Search for Hyperon EDM in J/ψ Decays

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国家重点研发项目“粲强子衰变和标准模型的精确检验”夏季年会

Outline

- Motivation
- EDM Measurement
- Results
- Summary

① Motivation

Matter-antimatter asymmetry

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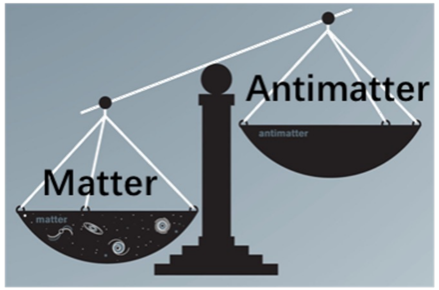
[1] *Pisma Zh. Eksp. Teor. Fiz., 1967, 5: 32-35.*
[2] *Phys.Rev. 108 (1957) 1645-1647*
[3] *Comptes Rendus Physique, 13.2 (2012), 168-175.*



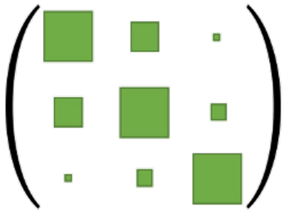
- Sakharov three conditions [1] :
  1. Baryon number B violation
  2. C and CP symmetry violation (CPV)
  3. Interactions out of thermal equilibrium

- CPV in Standard Model (SM)

CKM mechanism [2]

CPV from phase δ

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



$$\delta \neq 0 \quad \Rightarrow \quad \mathbf{V}^*_{\mathbf{CKM}} \neq \mathbf{V}_{\mathbf{CKM}}$$

Strong CP process [3]

- QCD "vacuum angle" $\bar{\theta}$:

$$\mathcal{L}_{\bar{\theta}} = -\frac{\alpha_s}{16\pi^2}\bar{\theta}\mathrm{Tr}(G^{\mu\nu}\tilde{G}_{\mu\nu})$$

- Measuring the Electric Dipole Moment (EDM) of atomic nuclei, atoms, and molecular systems:

$$|d_n| < 10^{-26} e \cdot cm \quad \Rightarrow \quad \bar{\theta} < 10^{-10}$$

CPV in SM not sufficient to explain matter-antimatter asymmetry
necessary to search for **new CPV sources beyond SM!**

Electric Dipole Moment

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- Electric Dipole Moment (EDM)

$$\boldsymbol{\delta} = d\ \mu_B \frac{\boldsymbol{s}}{2}$$

- Magnetic Dipole Moment (MDM)

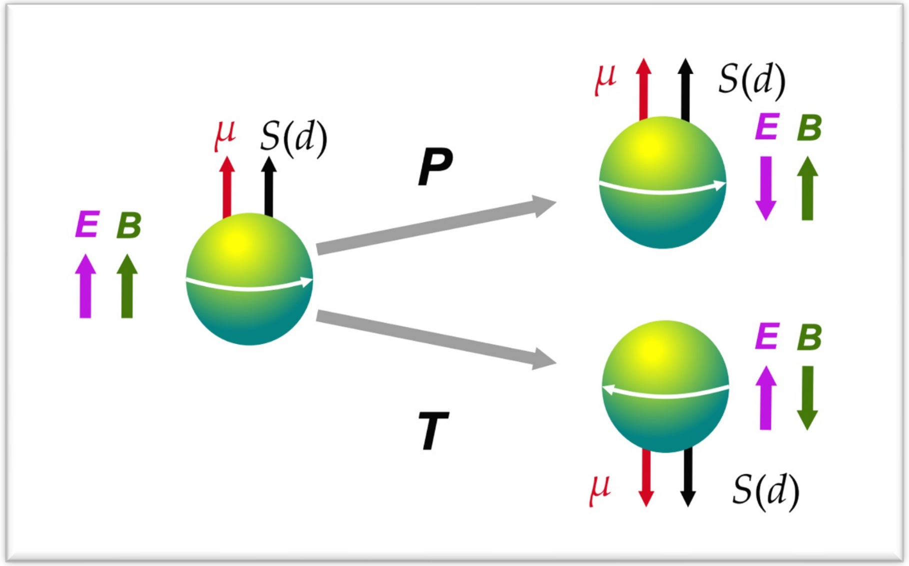
$$\boldsymbol{\mu} = g\ \mu_B \frac{\boldsymbol{s}}{2}$$

Particle spin: $\boldsymbol{s} = \mathrm{Tr}[\rho\boldsymbol{\sigma}] = \frac{2}{\hbar}\langle\widehat{\boldsymbol{S}}\rangle$

Magneton： μ_B

Electric dipole factor： d

Magnetic dipole factor： g

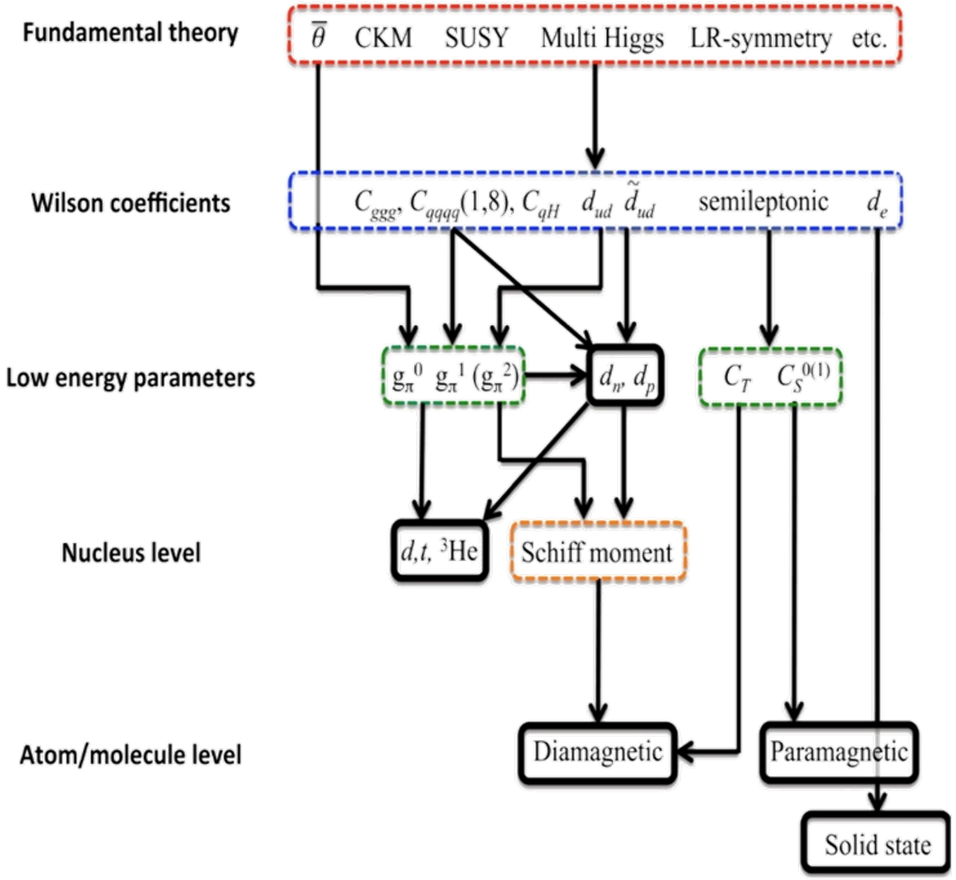


$$\mathcal{H} = -\boldsymbol{\mu}\cdot\boldsymbol{B} - \boldsymbol{\delta}\cdot\boldsymbol{E}$$

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

- $\boldsymbol{T}$ violation $\leftrightarrow$ $\boldsymbol{CP}$ violation, if $\boldsymbol{CPT}$ holds.
- **Non-zero EDM is a signal of CPV**

Why we choose Hyperon EDM?



