



第一届中国电子离子对撞机相关物理年会

Perturbative QCD analysis of the Λ EDM

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Based on: K.B. Chen, X.G. He, J.P. Ma and X.B. Tong, Phys. Rev. Lett. 136, 051902 (2026)



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 EDM limit: $|d_\Lambda| < 1.5 \times 10^{-16} e \text{ cm}$.

Obtained at Fermilab **more than 40 years ago**.

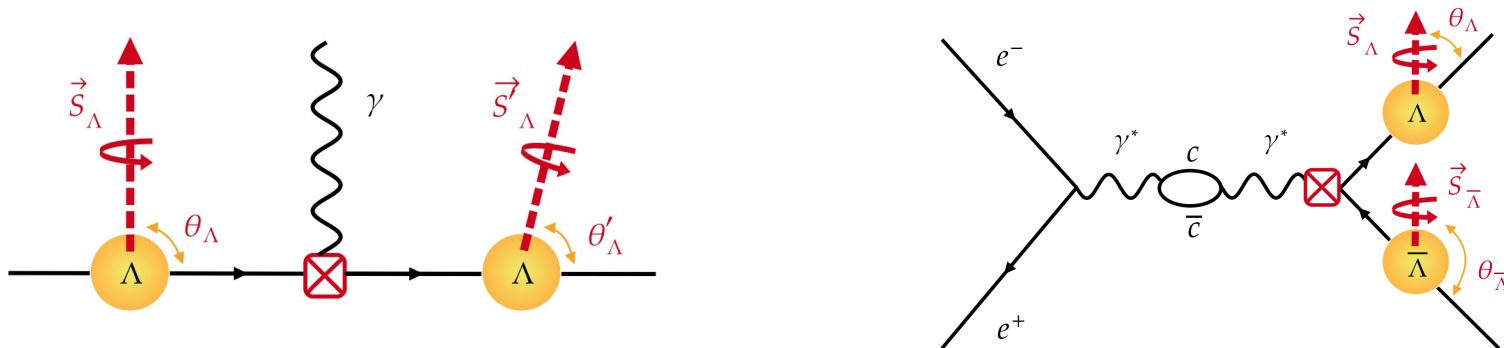
L. Pondrom et al., Phys. Rev. D 23, 814 (1981)



Motivation

■ New Λ EDM limit from BESIII

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



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

New bounds on Λ EDM obtained by BESIII:

$$-8.6 \times 10^{-19} < \text{Re}(d_\Lambda) < 3.3 \times 10^{-19} e \text{ cm},$$

$$-2.5 \times 10^{-19} < \text{Im}(d_\Lambda) < 7.2 \times 10^{-19} e \text{ cm}.$$

$$|d_\Lambda| < 6.5 \times 10^{-19} e \text{ cm} \quad (95\% \text{ CL})$$

~ 3 orders of magnitude
improvement

World's most precise measurement of Λ EDM!





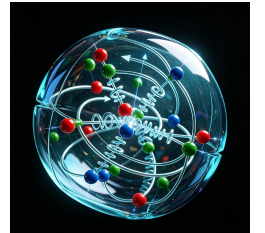
Motivation

- ✓ EDM measurements for other hyperons (Σ^+ , Σ^0 , Ξ^- , Ξ^0 , ...) are underway and are expected to achieve similar precision.
- ✓ With more data at BESIII and the planned Super Tau-Charm Factory, 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

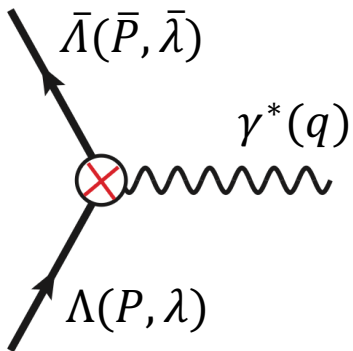
- CP-violating effective Lagrangian:

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

Quark EDM

Quark CEDM (chromoelectric dipole moment)

- The Λ EDM form factor:



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

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** \sim Hard coefficients \otimes light-cone distribution amplitudes (LCDAs)

What's special for EDM calculation?

