Confronting Higgcision with EDMs

JAE SIK LEE

Chonnam National University, Gwangju

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* based on K. Cheung, JSL, E. Senaha, P.-Y. Tseng, JHEP 1406 (2014) 149 [arXiv:1403.4775]

♠ *Preliminary*

- If the Higgs boson is a CP-mixed state, it couples to the fermions as follows:

$$\mathcal{L}_{H\bar{f}f} = -g_f\, H\, \bar{f}\left(g^S_{H\bar{f}f} + i g^P_{H\bar{f}f}\gamma_5\right) f \,,$$

$$\mathcal{L}_{HVV} = g\, M_W\, g_{HVV}\left(W^+_\mu W^{-\mu} + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu\right) H$$

where $g_f = g m_f/2M_W = m_f/v$ with $f = u, d, l$ denoting the up- and down-type quarks and charged leptons collectively.

- Then, the non-vanishing values of the products

$$g^S_{H\bar{f}f} \times g^P_{H\bar{f}^{(\prime)}f^{(\prime)}} \quad \text{and} \quad g_{HVV} \times g^P_{H\bar{f}f}$$

signal CP violation and give rise to nonzero values for electric dipole moments (EDMs)

♠ *Preliminary*

- The LHC Higgs data constrain the Higgs couplings to the third-generation quarks and leptons
- On the other hand, the EDM experiments mainly involve the first-generation fermions

Our aim is to study the implication of the Higgs data (Higgcision) on EDMs in the framework of two-Higgs-doublet models (2HDMs)

♠ *Contents*

♠ *Higgcision*

- Higgcision : Higgs Precision Cheung, JSL, Tseng
  - *"Higgcision Era begins"* JHEP 1305 (2013) 134 [arXiv:1302.3794]
  - *"Higgcision in the 2HDMs"* JHEP 1401 (2014) 085 [arXiv:1310.3937]
  - *"Higgcision Updates 2014"* to appear in PRD [arXiv:1407.8236]
  - *"Higgcision in ..."* in preparation
- The constraints on the Higgs couplings from the Higgs data:

$$C_u^S \equiv g^S_{H\bar{t}t}\,; \quad C_u^P \equiv g^P_{H\bar{t}t}\,; \quad C_v \equiv g_{HVV}$$

♠ *Higgcision*

- Relations among the Higgs couplings to fermions (2HDMs): generation independent & no tree-level FCNC

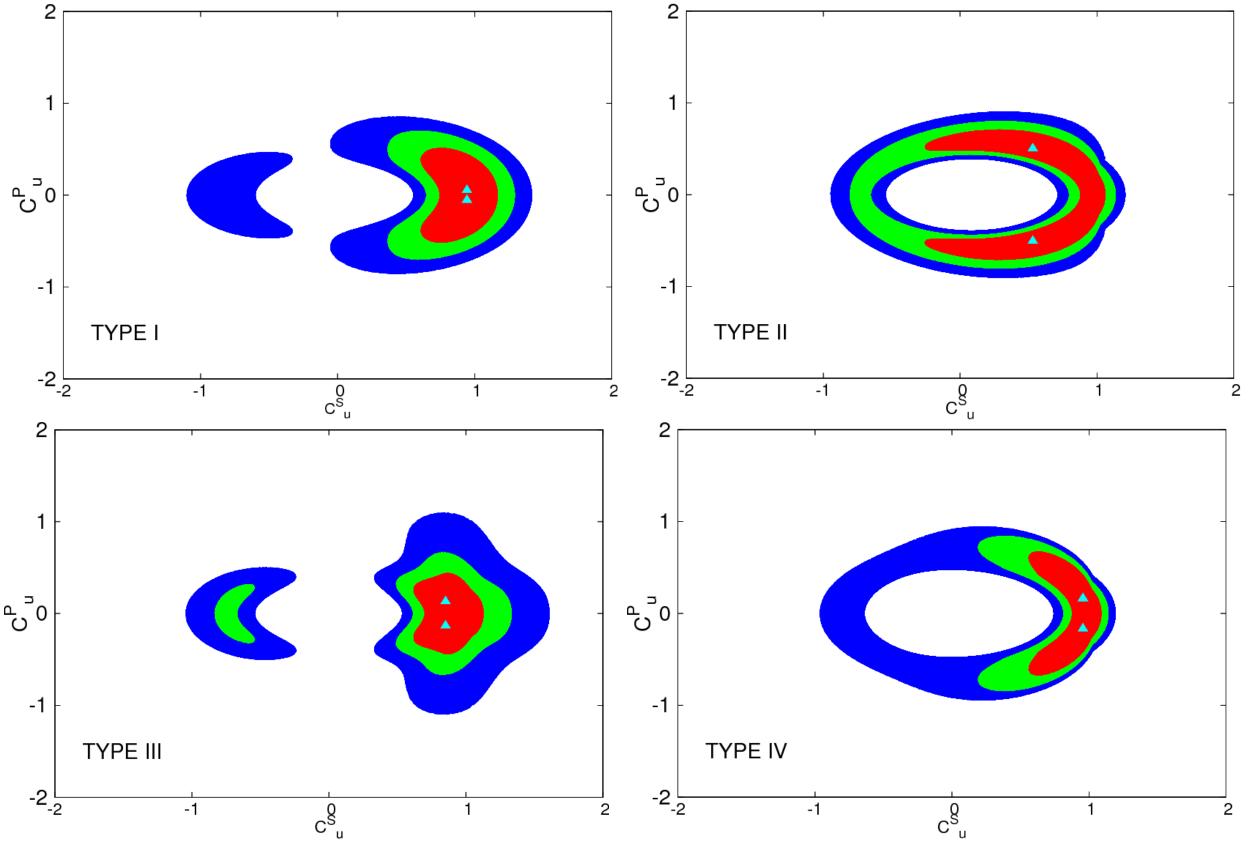
2HDM I	$C_d^S = C_u^S$	$C_l^S = C_u^S$	$C_d^P = -C_u^P$	$C_l^P = -C_u^P$
2HDM II	$C_d^S = \frac{O_{\phi_1 i}}{c_\beta}$	$C_l^S = \frac{O_{\phi_1 i}}{c_\beta}$	$C_d^P = t_\beta^2 C_u^P$	$C_l^P = t_\beta^2 C_u^P$
2HDM III	$C_d^S = C_u^S$	$C_l^S = \frac{O_{\phi_1 i}}{c_\beta}$	$C_d^P = -C_u^P$	$C_l^P = t_\beta^2 C_u^P$
2HDM IV	$C_d^S = \frac{O_{\phi_1 i}}{c_\beta}$	$C_l^S = C_u^S$	$C_d^P = t_\beta^2 C_u^P$	$C_l^P = -C_u^P$