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

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

EFT

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

Hyperon system also required by a global analysis of EDMs

Effective Field Theory
Bridging fundamental theories and experimental measurement.

- **EDM is very sensitive to BSM physics** across broad range of energy scales.
- e.g., **Strange quark** may have special coupling with new physics.

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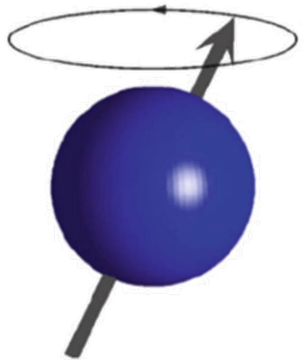
How to measure EDM?



- Direct approach: spin precession
  - Measuring spin polarization dynamics in electromagnetic fields $(d\boldsymbol{s}/dt)$
  - Extracting EDM & MDM utilizing spin precession $(d \,\&\, g)$

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

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

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

Requirements:
- Sizable polarized particle source
- Enough lifetime to process

$\tau_{\Lambda,\Sigma^{\pm}\Xi} \sim 10^{-10}$ s

$\tau_{\Sigma^0} \sim 10^{-20}$ s

Direct method is particularly challenging for short-lived hyperons!

EDM status

[1] *J. Phys. G 47 (2020) 1, 010501*
[2] *Phys. Rev. D 23 (1981) 814–816*

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[1]

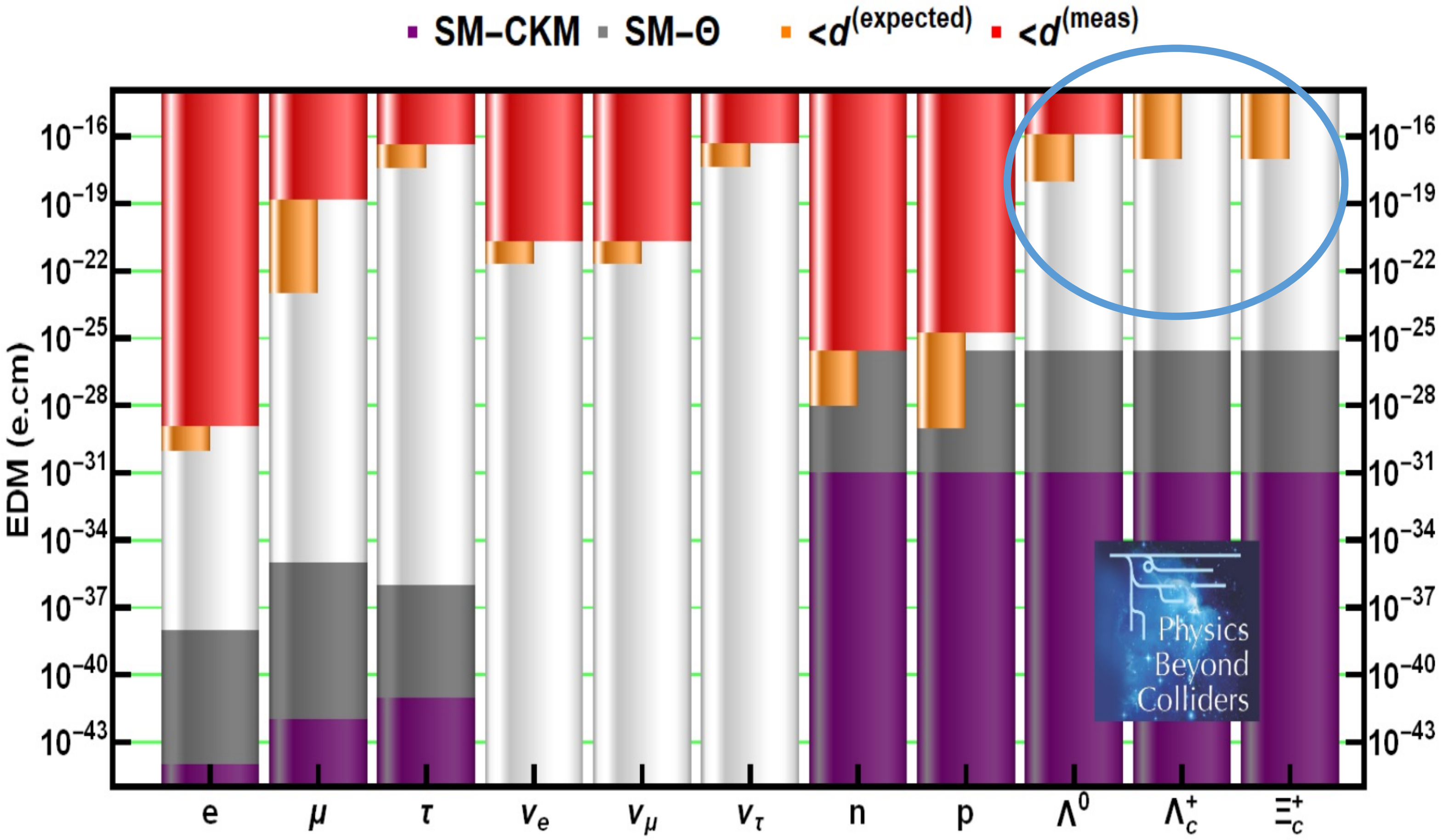
Best measurements limits from experimental results

Expected experimental results in the next few years

Safe BSM discovery territory

SM estimates from QCD $\bar{\theta}$ term (based on d_n measurement)

