Testing the Anomalous Color-Electric Dipole Moment of the charm Quark

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CP violation and electric dipole moment

- CP violation in standard model is far too small to explain the matter and antimatter asymmetry. Searching for new CP violation source is one of the most interesting projects in particle physics.
- New theories beyond SM can induce new CP violation terms, At low energy, they could generate electric and color electric dipole operators in loop diagrams.

$$L_{EDM} = -\frac{i}{2} d_c \bar{\psi} \sigma_{\mu\nu} \gamma_5 \psi F^{\mu\nu}$$

- Electric dipole moment of charm quark may provide new CP violation source and constrain the parameters of new physics.

Chromoelectric dipole moment of charm quark

Experiment status

- Electric dipole moments of some element particles are found to be very small. [PDG 2012]

$$d_n < 0.29 \times 10^{-25} e \cdot cm (90\% CL)$$

- BESII has accumulated large data sample of $\psi' \longrightarrow J/\psi + \pi^+\pi^-$.
- BESIII will collect more data with higher accuracy.

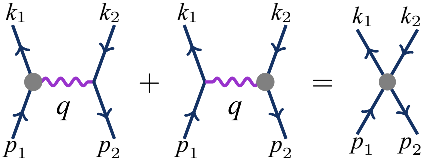
The study of this transition process may provide some information about the color electric dipole moment of charm quark.

Potential model

- Initial and Final charmonium states without CEDM. θ is mixing angle, determined from leptonic decay rate.

$$\psi' = cos\theta|2^3S_1\rangle + sin\theta|1^3D_1\rangle$$
$$J/\psi = |1^3S_1\rangle$$

- CEDM will modify the potential.



$$V_{cEDM}(\vec{r}) \simeq d_c \frac{(\sigma - \bar{\sigma}) \cdot \vec{r}}{r^3}$$

Potential model

- Energy shift

$$\triangle E =_0 \langle n^{2s+1}L_J | V_{CEDM} | n^{2s+1}L_J \rangle_0 = 0$$

- State mixing

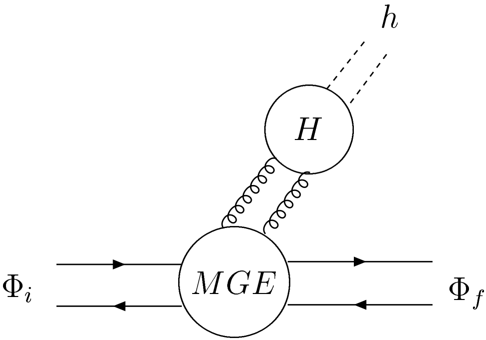
$$|n^3S_1\rangle = C_{n0}^{n0}|n^3S_1\rangle_0 + C_{n0}^{11}|1^1P_1\rangle_0 + \ldots$$
$$|1^3D_1\rangle = C_{12}^{12}|1^3D_1\rangle_0 + C_{12}^{11}|1^1P_1\rangle_0 + \ldots$$

- Order of Coefficients

$$C_{n0}^{n0} = 1 + O(d_c^2) \quad C_{12}^{12} = 1 + O(d_c^2)$$
$$C_{n0}^{11} = O(d_c) \quad C_{12}^{11} = O(d_c)$$

QCDME

The decay process described by QCDME. Amplitude contains two factor: MGE + H [PhysRevD.24.2874]



QCDME

For $\Psi(2^3S_1) \to J/\Psi(1^3S_1)\pi\pi$ and $\Psi(1^3D_1) \to J/\Psi(1^3S_1)\pi\pi$, the decay channel is E1E1.

$$M = M_{ij}\langle\pi\pi|E_iE_j|0\rangle$$

And we parameterized the hadronization factor as

$$\langle\pi\pi|E_iE_j|0\rangle = \frac{1}{\sqrt{2\omega_1 2\omega_2}}[(Aq_1^{\mu}q_{2\mu} + B\omega_1\omega_2)\delta_{ij}$$
$$+C(q_{1i}q_{2j} + q_{1j}q_{2i} - \frac{2}{3}\vec{q}_1 \cdot \vec{q}_2\delta_{ij})]$$

QCDME of CEDM

- CEDM induced new decay channels. The effective vertex in non-relativistic limit

$$CEDM: \qquad -i\frac{d_c}{2}(\boldsymbol{\sigma}-\bar{\boldsymbol{\sigma}})\cdot\boldsymbol{E}$$

- New decay channels

$$\text{M1CEDM1}: \quad |2^3S_1\rangle \longrightarrow |1^3S_1\rangle$$
$$\text{E1CEDM2}: \quad cos\theta|2^3S_1\rangle + sin\theta|1^3D_1\rangle \longrightarrow |1^3S_1\rangle$$

