Electric Dipole Moments in the MSSM

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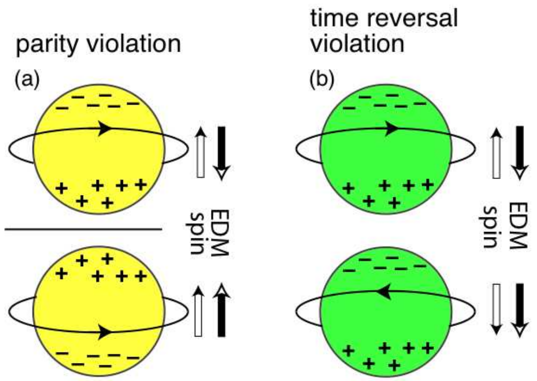
* based on JHEP 0810:049,2008, arXiv:0808.1819 [hep-ph] with J. Ellis and A. Pilaftsis

♠ *Preliminary*

- Electric Dipole Moments (EDMs): T violation ⇒ CP violation (under CPT)



$$\mathcal{H}^{\rm EDM} = -d\ \mathbf{E} \cdot \hat{\mathbf{s}}$$

$$|d_{\rm Tl}| < 9 \times 10^{-25}\ {\rm e\,cm}\,, \quad |d_{\rm Hg}| < 2 \times 10^{-28}\ {\rm e\,cm}\,, \quad |d_{\rm n}| < 3 \times 10^{-26}\ {\rm e\,cm}$$

B. C. Regan, E. D. Commins, C. J. Schmidt and D. DeMille, PRL**88** (2002) 071805; M. V. Romalis, W. C. Griffith and E. N. Fortson, PRL**86** (2001) 2505; C. A. Baker *et al.*, PRL**97** (2006) 131801

Question: No large CP phases?

♠ *Contents*

♠ *Introduction* (1/3)

- CP phases in the MSSM:

  – Φ_μ [1]: $W \supset \mu\, \hat{H}_2 \cdot \hat{H}_1$

  – Φ_i [3]: $-\mathcal{L}_{\rm soft} \supset \frac{1}{2}(M_3\, \widetilde{g}\widetilde{g} + M_2\, \widetilde{W}\widetilde{W} + M_1\, \widetilde{B}\widetilde{B} + {\rm h.c.})$

  – ${\rm Arg}\left(\mathbf{M}^2_{\widetilde{Q},\widetilde{L},\widetilde{u},\widetilde{d},\widetilde{e}}\right)_{i<j}$ [$5 \times 3 \;\to\; 0_{\rm NFV}$]:

$$-\mathcal{L}_{\rm soft} \supset \widetilde{Q}^\dagger\, \mathbf{M^2_{\widetilde{Q}}}\, \widetilde{Q} + \widetilde{L}^\dagger\, \mathbf{M^2_{\widetilde{L}}}\, \widetilde{L} + \widetilde{u}^*_R\, \mathbf{M^2_{\widetilde{u}}}\, \widetilde{u}_R + \widetilde{d}^*_R\, \mathbf{M^2_{\widetilde{d}}}\, \widetilde{d}_R + \widetilde{e}^*_R\, \mathbf{M^2_{\widetilde{e}}}\, \widetilde{e}_R$$

  – ${\rm Arg}\,(\mathbf{A}_{u,d,e})_{i,j}$ [$3 \times 9 \;\to\; (3 \times 3)_{\rm NFV}$]:

$$-\mathcal{L}_{\rm soft} \supset +(\widetilde{u}^*_R\, \mathbf{A_u}\, \widetilde{Q} H_2 - \widetilde{d}^*_R\, \mathbf{A_d}\, \widetilde{Q} H_1 - \widetilde{e}^*_R\, \mathbf{A_e}\, \widetilde{L} H_1 + {\rm h.c.})$$

  – ${\rm Arg}\,(m^2_{12})$ [1]: $-\mathcal{L}_{\rm soft} \supset -(m^2_{12} H_1 H_2 + {\rm h.c.})$

♠ *Introduction* $(2/3)$

- Physical observables depend on : Arg$(M_i\,\mu\,(m^2_{12})^*)$ and Arg$(\mathbf{A_f}\,\mu\,(m^2_{12})^*)$ M. Dugan, B. Grinstein and L. J. Hall, Nucl. Phys. B **255** (1985) 413; S. Dimopoulos and S. Thomas, Nucl. Phys. B **465** (1996) 23

Without flavour-mixing terms, we have the 12 physical CP phases

$$\mathrm{Arg}(M_1\,\mu)\,,\ \mathrm{Arg}(M_2\,\mu)\,,\ \mathrm{Arg}(M_3\,\mu)\,;$$

$$\mathrm{Arg}(A_e\,\mu)\,,\ \mathrm{Arg}(A_\mu\,\mu)\,,\ \mathrm{Arg}(A_\tau\,\mu)\,;$$

$$\mathrm{Arg}(A_d\,\mu)\,,\ \mathrm{Arg}(A_s\,\mu)\,,\ \mathrm{Arg}(A_b\,\mu)\,;$$

$$\mathrm{Arg}(A_u\,\mu)\,,\ \mathrm{Arg}(A_c\,\mu)\,,\ \mathrm{Arg}(A_t\,\mu)$$

$*$ We will take the Arg$(m^2_{12}) = 0$ convention throughout this talk

♠ *Introduction* (3/3)