SM estimates from CKM

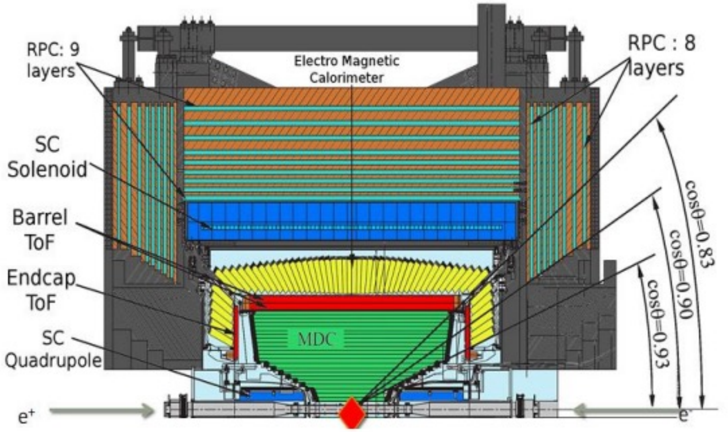


- EDM measurement in particle physics is relatively scarce.
- In hyperon family, **only Λ EDM measured directly** with large uncertainty. [2]

What can BESIII do? (1)

Electromagnetic Calorimeter
CsI(Tl): L=28 cm
Barrel σ_E=2.5%
Endcap σ_E=5.0%

Muon Counter
RPC
Barrel: 9 layers
Endcap: 8 layers
$\sigma_{spatial}$=1.48 cm



Main Drift Chamber
Small cell, 43 layer
σ_{xy}=130 μm
dE/dx~6%
σ_p/p= 0.5% at 1 GeV

Time Of Flight
Plastic scintillator
σ_T(barrel)=80 ps
σ_T(endcap)=110 ps
(update to 65 ps with MRPC)

BESIII: A hyperon factory

Decay	$\mathcal{B}$ (10^{-5})	Events at BESIII
$J/\psi \to \Lambda\bar{\Lambda}$	189 ± 9	18.9×10^6
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	150 ± 24	15.0×10^6
$J/\psi \to \Xi\bar{\Xi}$	97 ± 8	9.7×10^6
$\psi(2S) \to \Sigma\bar{\Sigma}$	23.2 ± 1.2	116×10^3
$\psi(2S) \to \Omega\bar{\Omega}$	5.66 ± 0.30	28×10^3

Front. Phys. 12(5), 121301 (2017), Phys. Rev. D 100, 114005 (2019)

- **10 billion J/ψ events** collected at BESIII:
  - Large Br. in J/ψ decay
  - Quantum entangled pair productions
  - High efficiency, background free

$\sim 10^7$ entangled hyperon pairs can be studied.

What can BESIII do? (2)

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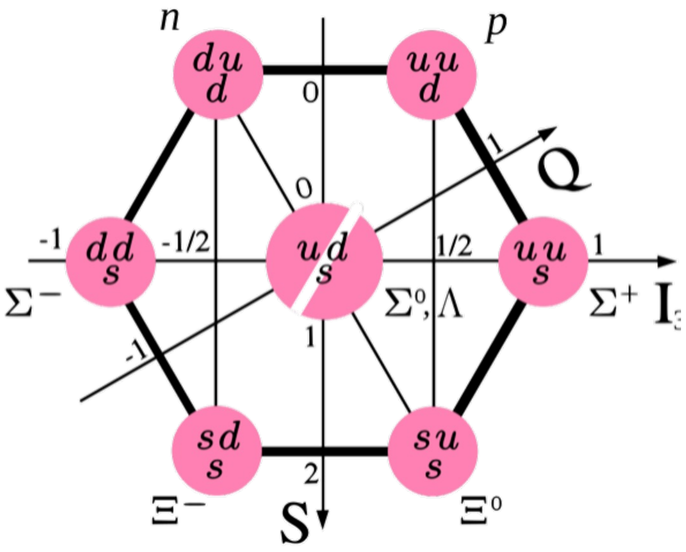
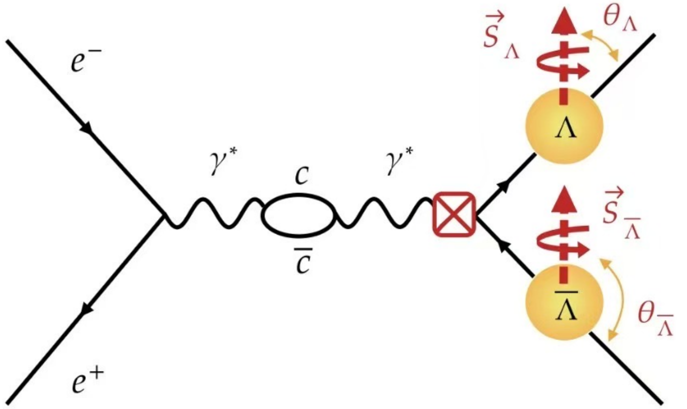
- **Indirect approach: time-like dipole form factors ($q^2 \neq 0$)**





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

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

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

- Extract form factors from full angular analysis

J.L.Fu, H.B.Li, et. al, Phys. Rev. D 108, L091301 (2023)

② EDM Measurement

Production of J/ψ

- Considering Z^0 contribution, J/ψ has longitudinal polarization, denoted by $\boldsymbol{P_L}$

$$P_L = \frac{\rho_{++} - \rho_{--}}{\rho_{++} + \rho_{--}}$$

$\boldsymbol{\rho_{mm'}}$: J/ψ spin density matrix

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

weak mixing angle

Decay dynamics in $J/\psi \to B\bar{B}$

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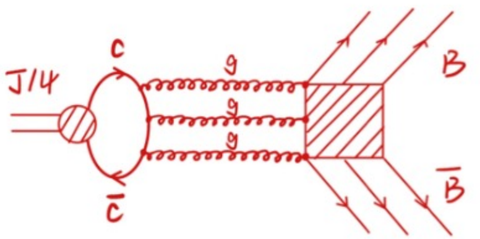
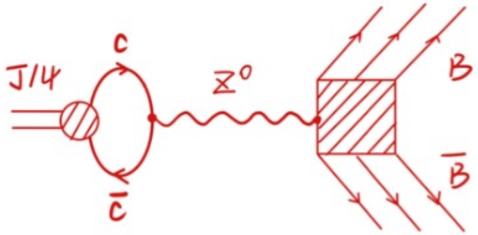
$$M(\lambda_1,\lambda_2) = \epsilon(\lambda)\bar{\mu}(\lambda_1)\left(F_V\gamma^\mu + \frac{i}{2M_B}\sigma^{\mu\nu}q_\nu H_\sigma + \gamma^\mu\gamma^5 F_A + \sigma^{\mu\nu}\gamma^5 q_\nu H_T\right)\nu(\lambda_2)$$

Physics Letters B 839 (2023) 137834



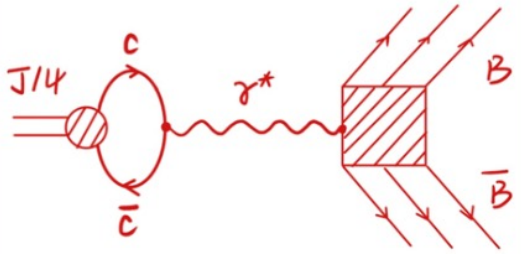
Dominant contribution
arXiv:hep-ph/0412158

