Improved bounds on heavy quark EDMs

Héctor Gisbert

TU Dortmund

In collaboration with Joan Ruiz Vidal.

Based on Phys.Rev.D 101 (2020) 11, 115010.

PANIC, September 5, 2021.

Electric dipole moments probing BSM physics

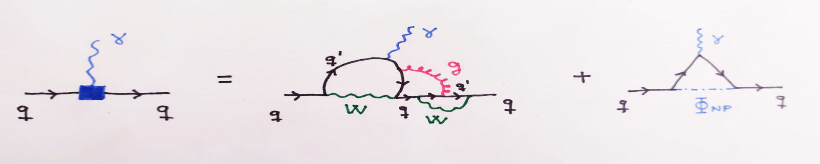
1. Almost all experimental data is well-explained by SM! but clear shortcomings in the SM...

Baryon asymmetry of the Universe

⋆ Observed: $\left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_{\rm exp} \sim 10^{-10}$ ⋆ SM: $\left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_{\rm SM} \sim 10^{-18}$

2. Sakharov conditions $\rightarrow$ CPV beyond the SM must exist!

3. $\boxed{\text{Electric dipole moments}}$ Sensitive to CPV! Any signal is BSM!



- LO SM contribution 3-loop!
- Current experimental upper limits well above its SM predictions!

4. B-anomalies ($b \rightarrow c\,\tau\,\bar{\nu}_\ell$ & $b \rightarrow s\,\ell^-\,\ell^+$) suggest a non-trivial flavor structure which could enhance the heavy quark EDMs!

Effective Theory Framework

- **Lagrangian:**

$$\mathcal{L}_{\text{eff}} = \sum_{i=1}^{2} \sum_{q} C_i^q(\mu)\, O_i^q(\mu) \;+\; C_3(\mu)\, O_3(\mu)$$

- **Operators:**

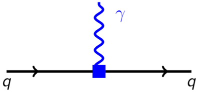
$$O_1^q \equiv -\frac{i}{2}\, e\, Q_q\, m_q\, \bar{q}^\alpha\, \sigma^{\mu\nu}\gamma_5\, q^\alpha\, F_{\mu\nu}$$

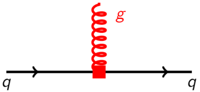
$$O_2^q \equiv -\frac{i}{2}\, g_s\, m_q\, \bar{q}^\alpha\, \sigma^{\mu\nu}\, T_a\, \gamma_5\, q^\alpha\, G^a_{\mu\nu}$$

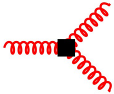
$$O_3 \equiv -\frac{1}{6}\, g_s\, f_{abc}\, \epsilon^{\mu\nu\lambda\sigma}\, G^a_{\mu\rho}\, G^{b\rho}_{\nu}\, G^c_{\lambda\sigma}$$

- **Wilson coefficients: EDM , CEDM , Weinberg .**

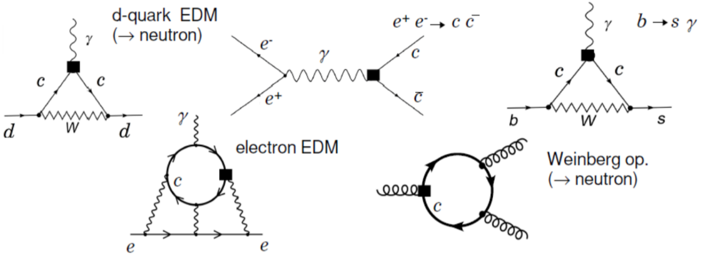
$$d_q(\mu) = e\, Q_q\, m_q(\mu)\, C_1^q(\mu)\,, \quad \widetilde{d}_q(\mu) = m_q(\mu)\, C_2^q(\mu)\,, \quad \omega(\mu) = -\frac{1}{2}\, g_s(\mu)\, C_3(\mu)\,.$$