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

 Helicity-flip

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

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

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

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

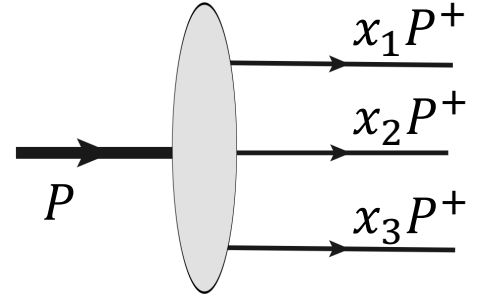
$$= \mathcal{V}_\Lambda([x]) (\gamma \cdot \hat{P} C)_{\alpha\beta} (\gamma_5 U)_\gamma + \mathcal{A}_\Lambda([x]) (\gamma \cdot \hat{P} \gamma_5 C)_{\alpha\beta} U_\gamma + \mathcal{T}_\Lambda([x]) (\hat{P}^\nu i \sigma_{\mu\nu} C)_{\alpha\beta} (\gamma^\mu \gamma_5 U)_\gamma + \dots$$

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 $x_2 \leftrightarrow x_3$

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

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

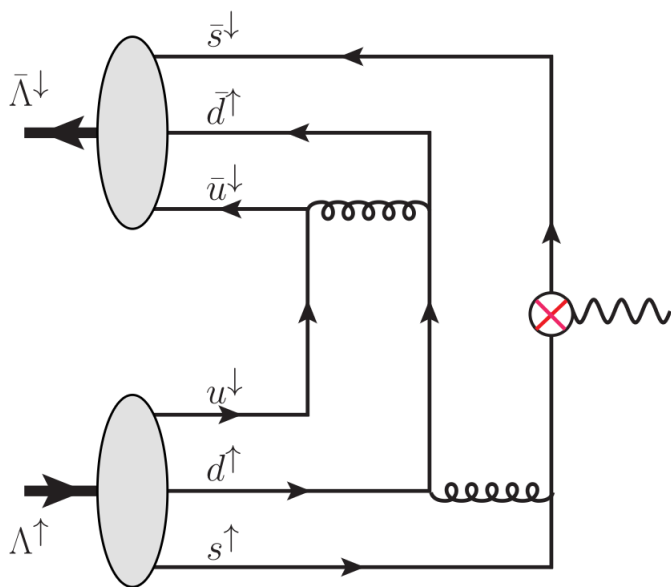
$$\mathcal{T}_\Lambda(x_1, x_2, x_3) = -\mathcal{T}_\Lambda(x_1, x_3, x_2)$$

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

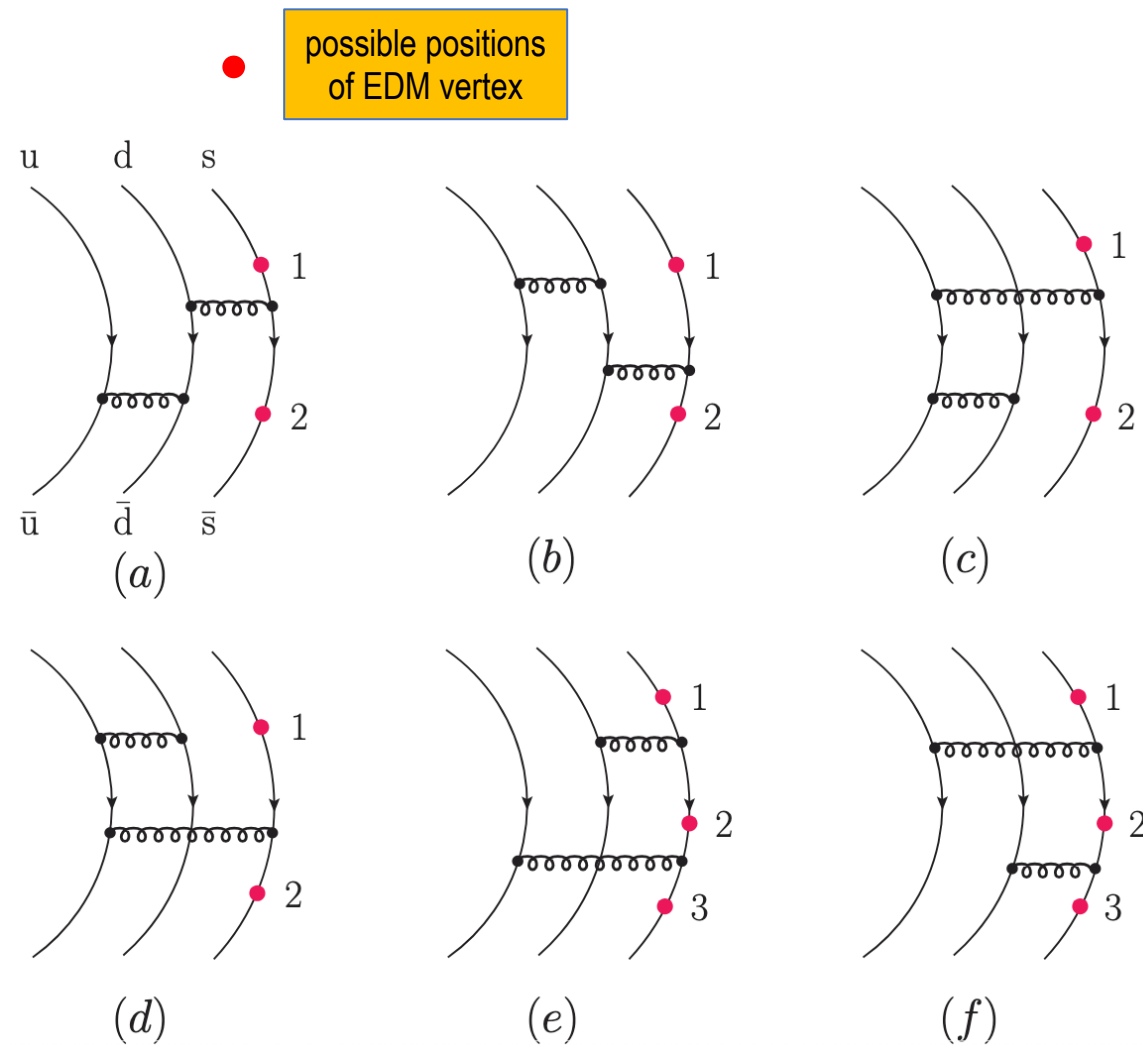
V. L. Chernyak et al., Z. Phys. C 42, 569 (1989)