Psionic form factor
$\boldsymbol{F_V}$ and $\boldsymbol{H_\sigma}$
can also be represented as $\boldsymbol{G_1}$ and $\boldsymbol{G_2}$



P violation term

Complex form factor, $F_A \neq 0$ indicate P violation



$\boldsymbol{H_T}$ is included in this term

$$H_T(q^2) = \frac{2e}{3m_{J/\psi}^2} g_V d_B(q^2)$$

Assuming $d_B(q^2) \equiv d_B(0)$

$d_B(q^2)$: electric dipole form factor
$d_B(0)$: electric dipole moment
Physics Letters B 551 (2003) 16–26

← EDM factor

Full angular formula of $e^+e^- \to J/\psi \to B\bar{B}$

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- Spin density matrix of $B\bar{B}$:

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

- Total angular distribution of J/ψ decay:
  - $J/\psi \to B\bar{B}, B = \Lambda^0, \Sigma^-, \Sigma^+$

$$\frac{d\sigma}{d\Omega_k d\Omega_p d\Omega_{\bar{p}}} = N \sum_{[\lambda]} R(\lambda_1,\lambda_2;\lambda_1',\lambda_2')\, D^{j=1/2}_{\lambda_1,\lambda_p}(\theta_1,\phi_1) D^{*j=1/2}_{\lambda_1',\lambda_p}(\theta_1,\phi_1) \left|h_{\lambda_p}\right|^2 D^{j=1/2}_{\lambda_2,\lambda_{\bar{p}}}(\theta_2,\phi_2) D^{*j=1/2}_{\lambda_2',\lambda_{\bar{p}}}(\theta_2,\phi_2) \left|h_{\lambda_{\bar{p}}}\right|^2$$

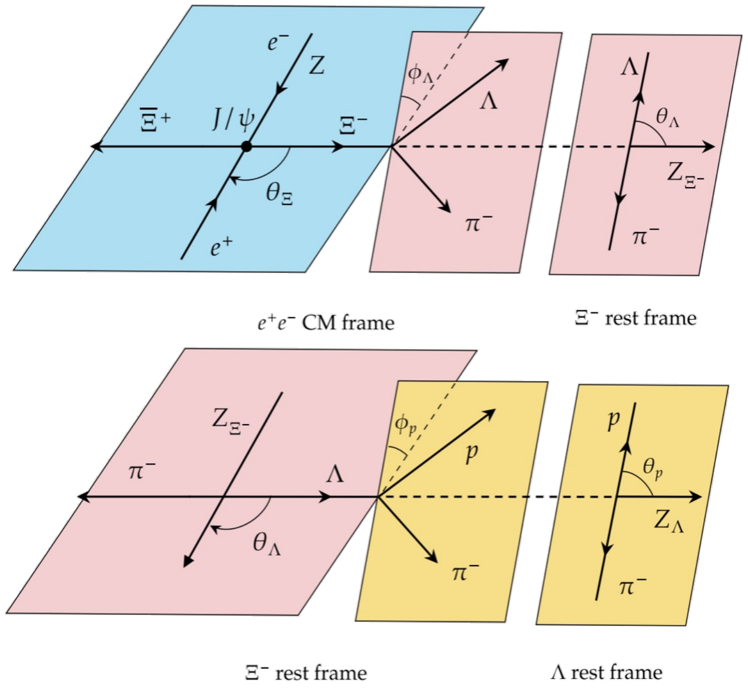
  - $J/\psi \to B\bar{B}, B = \Xi^0, \Xi^-, \Sigma^0$

$$\frac{d\sigma}{d\Omega_k d\Omega_\Lambda d\Omega_{\bar{\Lambda}} d\Omega_p d\Omega_{\bar{p}}} = N \sum_{[\lambda]} R(\lambda_1,\lambda_2;\lambda_1',\lambda_2')\, D^{*j=1/2}_{\lambda_1,\lambda_\Lambda}(\theta_1,\phi_1) D^{j=1/2}_{\lambda_1',\lambda'_\Lambda}(\theta_1,\phi_1) \mathcal{H}_{\lambda_\Lambda} \mathcal{H}^*_{\lambda_\Lambda'} D^{*j=1/2}_{\lambda_2,\lambda_{\bar{\Lambda}}}(\theta_2,\phi_2)$$

$$D^{j=1/2}_{\lambda_2',\lambda'_{\bar{\Lambda}}}(\theta_2,\phi_2) \mathcal{H}_{\lambda_{\bar{\Lambda}}} \mathcal{H}^*_{\lambda_{\bar{\Lambda}}'} D^{*j=1/2}_{\lambda_\Lambda,\lambda_p}(\theta_3,\phi_3) D^{*j=1/2}_{\lambda_\Lambda',\lambda_p}(\theta_3,\phi_3) \left|h_{\lambda_p}\right|^2 D^{*j=1/2}_{\lambda_{\bar{\Lambda}},\lambda_{\bar{p}}}(\theta_4,\phi_4) D^{j=1/2}_{\lambda_{\bar{\Lambda}}',\lambda_{\bar{p}}}(\theta_4,\phi_4) \left|h_{\lambda_{\bar{p}}}\right|^2$$

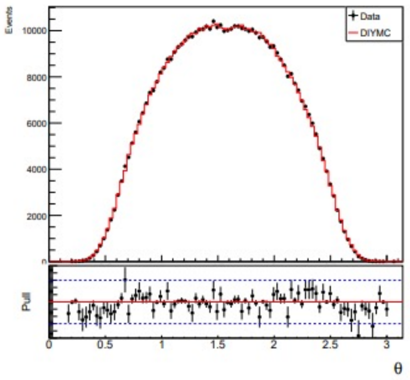
Jinlin Fu, Haibo Li, et. al, Phys. Rev. D 108, L091301 (2023)

Helicity angles

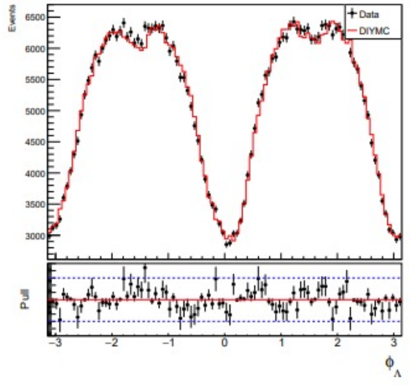


Right-hand coordinate system

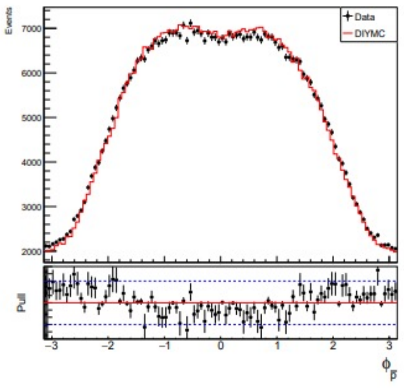
($J/\psi \to \Xi^-\bar{\Xi}^+$)