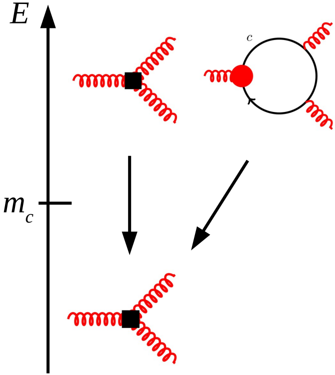
Indirect bounds on charm EDM



Bound	Ref.	Measurement	Method
$\boldsymbol{\lvert d_c\rvert < 4.4 \times 10^{-17}}$ ***e* cm**	Sala:2013osa	neutron EDM	Considers threshold contributions of d_c into d_d via $W^{\pm}$ loops.
$\lvert d_c\rvert < 3.4 \times 10^{-16}$ e cm	Sala:2013osa	BR($B \to X_s\gamma$)	Considers contributions from d_c to the Wilson coefficient C_7.
$\lvert d_c\rvert < 3 \times 10^{-16}$ e cm	Grozin:2009jq	electron EDM	Extracted from d_c threshold contribution to d_e through light-by-light scattering diagrams.
$\lvert d_c\rvert < 1 \times 10^{-15}$ e cm	Grozin:2009jq	neutron EDM	Similar approach than Ref. Sala:2013osa. Evaluates contributions in two steps: c-quark $\to$ d-quark $\to$ neutron.
$\lvert d_c\rvert < 5 \times 10^{-17}$ e cm	Blinov:2008mu	$e^+e^- \to c\bar{c}$	The total cross section (LEP) can be enhanced by the c-quark EDM vertex $c\bar{c}\gamma$.
$\lvert d_c\rvert < 8.9 \times 10^{-17}$ e cm	Escribano:1993xr	$\Gamma(Z \to c\bar{c})$	Measurement at the Z peak (LEP). Uses model dependent relationships to weight contributions from d_c and d_c^w.

Indirect bound on charm chromo-EDM

F. Sala, JHEP 03 (2014) 061



1. **Threshold contribution** of chromo-EDM into Weinberg operator:

$$\omega(m_c^-) = \omega(m_c^+) + \frac{g_s^3}{32\,\pi^2\,m_c}\tilde{d}_c(m_c^+)$$

2. Contribution of Weinberg operator to neutron EDM (**QCD sum rules**):

$$d_n = [\ldots]\, d_{u,d}(\mu_{\text{had}}) + [\ldots]\, \tilde{d}_{u,d}(\mu_{\text{had}})$$

$$+(22 \pm 10)\ \text{MeV}\ e\,\omega(\mu_{\text{had}})$$

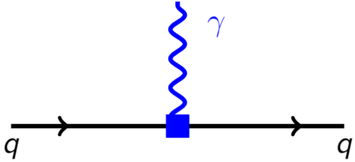
3. Assuming constructive interference:

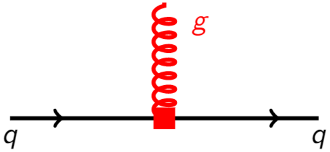
$$|\tilde{d}_c| \lesssim 1.0 \times 10^{-22}\ \text{cm}$$

Indirect bounds on bottom (chromo-) EDM

Bottom EDM			
Bound	Ref.	Measurement	Method
$\lvert d_b \rvert < 7 \times 10^{-15}$ e cm	Grozin:2009jq	electron EDM	From the b-quark EDM threshold contribution to d_e through light-by-light scattering diagrams
$\lvert d_b \rvert < 2 \times 10^{-12}$ e cm	Grozin:2009jq	neutron EDM	Similar estimation but evaluating contributions in two steps: b-quark $\to$ up-quark $\to$ neutron
$\boldsymbol{\lvert d_b \rvert < 2 \times 10^{-17}}$ $\boldsymbol{e}$ **cm**	Blinov:2008mu	$e^+e^- \to b\bar{b}$	The total cross section (LEP) might be enhanced by the charm qEDM vertex $b\bar{b}\gamma$.
$\lvert d_b \rvert < 1.22 \times 10^{-13}$ e cm	CorderoCid:2007uc	neutron EDM	Similar estimation than Grozin:2009jq. But neglects longitudinal component in the W propagator, thus missing emerging divergences.
$\lvert d_b \rvert < 8.9 \times 10^{-17}$ e cm	Escribano:1993xr	$\Gamma(Z \to b\bar{b})$	Measurement at the Z peak (LEP). Uses model dependent relationships to weight contributions from d_b and d_b^w.
Bottom chromo-EDM			
Bound	Ref.	Measurement	Method
$\boldsymbol{\lvert \tilde{d}_b \rvert \lesssim 1.1 \times 10^{-21}}$ **cm**	Konig:2014iqa	neutron EDM	Numerical result based on the the contribution of the beauty CEDM into the Weinberg operator derived in Chang:1990jv