■ Perturbative calculation

- Quark EDM contribution



A typical diagram for the s quark EDM contribution



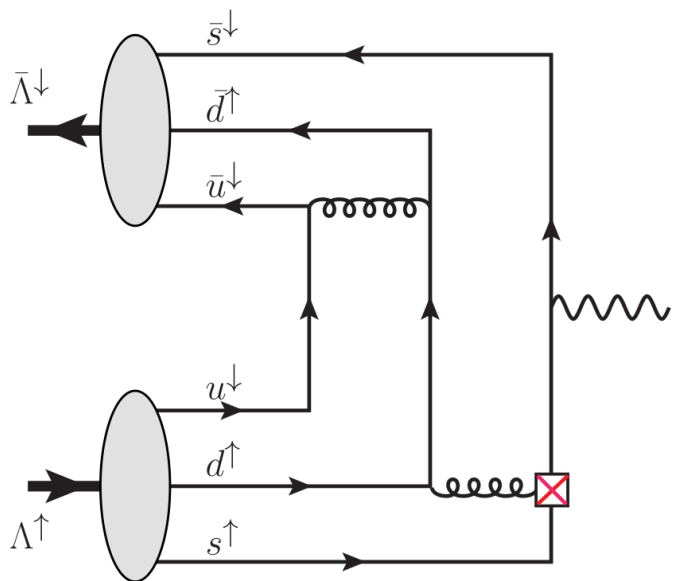
14 diagrams for each quark EDM contribution, 42 diagrams in total