(a) θ_Ξ distribution



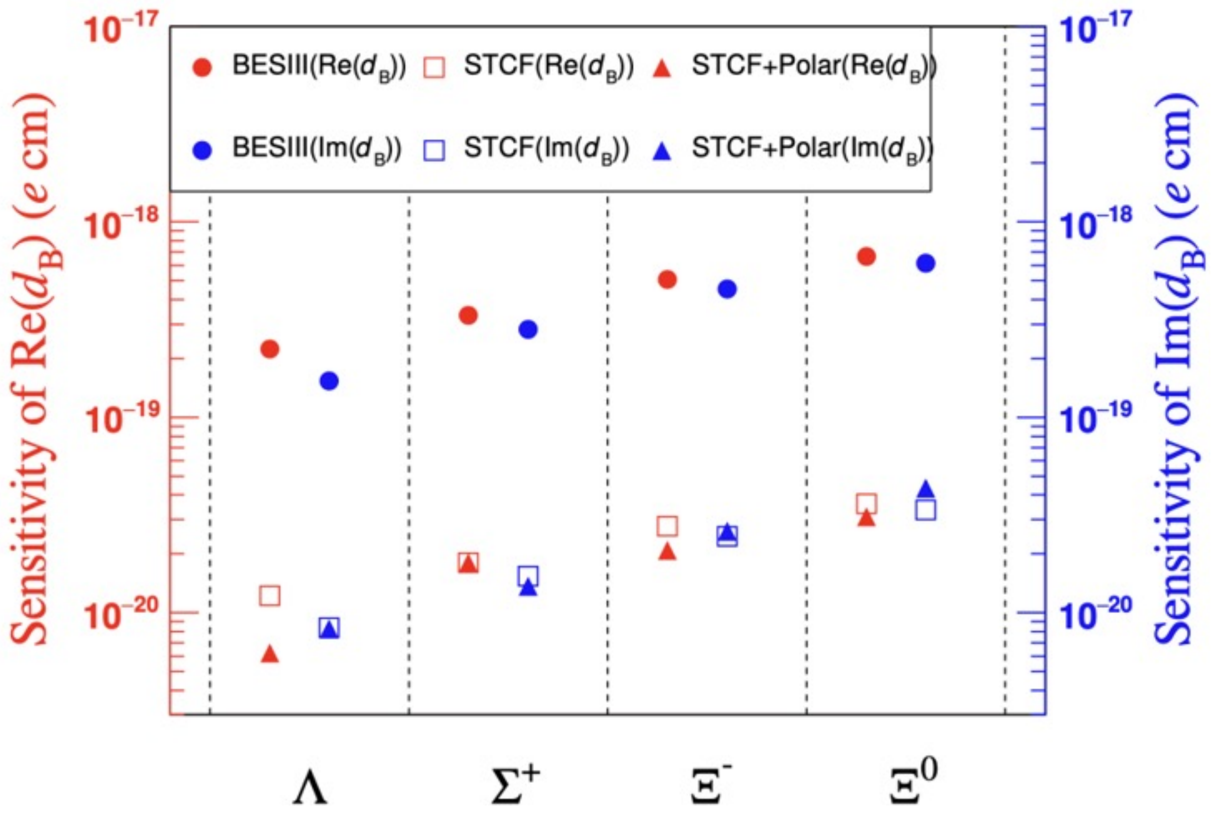
(d) ϕ_Λ distribution



(i) $\phi_{\bar{p}}$ distribution

Decay channel	Angles
$J/\psi \to \mathbf{\Lambda\bar{\Lambda}},\ \Lambda(\bar{\Lambda}) \to p\pi$	5
$J/\psi \to \mathbf{\Sigma^+\bar{\Sigma}^-},\ \Sigma^+(\bar{\Sigma}^-) \to p\pi$	5
$J/\psi \to \mathbf{\Sigma^0\bar{\Sigma}^0},\ \Sigma^0(\bar{\Sigma}^0) \to \Lambda\gamma,\ \Lambda(\bar{\Lambda}) \to p\pi$	7
$J/\psi \to \mathbf{\Xi^-\bar{\Xi}^+},\ \Xi^-(\bar{\Xi}^+) \to \Lambda\pi,\ \Lambda(\bar{\Lambda}) \to p\pi$	9
$J/\psi \to \mathbf{\Xi^0\bar{\Xi}^0},\ \Xi^0(\bar{\Xi}^0) \to \Lambda\pi,\ \Lambda(\bar{\Lambda}) \to p\pi$	9

EDM sensitivity estimation



Jinlin Fu, Haibo Li, et. al, Phys. Rev. D 108, L091301 (2023)

- SM: Hyperon EDM $\sim 10^{-26} e \cdot cm$
- **BESIII: Expected statistics** $\boldsymbol{\sim 10^{-19} e \cdot cm}$
  - Improved $\boldsymbol{\Lambda}$ EDM up-limit (FermiLab[2]: $|d_\Lambda| < 10^{-16} e \cdot cm$)

    Phys. Rev. D 23 (1981) 814–816
  - First measurement on $\boldsymbol{\Sigma}$ and $\boldsymbol{\Xi}$ EDM
- STCF: Improved by 2 order of magnitude

Data set

- 10 billion J/ψ **data** sample at $\sqrt{s} = 3.097\text{GeV}$
  - $(224.0 \pm 1.3)\times 10^6$ events in 2009
  - $(1088.5 \pm 4.4)\times 10^6$ events in 2012
  - $(8874.0 \pm 39.4)\times 10^6$ events in 2017~2019

- After event selection, separately:

Decay channel	BOSS version	Signal yields	Purity
$J/\psi \to \Lambda\bar{\Lambda}$	7.0.5	3,045k	99.9%
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	7.0.8	~ 500k	> 98%
$J/\psi \to \Sigma^0\bar{\Sigma}^0$		~ 1,000k	> 99%
$J/\psi \to \Xi^-\bar{\Xi}^+$		~ 500k	> 99%
$J/\psi \to \Xi^0\bar{\Xi}^0$		~ 300k	> 98%

Monte Carlo Samples

- **Inclusive MC** Sample:
  - 10 billion J/ψ events
  - For background study and event selection optimization
- **PHSP signal MC** Sample:
  - For maximum likelihood fit
- **DIY signal MC** Sample:
  - Input values fixed to published values
  - For data/MC comparison and systematic uncertainty analysis

EDM extraction from angular fit (1)

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Through **maximum likelihood fit**, EDM and other parameters can be extracted simultaneously.