- $O_{\phi_1 i} = \pm \left[1 - (O_{\phi_2 i})^2 - (O_{ai})^2\right]^{1/2}$ with $O_{\phi_2 i} = s_\beta\, C_u^S\,, \quad O_{ai} = -t_\beta\, C_u^P$

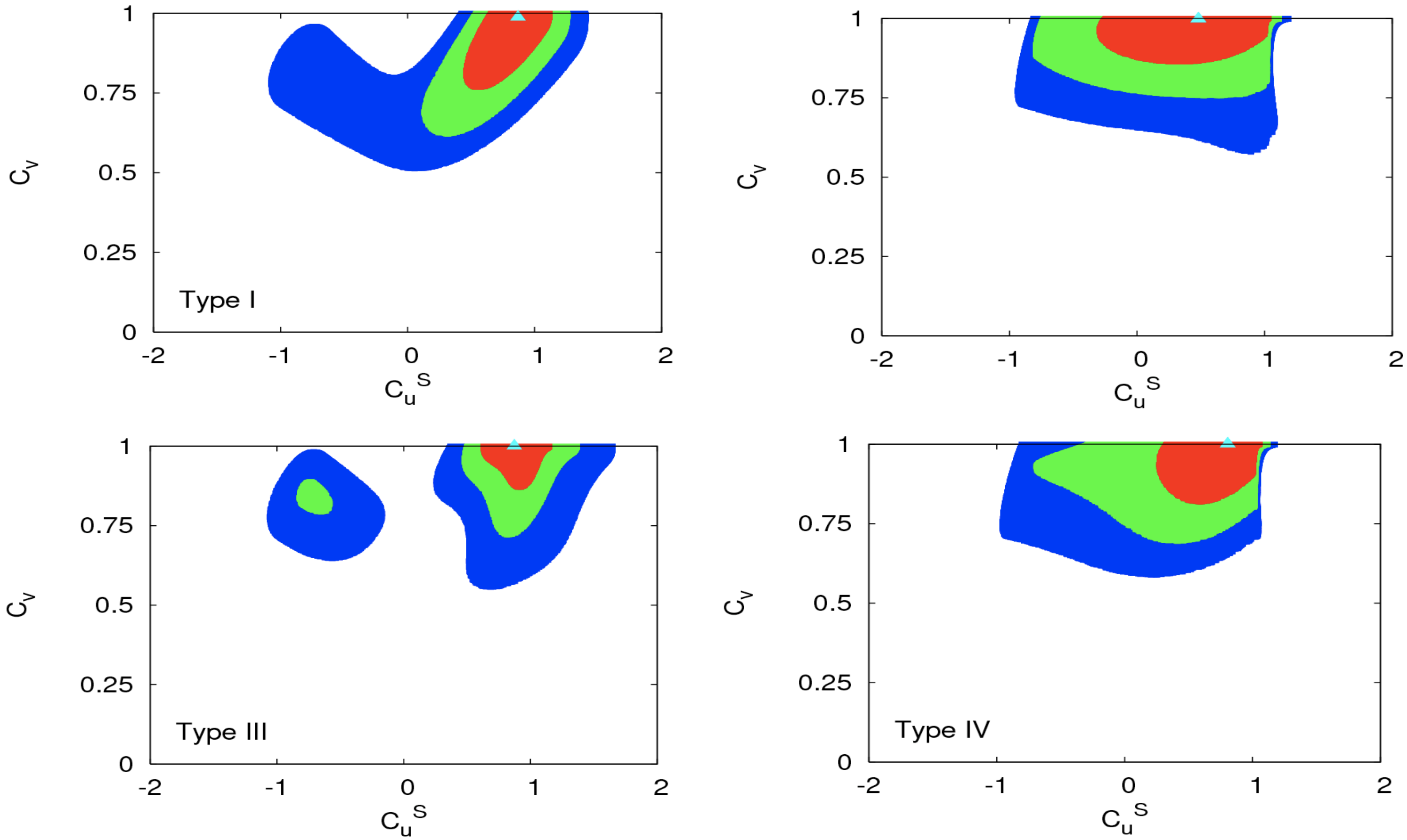
- $C_v = c_\beta O_{\phi_1 i} + s_\beta O_{\phi_2 i}$ with $s_\beta^2 = \frac{(1-C_v^2)}{(1-C_v^2)+(C_u^S-C_v)^2+(C_u^P)^2}$

♠ *Higgcision*

- Constraints from the Higgs data: Varying C_u^S, C_u^P, and C_v



$\Delta\chi^2 \leq 2.3\,(68.3\%)$ (red), $5.99\,(95\%)$ (green), and $11.83\,(99.7\%)$ (blue) CLs



JHEP 1401 (2014) 085 [arXiv:1310.3937], Cheung, JSL, Tseng ... *a bit older data*

♠ *EDMs*

- The "H"$-$mediated EDMs JHEP 0810 (2008) 049 [arXiv:0808.1819v6], Ellis, JSL, Pilaftsis

$$\mathcal{L} \;=\; -\frac{i}{2}\,d_f^E\,F^{\mu\nu}\,\bar{f}\,\sigma_{\mu\nu}\gamma_5\,f \;-\; \frac{i}{2}\,d_q^C\,G^{a\,\mu\nu}\,\bar{q}\,\sigma_{\mu\nu}\gamma_5 T^a\,q$$
$$+\frac{1}{3}\,d^G\,f_{abc}\,G^a_{\rho\mu}\,\widetilde{G}^{b\,\mu\nu}\,G^c{}_\nu{}^\rho \;+\; \sum_{f,f'} C_{ff'}(\bar{f}f)(\bar{f}'i\gamma_5 f')$$