Perturbative QCD prediction for Λ EDM

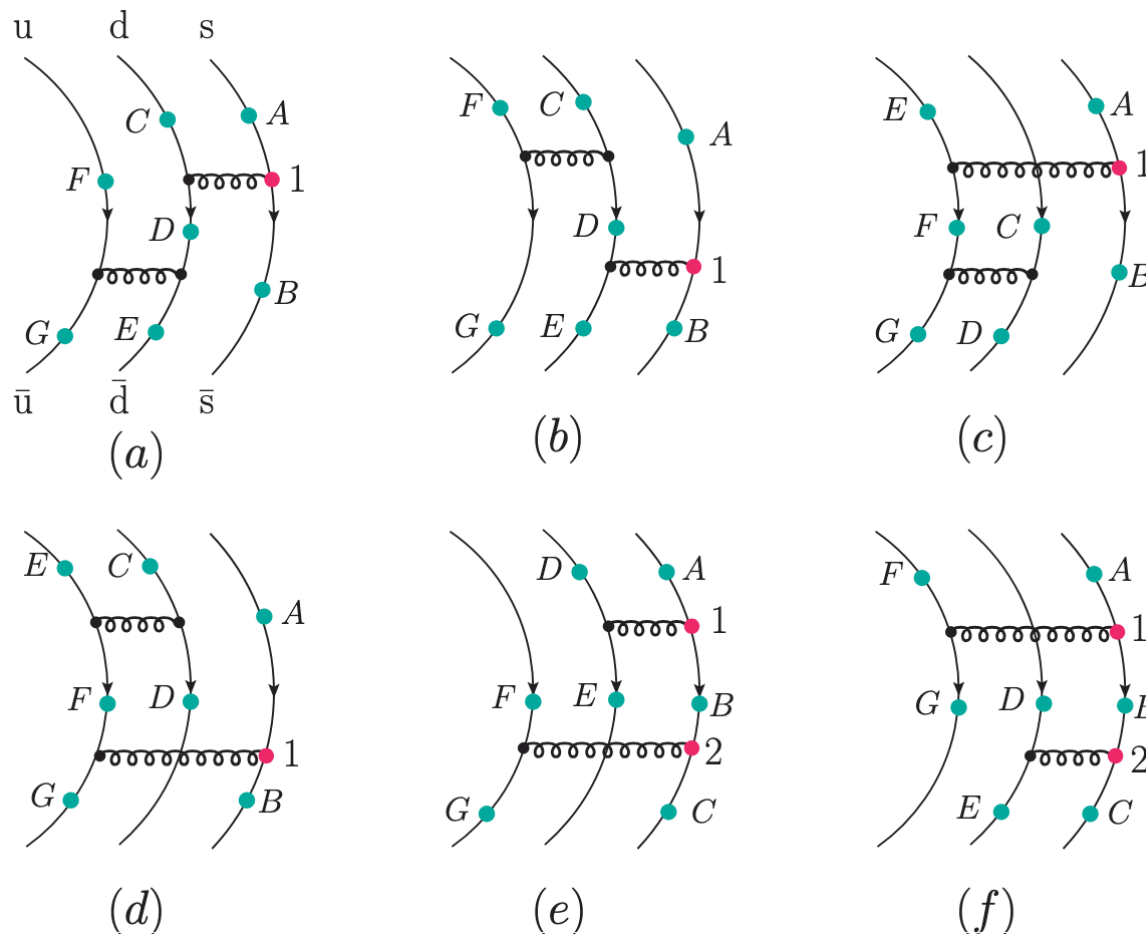
■ Perturbative calculation

- Quark CEDM contribution



A typical diagram for the s quark CEDM contribution

● possible positions of CEDM vertex
● possible positions of QED vertex



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



Perturbative QCD prediction for Λ EDM

Analytic results

$$d_\Lambda(Q) \Big|_{\text{EDMs}} = C_B \frac{(4\pi\alpha_s)^2}{Q^4} \int [d^3x][d^3y] \left\{ d_s [(\mathcal{V}_\Lambda([x])\mathcal{V}_{\bar{\Lambda}}([y]) - \mathcal{A}_\Lambda([x])\mathcal{A}_{\bar{\Lambda}}([y]))\mathcal{H}_s([x], [y]) \right. \\ \left. + (\mathcal{V}_\Lambda([x])\mathcal{A}_{\bar{\Lambda}}([y]) - \mathcal{A}_\Lambda([x])\mathcal{V}_{\bar{\Lambda}}([y]))\mathcal{C}_s([x], [y]) \right. \\ \left. + (d_d + d_u)(\mathcal{V}_\Lambda([x]) + \mathcal{A}_\Lambda([x]))\mathcal{T}_{\bar{\Lambda}}([y])\mathcal{H}_q([x], [y]) \right\} \quad C_B = 2/27 \\ [d^3x] = dx_1 dx_2 dx_3$$

$$d_\Lambda(Q) \Big|_{\text{CEDMs}} = e g_s C_B \frac{4\pi\alpha_s}{Q^4} \int [d^3x][d^3y] \left\{ \tilde{d}_s \tilde{\mathcal{H}}_s([x], [y]) [\mathcal{V}_\Lambda([x])\mathcal{V}_{\bar{\Lambda}}([y]) - \mathcal{A}_\Lambda([x])\mathcal{A}_{\bar{\Lambda}}([y])] \right. \\ \left. + [\tilde{d}_d \tilde{\mathcal{H}}_d([x], [y]) + \tilde{d}_u \tilde{\mathcal{H}}_u([x], [y])] [\mathcal{V}_\Lambda([x]) + \mathcal{A}_\Lambda([x])]\mathcal{T}_{\bar{\Lambda}}([y]) \right\} \quad d_\Lambda(Q) \propto 1/Q^4$$