- **Likelihood function**: $$\mathcal{L} = \prod_{i=1}^{N} [\mathcal{P}(\vec{\omega}; \xi^i)]^{S(m_i)} = \prod_{i=1}^{N} [\mathcal{C}\mathcal{W}(\vec{\omega}; \xi^i)\epsilon(\xi^i)]^{S(m_i)}$$
  - **Variables**: Helicity angles event by event
    $\xi^i = (\theta_1^i, \phi_1^i, \theta_2^i, \phi_2^i \ldots)$ for i-th event
  - **Fitting parameters**: Form factors and Decay parameters
    $\vec{\omega} = (Re(G_2), Im(G_2), P_L, Re(F_A), Im(F_A), Re(H_T), Im(H_T), \alpha_B, \alpha_{\bar{B}} \ldots)$
  - **Normalization factor**: Calculated from PHSP MC integral
    $\mathcal{C}^{-1} = \frac{1}{N_{MC}} \sum_{j=1}^{N_{MC}} \mathcal{W}(\vec{\omega}; \xi^j)\epsilon(\xi^j)$

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

EDM extraction from angular fit (2)

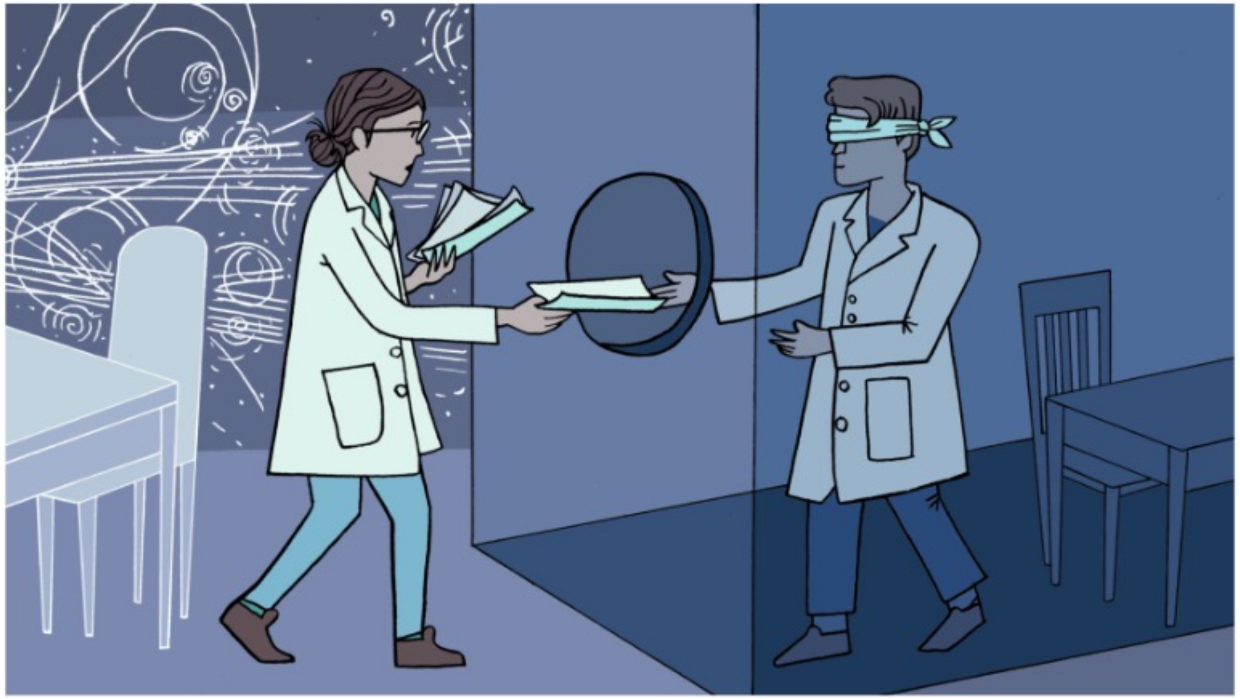
Through **maximum likelihood fit**, EDM and other parameters can be extracted simultaneously.

- **Likelihood function**: $$\mathcal{L} = \prod_{i=1}^{N} [\mathcal{P}(\vec{\omega}; \xi^i)]^{\mathcal{S}(m_i)} = \prod_{i=1}^{N} [C\mathcal{W}(\vec{\omega}; \xi^i)\epsilon(\xi^i)]^{\mathcal{S}(m_i)}$$
  - **Helicity angular distribution**: $\mathcal{W}(\vec{\omega}; \xi^i)$
  - **Detection efficiency:** $\epsilon(\xi^i)$
  - **Signal component:** $$\begin{cases} \mathcal{S}(m_i)_{sig} = 1 \\ \mathcal{S}(m_i)_{bkg} = -1 \end{cases}$$
  - **Minimum function:** $\boldsymbol{S = -ln\mathcal{L}}$

Blind analysis

To avoid personal biases, blind analysis is implemented:

- The mean values of parameter fitting results are blinded.
- The final results will be unblinded prior to publication for cross check.



③ Results

Λ EDM in $J/\psi \to \Lambda\bar{\Lambda}$ decays

Parameters	Fitting results
α_Λ	$(7.524 \pm 0.036 \pm 0.008) \times 10^{-1}$
$\alpha_{\bar{\Lambda}}$	$(-7.571 \pm 0.036 \pm 0.008) \times 10^{-1}$
$Re(G_2)$	$(9.71 \pm 0.06 \pm 0.24) \times 10^{-4}$
$Im(G_2)$	$(9.14 \pm 0.04 \pm 0.23) \times 10^{-4}$
P_L	$(-1.8 \pm 1.2 \pm 0.8) \times 10^{-3}$
$Re(F_A)$	$(-2.4 \pm 1.6 \pm 3.1) \times 10^{-6}$
$Im(F_A)$	$(-7.9 \pm 3.7 \pm 2.5) \times 10^{-6}$
$Re(H_T)$	$(-1.4 \pm 1.4 \pm 0.2) \times 10^{-6}/\text{GeV}$
$Im(H_T)$	$(1.3 \pm 1.2 \pm 0.4) \times 10^{-6}/\text{GeV}$
$\alpha_{J/\psi}$	$(4.748 \pm 0.022 \pm 0.017) \times 10^{-1}$
$\Delta\Phi$	$(7.522 \pm 0.042 \pm 0.013) \times 10^{-1}$
A_{CP}^{Λ}	$(-3.1 \pm 4.6 \pm 1.1) \times 10^{-3}$
$\sin^2(\theta_W)$	$(-1.5 \pm 1.2 \pm 2.6) \times 10^{-1}$
$Re(d_\Lambda)$	$(-3.1 \pm 3.2 \pm 0.5) \times 10^{-19}\text{e}\cdot\text{cm}$
$Im(d_\Lambda)$	$(2.9 \pm 2.6 \pm 0.6) \times 10^{-19}\text{e}\cdot\text{cm}$