- Amplitude of M1CEDM1:

$$M_{M1CEDM1} = M_{ij}\langle\pi\pi|B_iE_j|0\rangle$$
$$\langle\pi\pi|B_iE_j|0\rangle \simeq \mathcal{K}_{M1CEDM1}[(\vec{q}_1-\vec{q}_2)_i(\vec{q}_1\times\vec{q}_2)_j + (\vec{q}_1-\vec{q}_2)_j(\vec{q}_1\times\vec{q}_2)_i]$$

- Remain Problem: How to calculate $\mathcal{K}_{M1CEDM1}$

Calculate the $\mathcal{K}_{M1CEDM1}$

- Hadronization factor: insert a complete set of intermedia states $|N\rangle$

$$\langle \pi\pi|E_iE_j|0\rangle = \sum_N \langle\pi\pi|N\rangle\langle N|E_iE_j|0\rangle$$

- 2GA assumes that the 2-gluon state $|N\rangle = |g^c g^c\rangle$ dominate.

$$\langle \pi\pi|E_iE_j|0\rangle \simeq \langle\pi\pi|g^c g^c\rangle\langle g^c g^c|E_iE_j|0\rangle$$

$$\langle\pi\pi|g^c g^c\rangle \simeq constant$$

$$\langle g^c g^c|E_iE_j|0\rangle = -\frac{\omega_1\omega_2}{\sqrt{2\omega_1 2\omega_2}}[\vec{\epsilon}_{1,i}(\lambda_1)\vec{\epsilon}_{2,j}(\lambda_2) + \vec{\epsilon}_{1,i}(\lambda_1)\vec{\epsilon}_{2,j}(\lambda_2)]$$

- At last, we can calculate $\mathcal{K}_{M1CEDM1}$ by comparing with E1E1 process

$$\frac{\Gamma_{M1EDM1}|_{2GA}}{\Gamma_{M1EDM1}|_{SPA}} = \frac{\Gamma_{E1E1}|_{2GA}}{\Gamma_{E1E}|_{SPA}}$$

Total decay channels

- E1E1: $C_{20}^{20}, C_{12}^{12}, C_{10}^{10} = 1 + O(d_c^2)$

$$cos\theta C_{20}^{20}|2^3S_1\rangle + sin\theta C_{12}^{12}|1^3D_1\rangle \longrightarrow C_{10}^{10}|1^3S_1\rangle$$

- E1M1: $C_{20}^{11} = O(d_c)$

$$\left(cos\theta C_{20}^{11} + sin\theta C_{10}^{11}\right)|1^1P_1\rangle \longrightarrow C_{10}^{10}|1^3S_1\rangle$$

$$cos\theta C_{20}^{20}|2^3S_1\rangle + sin\theta C_{12}^{12}|1^3D_1\rangle \longrightarrow C_{20}^{12}|1^1P_1\rangle$$

- M1CEDM1: $O(d_c)$

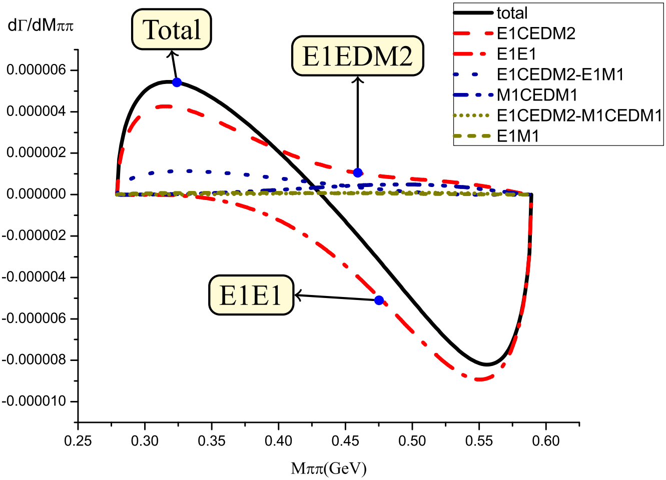
$$cos\theta|2^3S_1\rangle \rightarrow |1^3S_1\rangle$$

