times 10^{-5} e\tilde{d}_u$$

- Compare with the neutron EDM d_n

$$d_n = -(0.20 \pm 0.01)d_u + (0.78 \pm 0.03)d_d + (0.0027 \pm 0.0016)d_s - (0.55 \pm 0.28)e\tilde{d}_u - (1.1 \pm 0.55)e\tilde{d}_d$$

R. Alarcon et al., arXiv:2203.08103

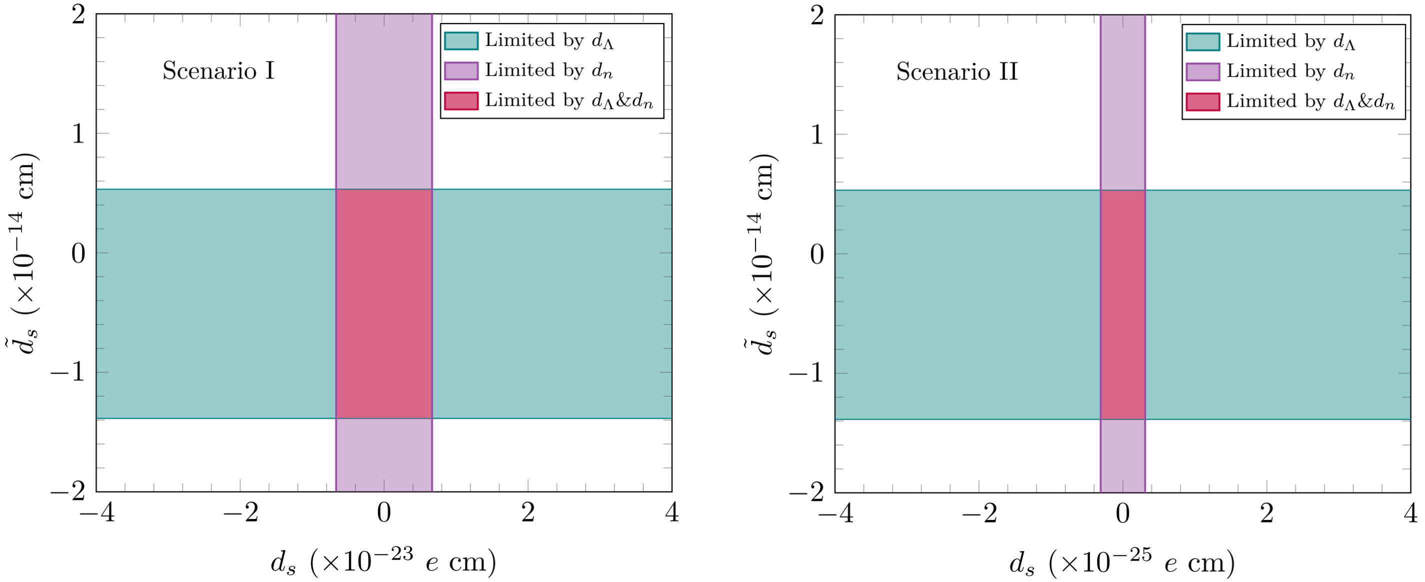
✓ No $\tilde{d}_s$ contribution for the neutron EDM.
✓ Unique constrain for $\tilde{d}_s$ from Λ EDM.

Numerical estimation

■ Numerical constraints

$$-8.6\times10^{-19} < \mathrm{Re}(d_\Lambda) < 3.3\times10^{-19} e\ \mathrm{cm},$$

$$|d_n| < 1.8\times10^{-26}\ e\ \mathrm{cm}$$ *C. Abel et al.,PRL 124, 081803 (2020)*



Scenario I: $d_s \gg d_u, d_d$

Scenario II: $d_s = d_u = d_d$

$\tilde{d}_u$ and $\tilde{d}_d$ are neglected

Implications

- ✓ Neutron EDM bound: give stringent constraint on d_s.
- ✓ Λ EDM bound: sensitive to both d_s and $\tilde{d}_s$, strong correlated.
- ✓ Combined: reducing $\tilde{d}_s$ to a finite region.
- ✓ Future measurements on Λ EDM have unique power in probing quark CEDM.

$$|\tilde{d}_s| < 1.4\times10^{-14}\mathrm{cm}$$

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Summary

- Hyperon EDMs are sensitive probes of CP-violation beyond the SM. BESIII's new Λ EDM bound improves the Λ EDM limit by $\sim$3 orders of magnitude.
- Based on pQCD calculation, we derive QCD factorization formulas linking Λ EDM to quark EDMs d_q and CEDMs $\tilde{d}_q$ through convolutions with Λ LCDAs.
- Numerical results show that Λ EDM is sensitive to the s-quark dipole couplings d_s and $\tilde{d}_s$. Combined constraints from Λ and neutron EDMs yield limits on d_s and $\tilde{d}_s$.
- Future measurements on Λ EDM have unique power in probing s-quark CEDM.

谢谢！