Hard coefficients:

$$\mathcal{H}_s([x], [y]) = \frac{-2}{\bar{x}_1^2 \bar{y}_1^2 x_3 y_3} - \frac{1}{2x_2 x_3 y_2 y_3} \left(\frac{1}{\bar{x}_3 \bar{y}_2} - \frac{1}{\bar{x}_1 \bar{y}_2} - \frac{1}{\bar{x}_2 \bar{y}_1} \right) \quad \tilde{\mathcal{H}}_s([x], [y]) = Q_s \left[\frac{1}{\bar{x}_1 \bar{y}_1} \left(\frac{1}{x_3 y_3} + \frac{1}{x_2 y_2} \right) + \frac{2}{x_2 x_3 y_2 y_3} \right] \\ + Q_d \left[\frac{1}{x_1 y_1} \left(\frac{1}{x_3 y_3} + \frac{1}{\bar{x}_2 \bar{y}_2} \right) + \frac{2}{x_3 y_3 \bar{x}_2 \bar{y}_2} \right] \\ + Q_u \left[\frac{1}{x_1 y_1} \left(\frac{1}{\bar{x}_3 \bar{y}_3} + \frac{1}{x_2 y_2} \right) + \frac{2}{x_2 y_2 \bar{x}_3 \bar{y}_3} \right] \quad \tilde{\mathcal{H}}_d([x], [y]) = -Q_s \left[\frac{2}{x_2 y_2} \left(\frac{1}{x_3 y_3} + \frac{1}{\bar{x}_1 \bar{y}_1} \right) + \frac{4}{x_3 y_3 \bar{x}_1 \bar{y}_1} \right] \\ - Q_d \left[\frac{2}{\bar{x}_2 \bar{y}_2} \left(\frac{1}{x_3 y_3} + \frac{1}{x_1 y_1} \right) + \frac{4}{x_1 x_3 y_1 y_3} \right] \\ - Q_u \left[\frac{2}{x_2 y_2} \left(\frac{1}{\bar{x}_3 \bar{y}_3} + \frac{1}{x_1 y_1} \right) + \frac{4}{x_1 y_1 \bar{x}_3 \bar{y}_3} \right]$$

$$\mathcal{C}_s([x], [y]) = \frac{-1}{2x_2 x_3 y_2 y_3} \left(\frac{1}{\bar{x}_3 \bar{y}_2} - \frac{1}{\bar{x}_1 \bar{y}_2} + \frac{1}{\bar{x}_2 \bar{y}_1} \right) \\ \mathcal{H}_q([x], [y]) = \frac{-1}{x_1 x_3 y_1 y_3} \left(\frac{1}{\bar{x}_2 \bar{y}_3} - \frac{1}{\bar{x}_1 \bar{y}_3} + \frac{1}{\bar{x}_1 \bar{y}_2} \right) + \frac{2}{\bar{x}_2^2 \bar{y}_2^2} \left(\frac{1}{x_3 y_3} + \frac{1}{x_1 y_1} \right) \quad \tilde{\mathcal{H}}_u = \tilde{\mathcal{H}}_d(Q_u \leftrightarrow Q_d)$$



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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)

$$\mathcal{A}_\Lambda([x]) = f_\Lambda f_{as}([x]) = 120 f_\Lambda x_1 x_2 x_3, \quad \mathcal{V}_\Lambda([x]) = \mathcal{T}_\Lambda([x]) = 0, \quad f_\Lambda \approx 6 \times 10^{-3} \text{GeV}^2$$

➡ Only s quark contribute: $d_\Lambda = 1.72 \times 10^{-4} d_s + 2.06 \times 10^{-5} e \tilde{d}_s$