- Reminder:

$$H_T = \frac{2e}{3m_{J/\psi}^2} g_V d_\Lambda$$

- **The upper limit of Λ EDM @95%C.L.**

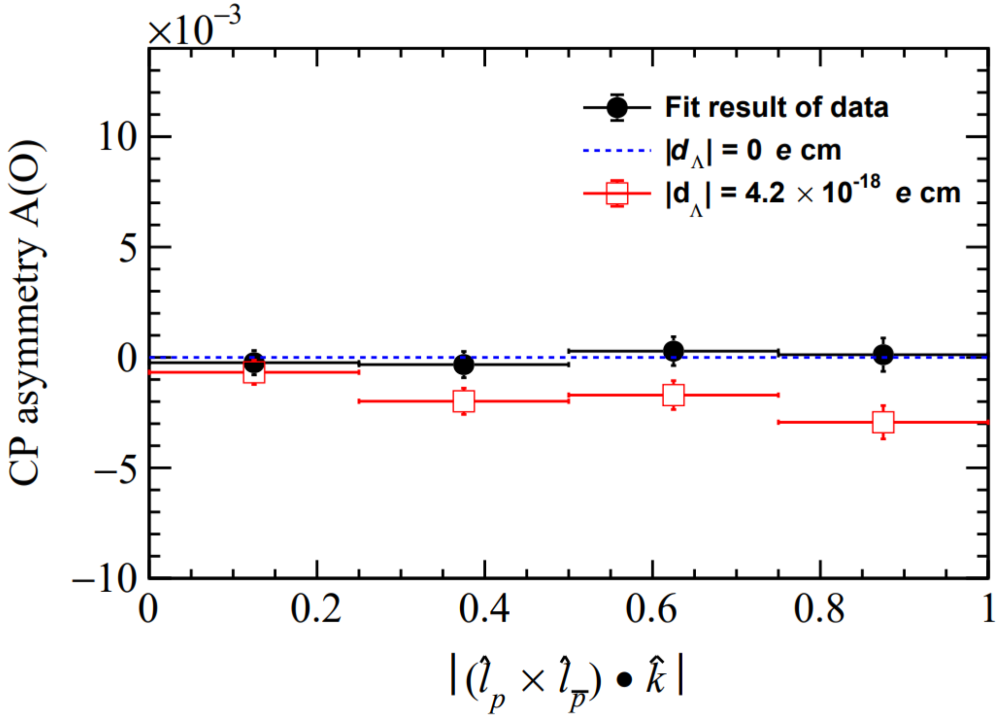
$$-8.6 \times 10^{-19} < Re(d_\Lambda) < 3.3 \times 10^{-19}\ e\ \text{cm},$$

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

$$|d_\Lambda| < 6.5 \times 10^{-19} e\ cm$$

arXiv:2506.19180 [hep-ex](2025)

Λ EDM visualization



- **Triple-product asymmetry (TPA):**

$$O \equiv \left(\hat{l}_p \times \hat{l}_{\bar{p}}\right) \cdot \hat{k} \sim Re(H_T)$$

  - $\hat{l}_p(\hat{l}_{\bar{p}})$: unit momentum of $p(\bar{p})$ in $\Lambda(\bar{\Lambda})$ rest frame
  - $\hat{k}$: unit momentum of Λ in the center-of-mass frame of e^+e^- system.

- **Asymmetry of TPA:**

$$A(O) = \frac{N_{\text{event}}(O>0) - N_{\text{event}}(O<0)}{N_{\text{event}}(O>0) + N_{\text{event}}(O<0)}$$

arXiv:2506.19180 [hep-ex](2025)

Constrain on fundamental parameters

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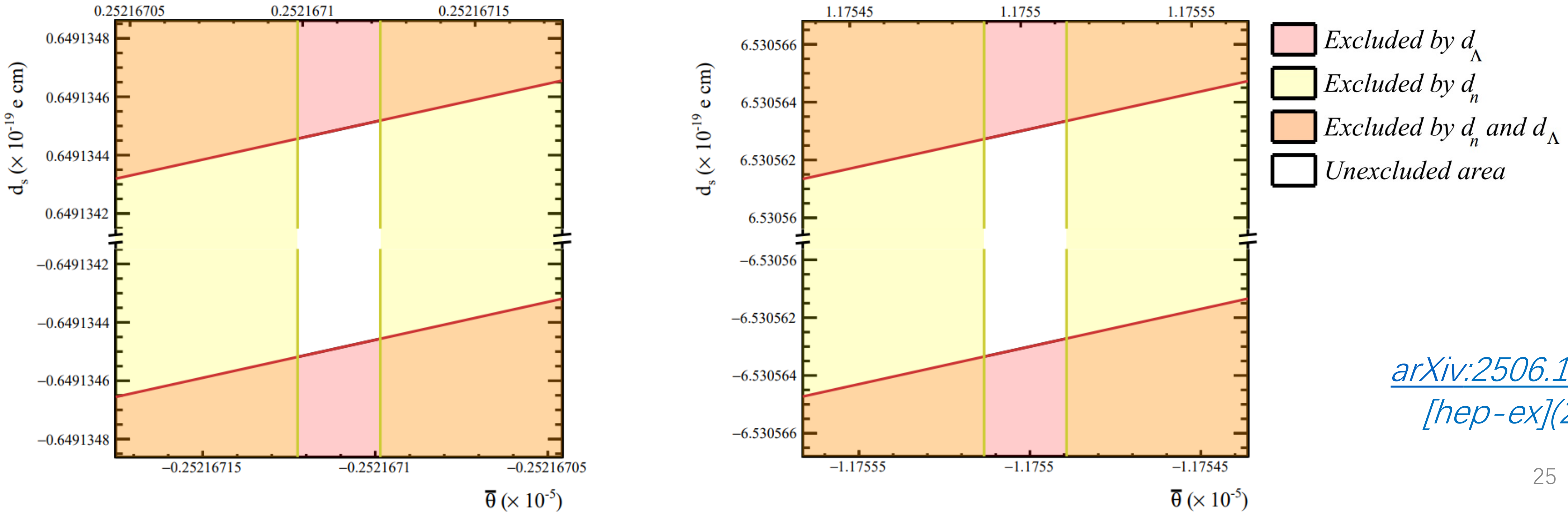
Theoretically:

$$\boldsymbol{d_\Lambda} = (-2.6 \pm 0.4) \times 10^{-16} \boldsymbol{\bar{\theta}} e \cdot cm + \boldsymbol{d_s}$$

$$\boldsymbol{d_n} = (-1.5 \pm 0.7) \times 10^{-16} \boldsymbol{\bar{\theta}} e \cdot cm - (0.20 \pm 0.01) d_u + (0.78 \pm 0.03) d_d + (0.0027 \pm 0.016) \boldsymbol{d_s}$$