  - The major Higgs-mediated contribution to the particle EDMs (d_f^E) and CEDMs (d_q^C) comes from the two-loop Barr–Zee-type diagrams

$$\left(d_f^E\right)^H = (d_f^E)^{\rm BZ}\,; \quad \left(d_q^C\right)^H = (d_q^C)^{\rm BZ}$$

– For the Weinberg operator, we consider the contributions from the Higgs-mediated two-loop diagrams:

$$(d^G)^H \;=\; \frac{4\sqrt{2}\,G_F\,g_s^3}{(4\pi)^4}\sum_{q=t,b} g^S_{H\bar{q}q}\,g^P_{H\bar{q}q}\,h(z_{Hq})\,,$$

– For the four-fermion operators, we consider the t-channel exchanges of the CP-mixed state H:

$$(C_{ff'})^H \;=\; g_f\,g_{f'}\,\frac{g^S_{H\bar{f}f}\,g^P_{H\bar{f}'f'}}{M_H^2}\;.$$

♠ *EDMs*

- The details of the two-loop Barr–Zee EDMs and CEDMs:

$$\left(d_f^E\right)^{\rm BZ} = \left(d_f^E\right)^{\gamma H} + \left(d_f^E\right)^{ZH}$$

$$\left(d_{q_l}^C\right)^{\rm BZ} = -\frac{g_s\,\alpha_s\,\alpha_{\rm em}\,m_{q_l}}{16\pi^2 s_W^2 M_W^2}\sum_{q=t,b}\left[g^P_{H\bar{q}_l q_l} g^S_{H\bar{q}q}\,f(\tau_{qH}) + g^S_{H\bar{q}_l q_l} g^P_{H\bar{q}q}\,g(\tau_{qH})\right]$$

$$\begin{aligned}(-Q_f)^{-1}\times\left(\frac{d_f^E}{e}\right)^{\gamma H} = & \sum_{q=t,b}\left\{\frac{3\alpha_{\rm em}^2\,Q_q^2\,m_f}{8\pi^2 s_W^2 M_W^2}\left[g^P_{H\bar{f}f} g^S_{H\bar{q}q}\,f(\tau_{qH}) + g^S_{H\bar{f}f} g^P_{H\bar{q}q}\,g(\tau_{qH})\right]\right\} \\ & + \frac{\alpha_{\rm em}^2\,m_f}{8\pi^2 s_W^2 M_W^2}\left[g^P_{H\bar{f}f} g^S_{H\tau^+\tau^-}\,f(\tau_{\tau H}) + g^S_{H\bar{f}f} g^P_{H\tau^+\tau^-}\,g(\tau_{\tau H})\right] \\ & - \frac{\alpha_{\rm em}^2\,m_f}{32\pi^2 s_W^2 M_W^2}\,g^P_{H\bar{f}f}\,g_{HVV}\,\mathcal{J}_W^\gamma(M_H)\end{aligned}$$

$$
\begin{aligned}
\left(\frac{d_f^E}{e}\right)^{ZH} &= \frac{\alpha_{\rm em}^2 v_{Z\bar{f}f}}{16\sqrt{2}\pi^2 c_W^2 s_W^4}\,\frac{m_f}{M_W}\sum_{q=t,b}\frac{3Q_q m_q}{\sqrt{2}M_W} \\
&\times \left[g^S_{H\bar{f}f}\left(v_{Z\bar{q}q}g^P_{H\bar{q}q}\right)\frac{m_q}{M_H^2}\int_0^1 {\rm d}x\frac{1}{x}J\left(r_{ZH},\frac{r_{qH}}{x(1-x)}\right)\right. \\
&\quad \left. + g^P_{H\bar{f}f}\left(v_{Z\bar{q}q}g^S_{H\bar{q}q}\right)\frac{m_q}{M_H^2}\int_0^1 {\rm d}x\frac{1-x}{x}J\left(r_{ZH},\frac{r_{qH}}{x(1-x)}\right)\right] \\
&- \frac{\alpha_{\rm em}^2 v_{Z\bar{f}f}}{16\sqrt{2}\pi^2 c_W^2 s_W^4}\,\frac{m_f}{M_W}\,\frac{m_\tau}{\sqrt{2}M_W} \\
&\times \left[g^S_{H\bar{f}f}\left(v_{Z\tau^+\tau^-}g^P_{H\tau^+\tau^-}\right)\frac{m_\tau}{M_H^2}\int_0^1 {\rm d}x\frac{1}{x}J\left(r_{ZH},\frac{r_{\tau H}}{x(1-x)}\right)\right. \\
&\quad \left. + g^P_{H\bar{f}f}\left(v_{Z\tau^+\tau^-}g^S_{H\tau^+\tau^-}\right)\frac{m_\tau}{M_H^2}\int_0^1 {\rm d}x\frac{1-x}{x}J\left(r_{ZH},\frac{r_{\tau H}}{x(1-x)}\right)\right] \\
&\quad + \frac{\alpha_{\rm em}^2\, v_{Z\bar{f}f}\, m_f}{32\pi^2 s_W^4 M_W^2}\, g^P_{H\bar{f}f}\, g_{HVV}\, \mathcal{J}^Z_W(M_H)
\end{aligned}
$$

with $v_{Z\bar{f}f} = T^f_{3L}/2 - Q_f s_W^2$

♠ *EDMs*

- Observables EDMs: B. C. Regan, E. D. Commins, C. J. Schmidt and D. DeMille, Phys. Rev. Lett. **88** (2002) 071805; C. A. Baker *et al.*, Phys. Rev. Lett. **97** (2006) 131801; W. C. Griffith, M. D. Swallows, T. H. Loftus, M. V. Romalis, B. R. Heckel and E. N. Fortson, Phys. Rev. Lett. **102** (2009) 101601; J. Baron *et al.* [ACME Collaboration], Science **343** (2014) 6168, 269

$$|d_{\rm Tl}| \leq d_{\rm Tl}^{\rm EXP}\,, \quad |d_{\rm n}| \leq d_{\rm n}^{\rm EXP}\,,$$
$$|d_{\rm Hg}| \leq d_{\rm Hg}^{\rm EXP}\,, \quad |d_{\rm ThO}/\mathcal{F}_{\rm ThO}| \leq d_{\rm ThO}^{\rm EXP}$$

with the current experimental bounds

$$d_{\rm Tl}^{\rm EXP} = 9\times 10^{-25}\,e\,{\rm cm}\,, \quad d_{\rm n}^{\rm EXP} = 2.9\times 10^{-26}\,e\,{\rm cm}\,,$$
$$d_{\rm Hg}^{\rm EXP} = 3.1\times 10^{-29}\,e\,{\rm cm}\,, \quad d_{\rm ThO}^{\rm EXP} = 8.7\times 10^{-29}\,e\,{\rm cm}\,.$$