- E1CEDM2: $O(d_c)$

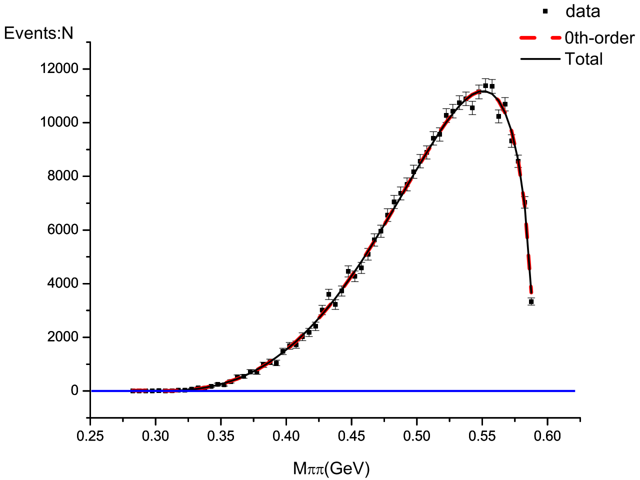
$$cos\theta|2^3S_1\rangle + sin\theta|1^3D_1\rangle \rightarrow |1^3S_1\rangle$$

- Interference: E1M1--E1CEDM2, M1CEDM1--E1CEDM2

CEDM contribution

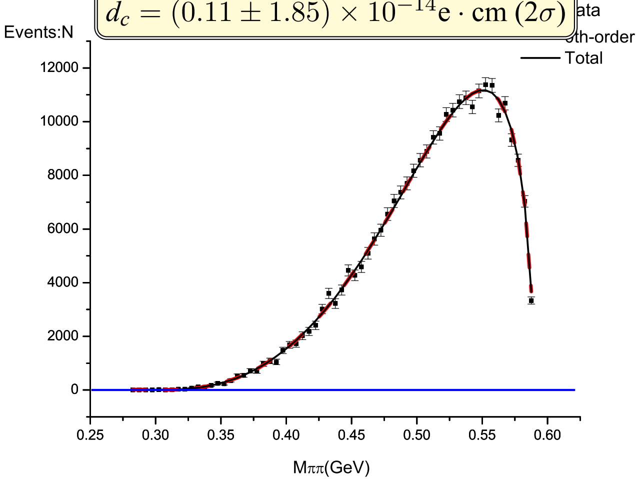


Fit with data



Fit with data

$$d_c = (0.11 \pm 1.85) \times 10^{-14} \mathrm{e} \cdot \mathrm{cm}\ (2\sigma)$$



Result Analysis

- Fitting result:
  1. Central value: $\mathbf{1.10 \times 10^{-15}}$e·cm
  2. 2σ bound: $\mathbf{1.96 \times 10^{-14}}$e · cm
- Analysis
  1. Still consistent with zero.
  2. Model dependence: 12%. Comparing result of Cornell potential and Chen-kuang potential [PhysRevD.46.1165]
  3. Soft pion coefficients $\mathcal{K}$ lead to 34% ~ 40% uncertainty.

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  3. Soft pion coefficients $\mathcal{K}$ lead to 34% ~ 40% uncertainty.
- Conclusion: First experimentally determined upper bound (95%C.L.)

$$|d_c| < 3 \times 10^{-14} \mathrm{e} \cdot \mathrm{cm}$$

CP odd operator

- Construct CP-odd operator for process $e^+e^- \to \psi' \to J/\psi\pi^+\pi^-$

$$\mathcal{O} = \hat{p}\cdot(\vec{q}_1 - \vec{q}_2)\hat{p}\cdot\frac{\vec{q}_1\times\vec{q}_2}{|\vec{q}_1\times\vec{q}_2|}$$

- The exceptation value of operator $\mathcal{O}$ is zero for E1E1 channel because it violate CP. The lowest non-zero contribution comes from interference between E1E1 and CEDM channels.
- Numerical result

$$\langle\mathcal{O}\rangle = \frac{\mathcal{A}d_c}{1000m_c}\Big\{2.534\mathcal{K}_{M1CEDM1} - 0.964\mathcal{K}_{E1CEDM2} + \frac{\mathcal{C}}{\mathcal{A}}[0.0123\mathcal{K}_{E1M1} + 0.0715\mathcal{K}_{M1EDM1} + 0.321\mathcal{K}_{E1CEDM2}]\Big\} = 0.63\times10^{-2}d_c$$

- This test is much more sensitive, BES will try to measure the asymmetry observable $A_{\mathcal{O}}$

$$A_{\mathcal{O}} = [N_{events}(\mathcal{O}>0) - N_{events}(\mathcal{O}<0)]/[N_{events}(\mathcal{O}>0) + N_{events}(\mathcal{O}<0)]$$

Conclusion and outlook

- We get the upper bound of $|d_c| < 3 \times 10^{-14}$e $\cdot$ cm at 2σ C.L.
- This result is very large compared with other particles. It is still possible to find non zero CEDM in charm quark.
- BESIII will accumulate more events with higher accuracy, especially at the low momentum region, this could greatly improve our result in future.
- The measurement of the CP-odd operator could determine the dc to a higher precision.

The End

Thank You