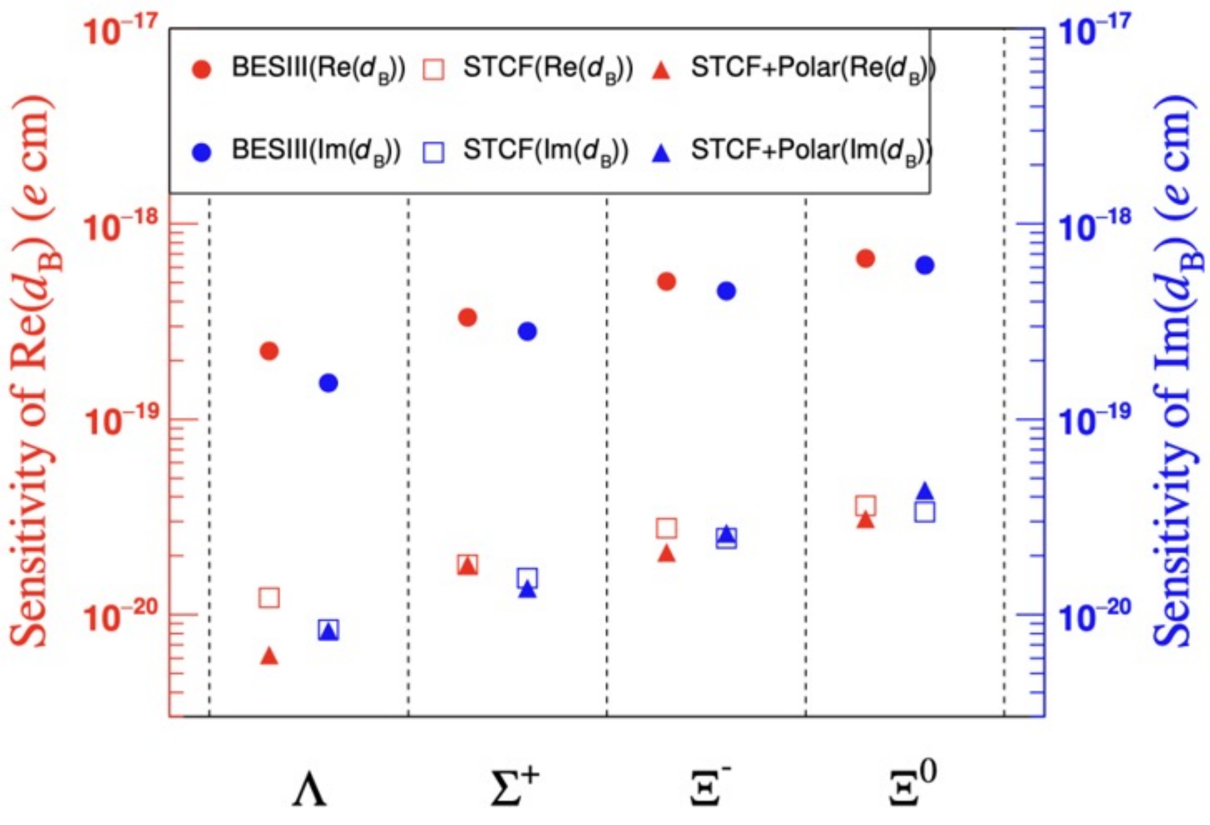
Constrain with/without $SU(3)$ flavor symmetry:

$d_s = d_u = d_d$ $\qquad\qquad$ $d_s \gg d_u, d_d$



arXiv:2506.19180 [hep-ex](2025)

Hyperon EDM sensitivity

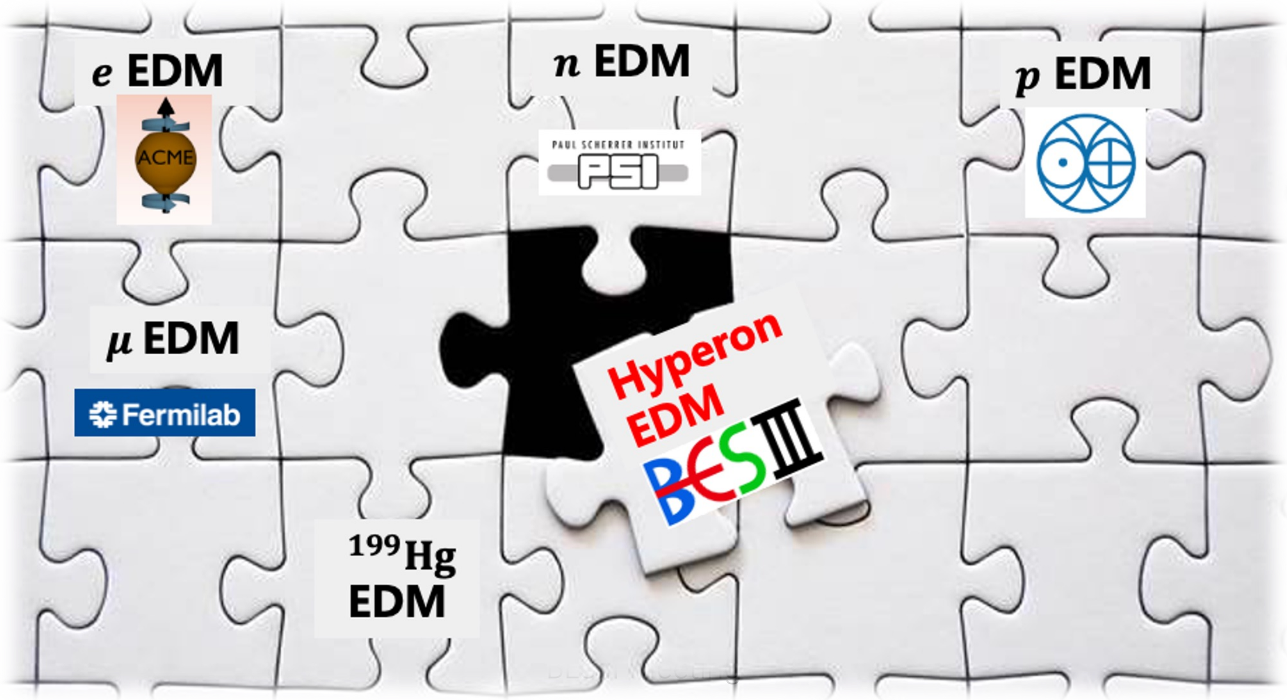


Jinlin Fu, Haibo Li, et. al, Phys. Rev. D 108, L091301 (2023)

- Statistical uncertainty of hyperon EDM has reached $\sim 10^{-19} e \cdot cm$ based on BESIII data sample.
- Analysis on $\Sigma^+, \Sigma^0, \Xi^-, \Xi^0$ EDM is ongoing.

④ Summary

- Electric Dipole Moment (EDM) is a key probe for new CPV beyond SM.
- BESIII delivers abundant quantum-correlated J/ψ events, enabling global EDM analysis on hyperon system.
- This work fills a critical gap in hyperon EDM measurement, setting stronger constraints on fundamental parameters.



Thank you!

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