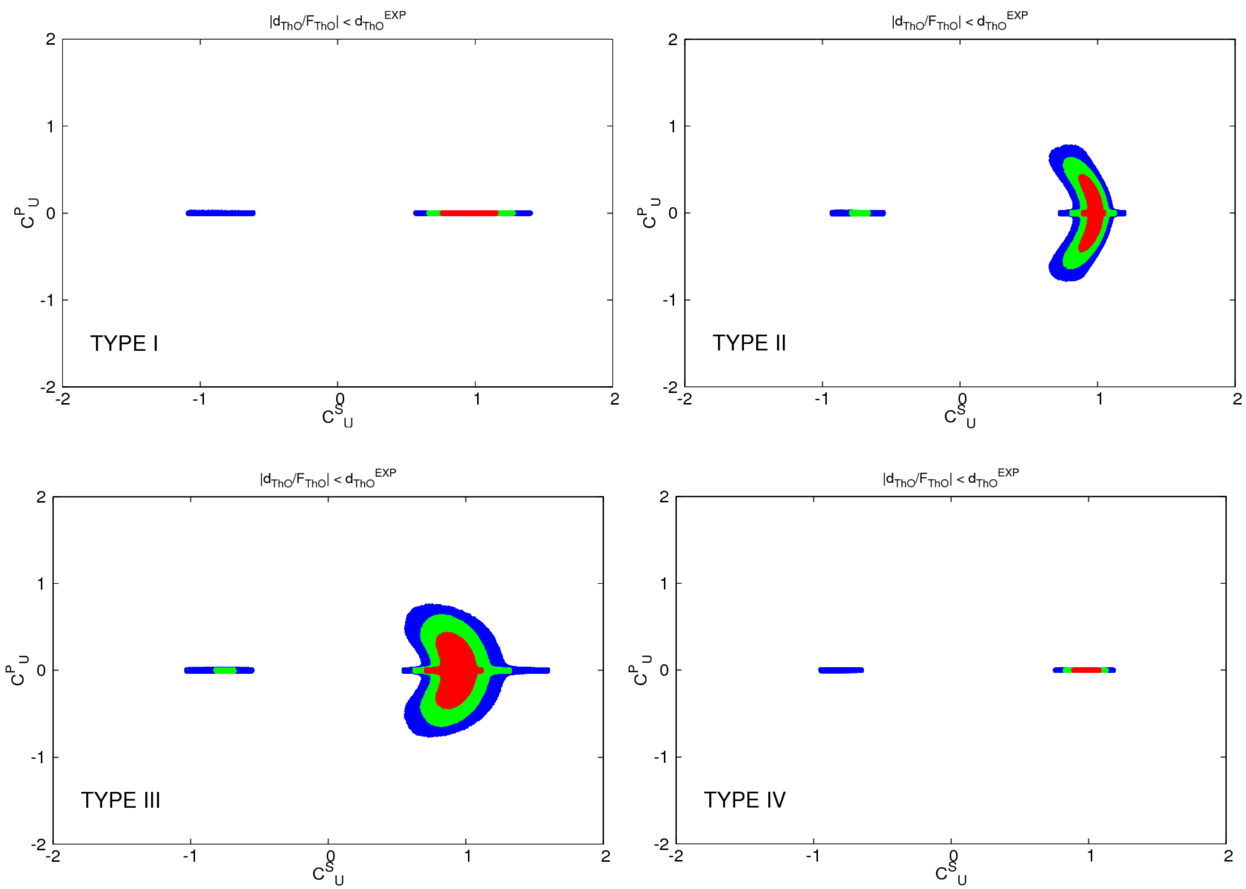
- In principle, the EDMs for Thallium, neutron, Mercury, and thorium monoxide can be calculated in terms of

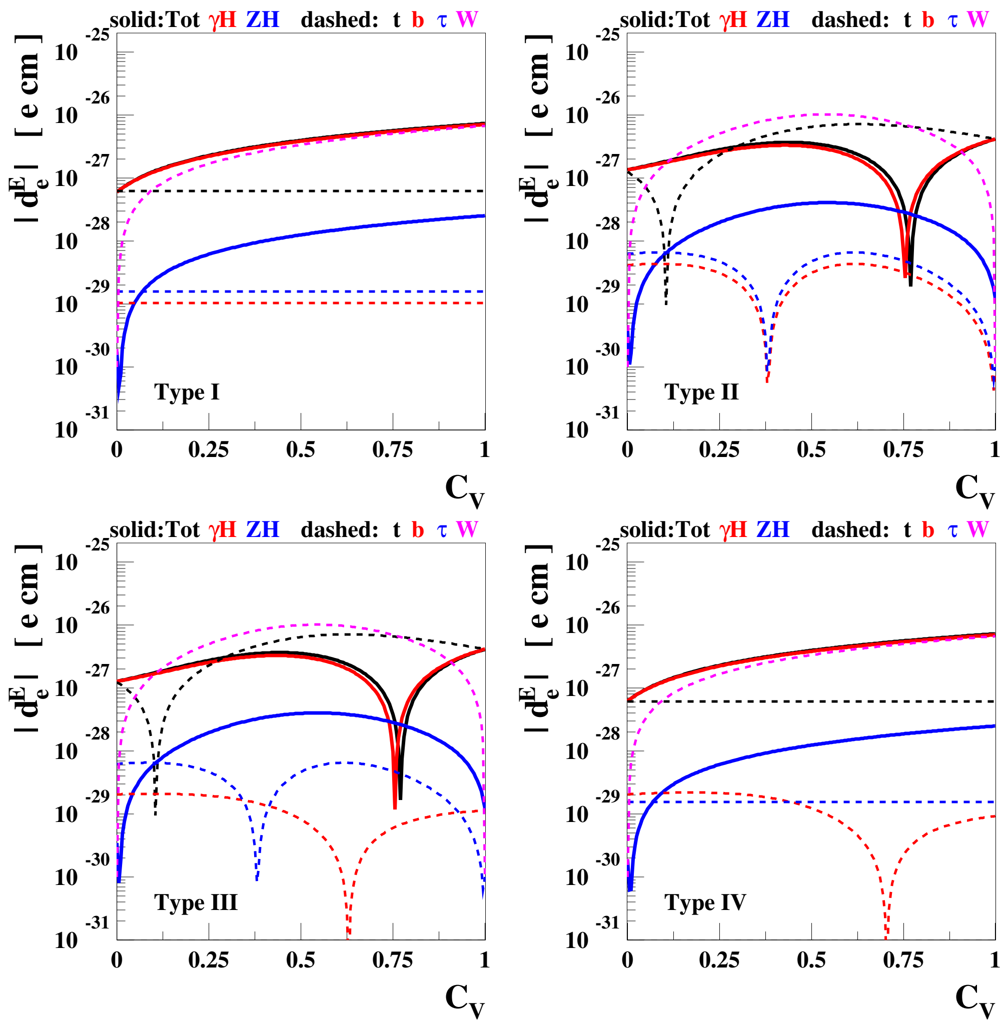
$$d_f^E\,, \quad d_q^C\,, \quad d^G\,, \quad C_{ff'}$$