Summary of bounds on heavy quark (chromo-) EDM





$$\Downarrow$$

$$|d_c(m_c)| < 4.4 \times 10^{-17}\, e\,\text{cm}$$
$$|d_b(m_b)| < 2.0 \times 10^{-17}\, e\,\text{cm}$$

$$\overset{?}{\Longrightarrow}$$

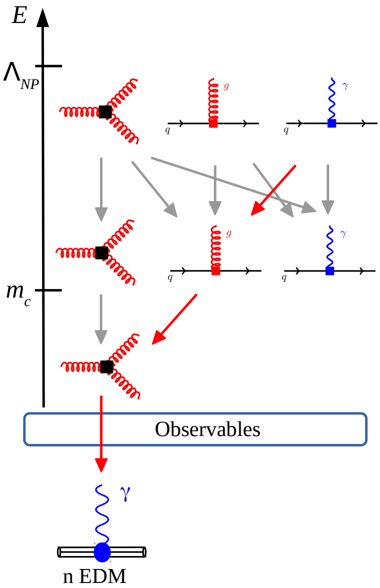
$$\Downarrow$$

$$|\tilde{d}_c(m_c)| < 1.0 \times 10^{-22}\,\text{cm}$$
$$|\tilde{d}_b(m_b)| < 1.1 \times 10^{-21}\,\text{cm}$$

5 orders of magnitude of difference between them!

Is there any way to relate them?

Operator mixing under RGEs



- **RGEs:** $\vec{C} \equiv (d_q,\ \tilde{d}_q,\ \omega)$

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\,\vec{C}(\mu) = \hat{\gamma}^{\mathrm{T}}\,\vec{C}(\mu)$$

- **Anomalous dimension:**

$$\hat{\gamma} = \frac{\alpha_s}{4\,\pi}\,\gamma_s^{(0)} + \left(\frac{\alpha_s}{4\,\pi}\right)^2 \gamma_s^{(1)} + \frac{\alpha_e}{4\,\pi}\,\gamma_e^{(0)} + \cdots$$

$$\gamma_s^{(0)} = \begin{bmatrix} 8\,C_F & 0 & 0 \\ 8\,C_F & 16\,C_F - 4\,N_C & 0 \\ 0 & -2\,N_C & N_C + 2f + \beta_0 \end{bmatrix}$$

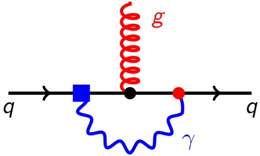
$$\gamma_s^{(1)} = \begin{bmatrix} \times & 0 & 0 \\ \times & \times & 0 \\ \times & \times & \times \end{bmatrix}$$

YES! QED corrections are small (10^{-2}) but there is a wide margin for improvement (10^{-5})!

How do we extract the bounds?

Quark EDM does not mix into the chromo-EDM, first contribution only appears at $\mathcal{O}(\alpha_e)$ from photon-loop diagrams:

1. **Computation of $(\gamma_e)_{12}^{(0)}$ applying the standard techniques:**



$+$

$\Longrightarrow$ $\boxed{(\gamma_e)_{12}^{(0)} = 8}$

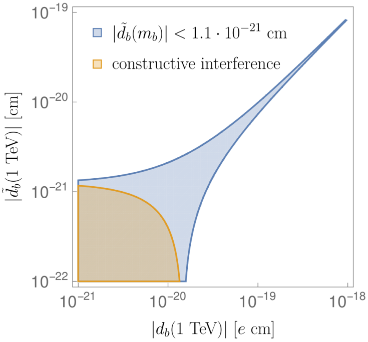
2. **Evolution of charm and bottom chromo-EDMs ($M_{\text{NP}} \sim 1\,\text{TeV}$):**

$$\tilde{d}_c(m_c) = -0.04\,\frac{d_c(M_{\text{NP}})}{e} + 0.74\,\tilde{d}_c(M_{\text{NP}}) + \ldots$$

$$\tilde{d}_b(m_b) = 0.08\,\frac{d_b(M_{\text{NP}})}{e} + 0.88\,\tilde{d}_b(M_{\text{NP}}) + \ldots$$

Mixing of ω into $\tilde{d}_q$ is neglected due to the strong bounds from the neutron EDM.