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

- **Including the next term:**

$$\mathcal{T}_\Lambda([x], \mu) = 7 \sqrt{3/2} f_{as}([x]) (x_3 - x_2) \pi_{10}(\mu)$$

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

$$\mathcal{V}_\Lambda([x], \mu) = -\frac{7}{2} \sqrt{3/2} f_{as}([x]) (x_3 - x_2) [\varphi_{10}(\mu) - 3\varphi_{11}(\mu)]$$

shape parameters:

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

$\varphi_{00}, \varphi_{10}, \varphi_{11}, \pi_{10}$



Numerical estimation

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

- Shape parameters from lattice

$$\begin{aligned} \varphi_{00}(\mu_0) &= 4.75 \times 10^{-3} \text{ GeV}^2 & \varphi_{11}(\mu_0) &= 0.242 \times 10^{-3} \text{ GeV}^2 \\ \varphi_{10}(\mu_0) &= 0.563 \times 10^{-3} \text{ GeV}^2 & \pi_{10}(\mu_0) &= 0.237 \times 10^{-3} \text{ GeV}^2 \end{aligned} \quad \mu_0 = 2 \text{ GeV}$$

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

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

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

- Compare with the neutron EDM d_n

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

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

R. Alarcon et al., arXiv:2203.08103

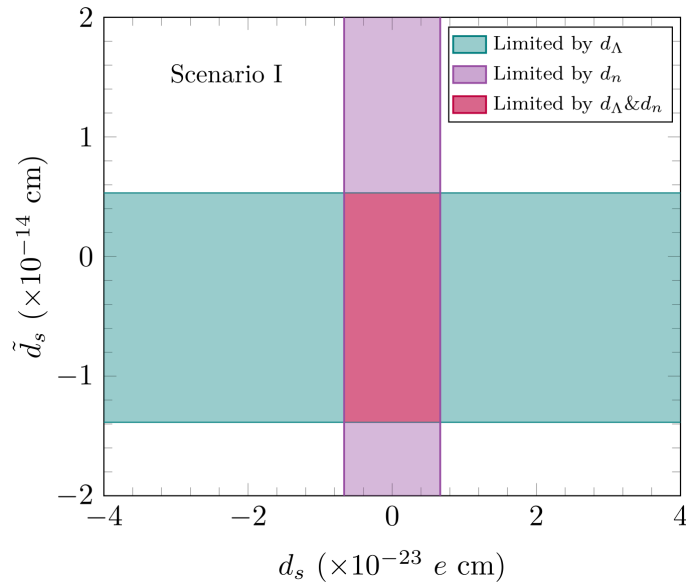


Numerical estimation

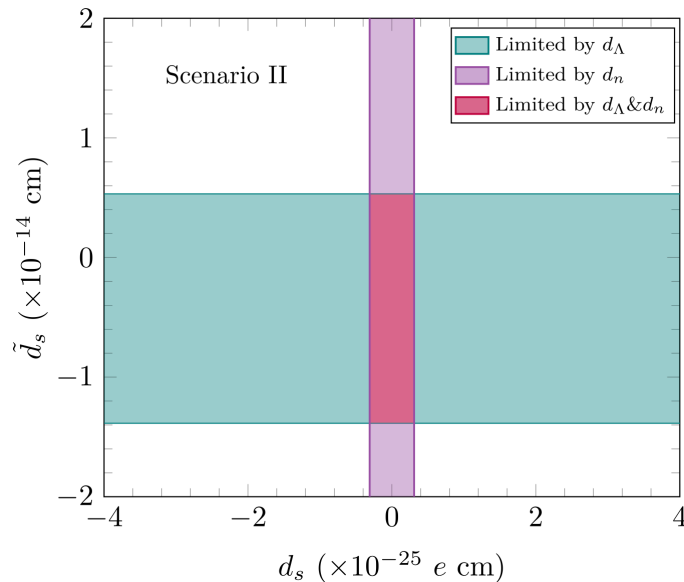
Numerical constraints

$$-8.6 \times 10^{-19} < \text{Re}(d_\Lambda) < 3.3 \times 10^{-19} e \text{ cm},$$

$$|d_n| < 1.8 \times 10^{-26} e \text{ cm} \quad C. Abel et al., PRL 124, 081803 (2020)$$



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.

$$|\tilde{d}_s| < 1.4 \times 10^{-14} \text{ cm}$$



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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 ~ 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 quark CEDM.

谢谢!