- The theoretical calculation of EDMs requires expertise in various fields of Physics such as non-perturbaive QCD, Nuclear & Atomic Physics and suffers from large uncertainties of the order of $\sim \mathcal{O}(10)$

♠ *Results*

- Constraints from $d_{\rm ThO}$:

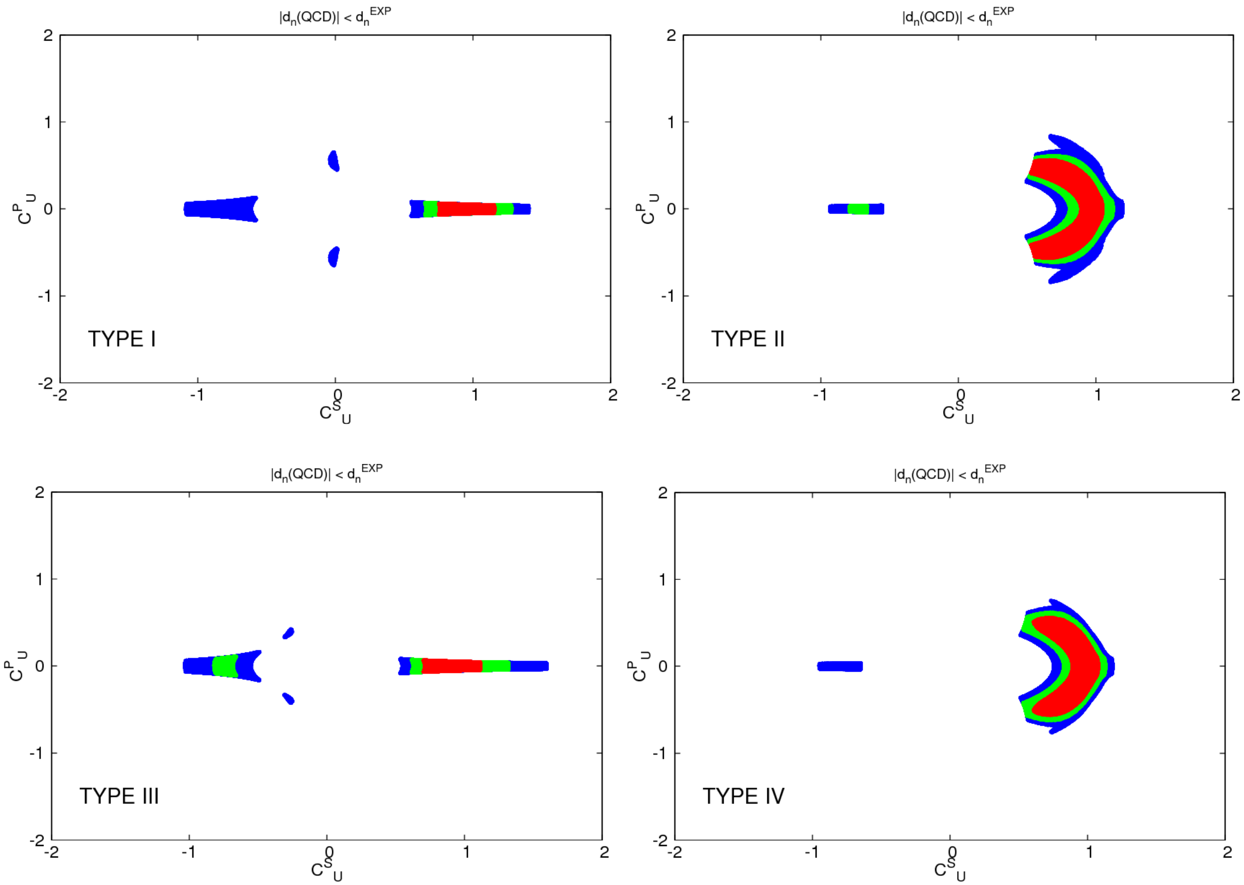


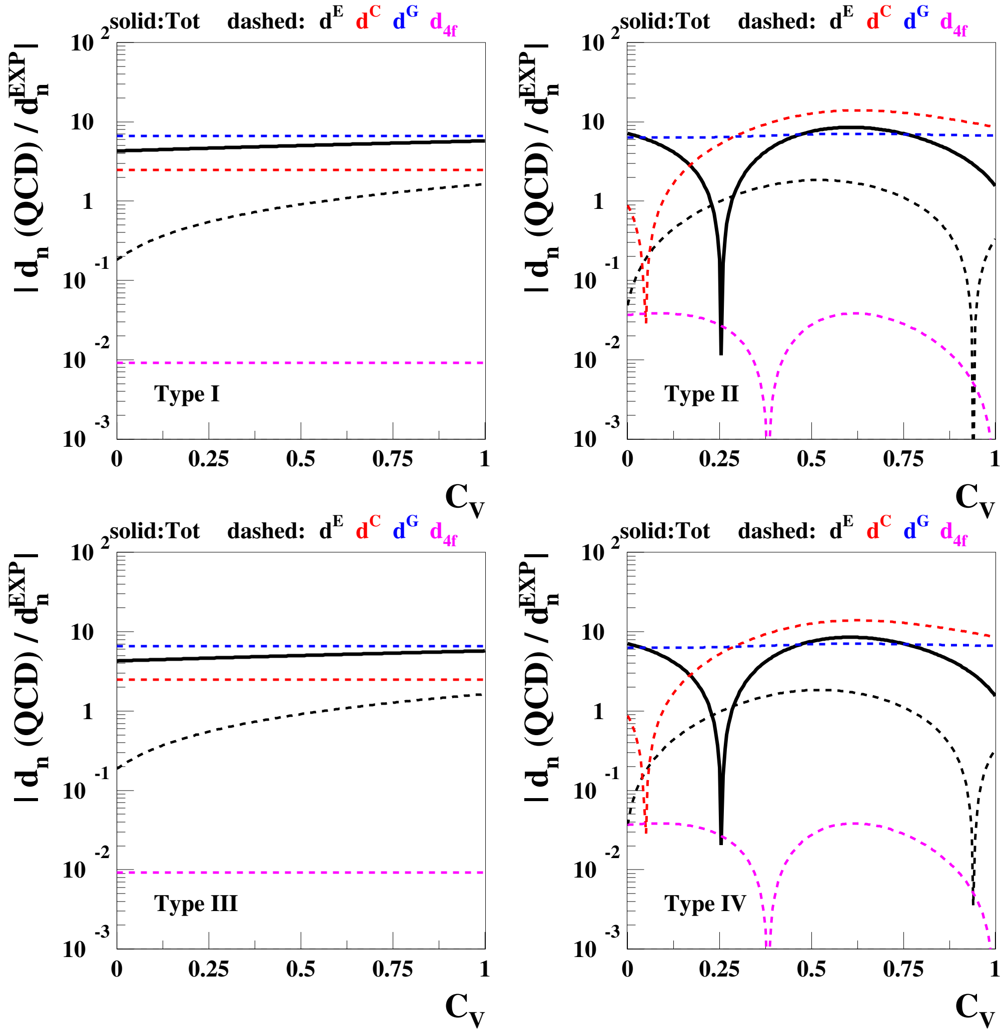


... $C_u^S = C_u^P = 1/2$ taken

♠ *Results*

- Constraints from $d_{\rm n}$:

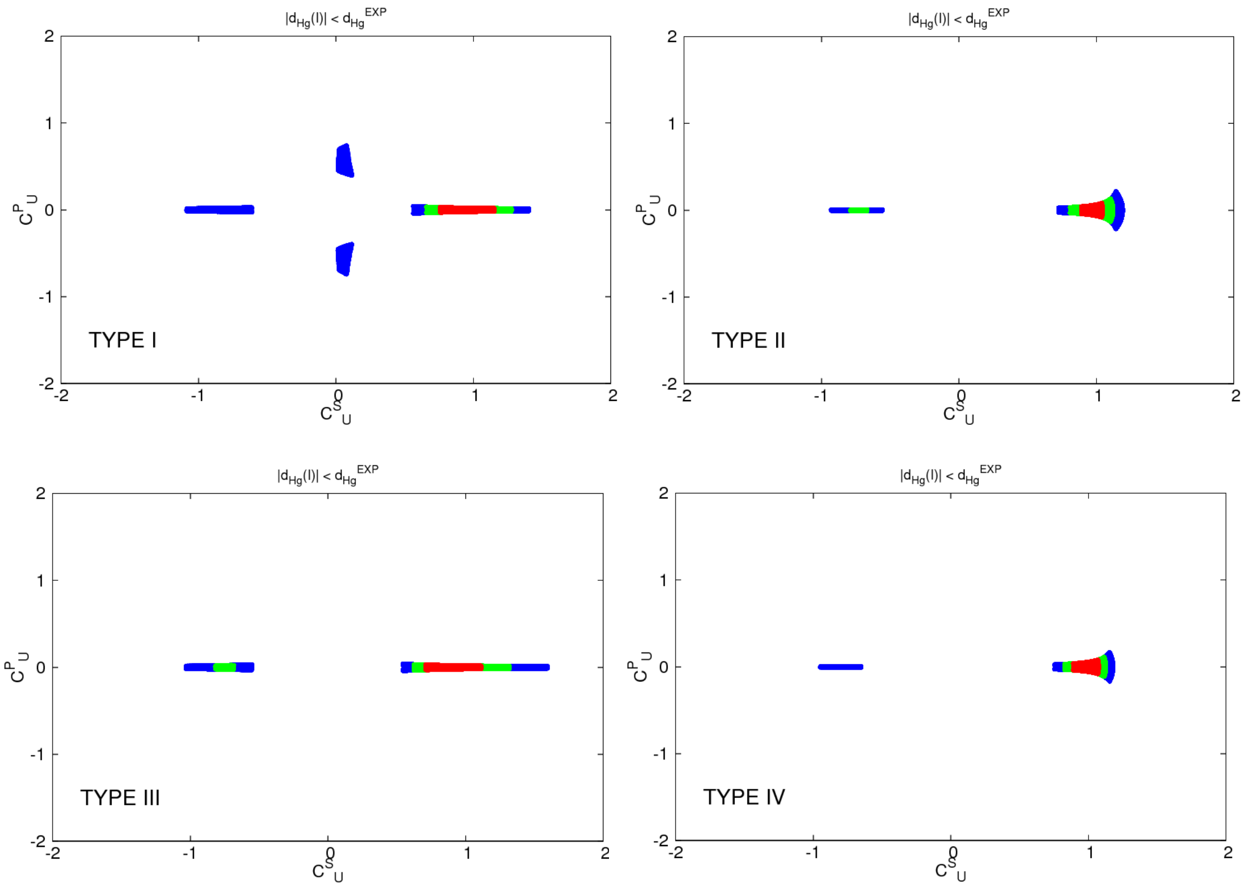


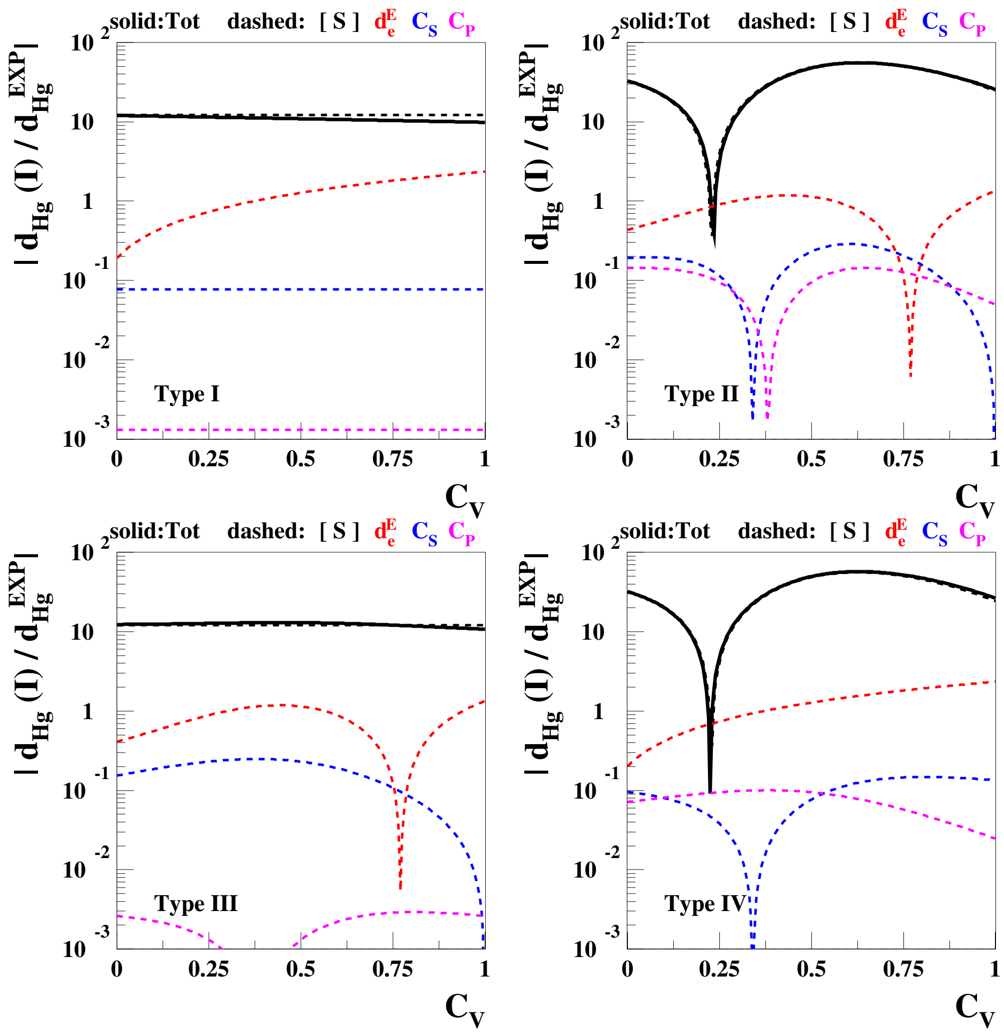


... $C_u^S = C_u^P = 1/2$ taken

♠ *Results*

- Constraints from $d_{\rm Hg}$:

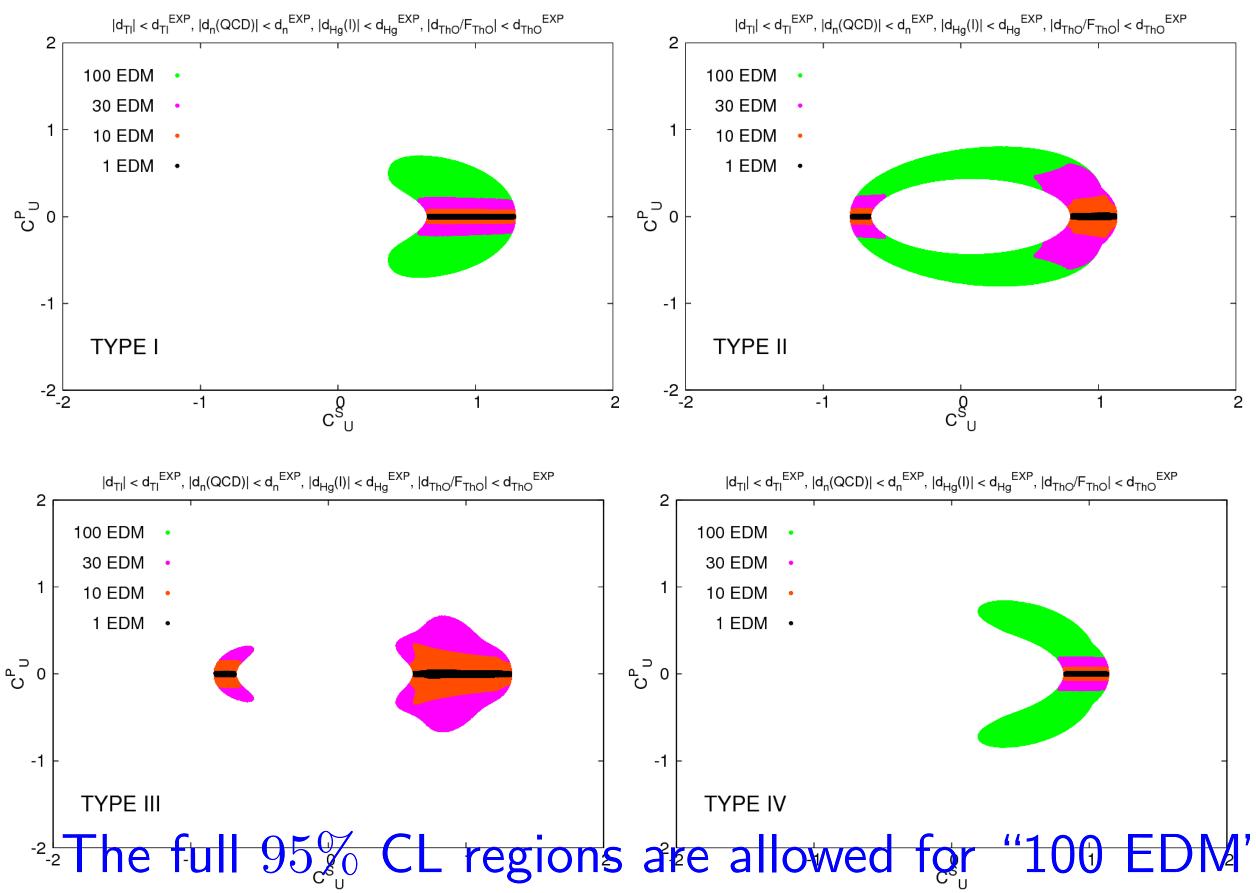




… $C_u^S = C_u^P = 1/2$ taken

♠ *Results*

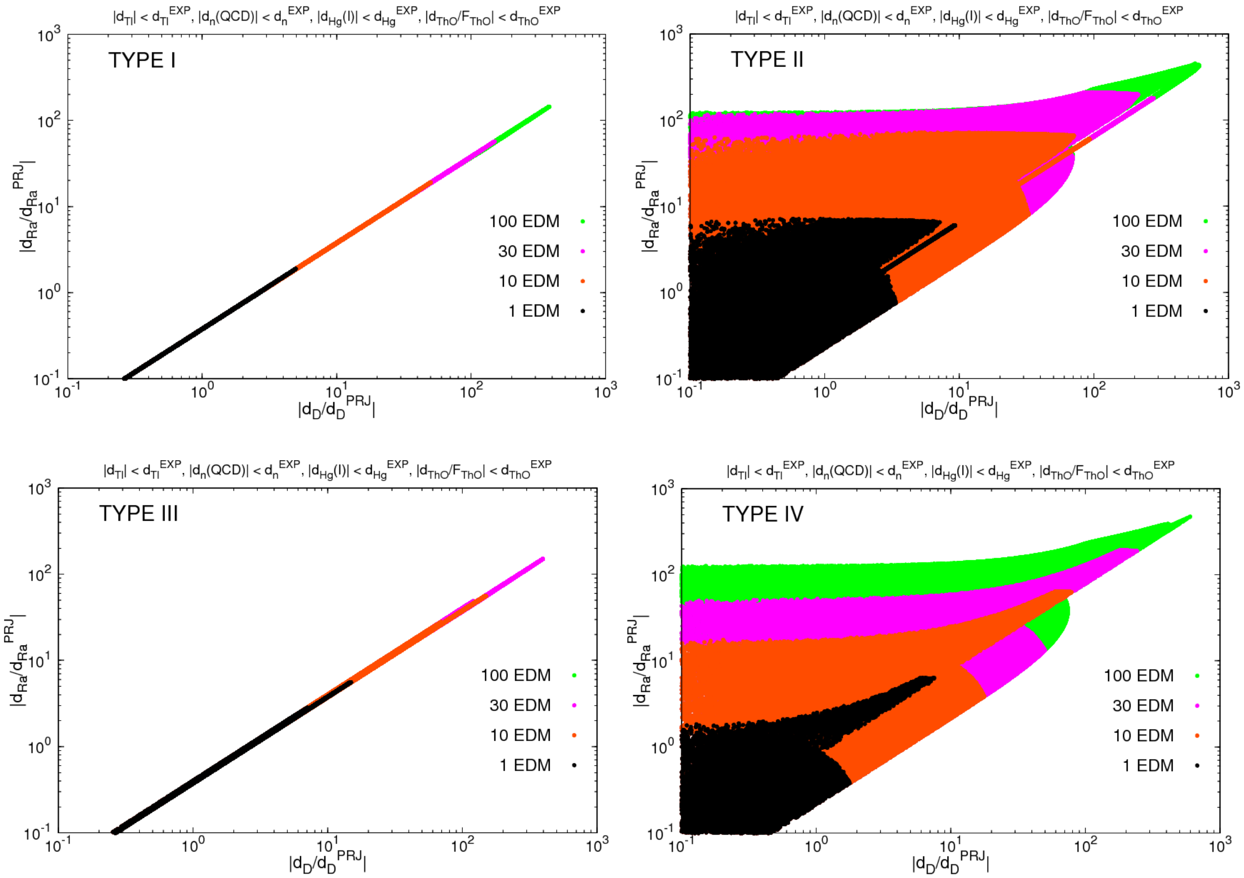
- Constraints combined with the 95% CL regions: "1 EDM" (black): $|C_u^P| \leq 7 \times 10^{-3}\ (\mathrm{I}), 2 \times 10^{-2}\ (\mathrm{II}), 3 \times 10^{-2}\ (\mathrm{III}), 6 \times 10^{-3}\ (\mathrm{IV})$



The full 95% CL regions are allowed for "100 EDM"

♠ *Results*

- Future prospects: $\left|d_{\rm D}/d_{\rm D}^{\rm PRJ}\right|$ vs $\left|d_{\rm Ra}/d_{\rm Ra}^{\rm PRJ}\right|$ $d_{\rm D}^{\rm PRJ} = 3 \times 10^{-27}\,e\,{\rm cm},\ d_{\rm Ra}^{\rm PRJ} = 1 \times 10^{-27}\,e\,{\rm cm}$



♠ *Summary*

- The current LHC data on the observed 125.5 Higgs boson H give definite predictions for d_e^E and $d_{u,d}^{E,C}$ through the two-loop Barr–Zee diagrams in the framework of 2HDMs.

- The electron EDM d_e^E, for example, receives the dominant contributions from the top and W-boson loops to the γ-γ-H Barr–Zee diagrams. A cancellation may occur between the two dominant contributions around $C_v = 1$ in Types II and III.

- The Thallium and ThO EDMs are dominated by d_e^E, the neutron EDM by $d_{u,d}^C$ and d^G, and the Mercury EDM by $d_{u,d}^C$ through the Schiff moment. For the neutron EDM, we observe a cancellation occurs between the contributions from $d_{u,d}^C$ and d^G around $C_v = 1$ in Types II and IV.

- The ThO (neutron) EDM constraint is relatively weaker in Types II and III (Types II and IV), while the Mercury EDM constraint is almost equally stringent in all four types.

- The coupling $|C_u^P|$ is restricted to be smaller than about 10^{-2} by the combined EDM constraints.

- Even for $|C_u^P| \lesssim 10^{-2}$, the deuteron and Radium EDMs can be ~ 10 times as large as the projected experimental sensitivities.