Improved limits on heavy quark EDMs



Assuming constructive interference:

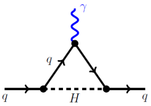
$$|d_c(m_c)| < 4.4 \times 10^{-17}\, e\,\mathrm{cm} \qquad \Longrightarrow \qquad |d_c(m_c)| < 1.5 \times 10^{-21}\, e\,\mathrm{cm}$$

$$|d_b(m_b)| < 2.0 \times 10^{-17}\, e\,\mathrm{cm} \qquad\qquad\qquad |d_b(m_b)| < 1.2 \times 10^{-20}\, e\,\mathrm{cm}$$

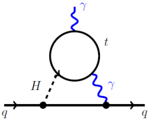
Higher values of the NP scale, *e.g.* $M_{\mathrm{NP}} = 10$ TeV, yield a 30% stronger bounds!

Implications for BSM of the new bounds

1. **THDM:**
   - Aligned to avoid FCNCs at tree level ($Y_d = \varsigma_d M_d$, $Y_u = \varsigma_u^\dagger M_u$).
   - d_q arise at one-loop level mediated by neutral or charged scalars:

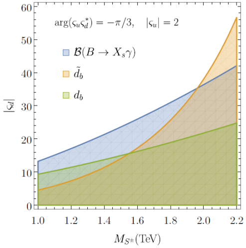


$d_q \propto m_q^3/m_H^2$



$d_q \propto m_q \frac{\alpha}{\pi}$

   - Mass factors suppress $d_{u,d}$, dominated by two-loop Barr-Zee diagrams.
   - Heavy quark EDMs are much larger and, even with weaker experimental bounds, they can be more restrictive.



e.g. d_b in color octet scalars (Manohar-Wise model):

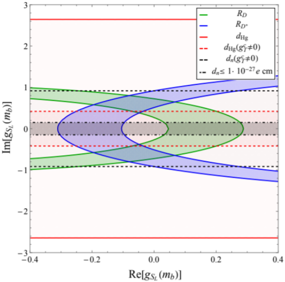
- $\mathcal{B}(B \to X_s\gamma)$ dominates the constraints!
- Our d_b bounds are more restrictive than $\mathcal{B}(B \to X_s\gamma)$ and even surpass $\tilde{d}_b$ for $M_{S^\pm} \gtrsim 1.5$ TeV!
- New d_b bound dominate constraints for $\arg(\varsigma_u \varsigma_d^*) \gtrsim 15°$!
- Needs full phenomenological analysis of EDMs in MW model including further operators.

Implications for BSM of the new bounds

2. **Scalar leptoquarks:**
   - Two scalar leptoquarks (R_2 and S_3) with UV-completion (1806.05689).
   - Can explain the anomalies in $b \to c\,\tau\,\bar{\nu}_\ell$ and $b \to s\,\ell^-\,\ell^+$ transitions.
   - R_2 leptoquark generates a rich EDM phenomenology!
   - $\mathrm{Im}(g_{S_L})$ arises from the LQ couplings that generate the charm EDM:

$$\mathcal{L}_{\text{eff}} \supset -\frac{4\,G_F}{\sqrt{2}}\,V_{cb}\,g_{S_L}\,(\bar{c}_R b_L)\,(\bar{\tau}_R \nu_\tau)$$

   - Direct link between $b \to c\,\tau\,\bar{\nu}_\ell$ transitions and EDMs (1809.09114).



- Combining R_D and R_{D^*} results in allowed regions for g_{S_L} which induce a sizeable d_c!
- If no signal is observed in the planned d_n experiments, $10^{-27}\,e\,\mathrm{cm}$ (1710.02504), the resulting upper limits on d_c (extracted with the method presented here) will rule out this model as an explanation for the B-anomalies.

Conclusions

- NP models with additional CP violation sources are currently being constrained by searches for EDMs.
- Using the stringent limits on their chromo-EDMs, new bounds on the EDM of charm and bottom quarks have been derived
- The new limits improve the previous ones by about three orders of magnitude:

$$\begin{aligned} |d_c(m_c)| &< 4.4 \times 10^{-17}\, e\,\mathrm{cm} \\ |d_b(m_b)| &< 2.0 \times 10^{-17}\, e\,\mathrm{cm} \end{aligned} \quad \Longrightarrow \quad \begin{aligned} |d_c(m_c)| &< 1.5 \times 10^{-21}\, e\,\mathrm{cm} \\ |d_b(m_b)| &< 1.2 \times 10^{-20}\, e\,\mathrm{cm} \end{aligned}$$

- The implications for different Standard Model extensions have been discussed.