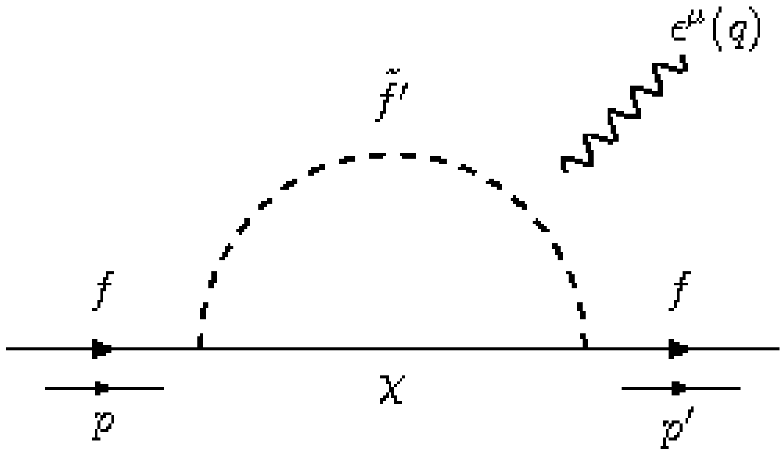
- Our convention for EDMs and CEDMs:

$$\mathcal{L}_{\rm (C)EDM} \;=\; -\,\frac{i}{2}\,d_f^E\,F^{\mu\nu}\,\bar{f}\,\sigma_{\mu\nu}\gamma_5\,f \;-\; \frac{i}{2}\,d_q^C\,G^{a\,\mu\nu}\,\bar{q}\,\sigma_{\mu\nu}\gamma_5 T^a\,q\,,$$

$$\begin{aligned} d_f^E/e &= (d_f^E/e)^{\tilde{\chi}^\pm} + (d_f^E/e)^{\tilde{\chi}^0} + (d_f^E/e)^{\tilde{g}} + (d_f^E/e)^{H} \\ d_q^C &= (d_q^C)^{\tilde{\chi}^\pm} + (d_q^C)^{\tilde{\chi}^0} + (d_q^C)^{\tilde{g}} + (d_q^C)^{H} \end{aligned}$$

where $f = e, u, d, s$ and $q = u, d$

- Generically, the χ-mediated one-loop f EDM is given by See, for example, T. Ibrahim and P. Nath, Rev. Mod. Phys. **80** (2008) 577, [arXiv:0705.2008 [hep-ph]]; S. Abel, S. Khalil and O. Lebedev, Nucl. Phys. B **606** (2001) 151, [arXiv:hep-ph/0103320]



$$
\begin{aligned}
\mathcal{L}_{\chi\chi A} &= -e\, Q_\chi\, (\bar{\chi}\gamma_\mu\chi) A^\mu \\
\mathcal{L}_{\tilde{f}'\tilde{f}'A} &= -ie\, Q_{\tilde{f}'}\, \tilde{f}'^* \overleftrightarrow{\partial}_\mu\, \tilde{f}' A^\mu \\
\mathcal{L}_{\chi f \tilde{f}'} &= g^{\chi f \tilde{f}'}_{L\,ij}\, (\bar{\chi}_i P_L f)\, \tilde{f}'^*_j \\
&\quad + g^{\chi f \tilde{f}'}_{R\,ij}\, (\bar{\chi}_i P_R f)\, \tilde{f}'^*_j \; + \; \text{h.c.}
\end{aligned}
$$

$$
\left(\frac{d^E_f}{e}\right)^{\chi} = \frac{m_{\chi_i}}{16\pi^2 m^2_{\tilde{f}'_j}} \Im\mathrm{m}[(g^{\chi f \tilde{f}'}_{R\,ij})^* g^{\chi f \tilde{f}'}_{L\,ij}] \left[Q_\chi\, A(m^2_{\chi_i}/m^2_{\tilde{f}'_j}) + Q_{\tilde{f}'}\, B(m^2_{\chi_i}/m^2_{\tilde{f}'_j}) \right]
$$

$$
A(r) = \frac{1}{2(1-r)^2}\left(3 - r + \frac{2\ln r}{1-r}\right), \quad B(r) = \frac{1}{2(1-r)^2}\left(1 + r + \frac{2r\ln r}{1-r}\right)
$$

♠ *One-loop EDMs* (2/5)

- Explicitly, the chargino-mediated one-loop EDMs of charged leptons and quarks:

$$\left(\frac{d_l^E}{e}\right)^{\tilde\chi^\pm} = \frac{1}{16\pi^2}\sum_i \frac{m_{\tilde\chi_i^\pm}}{m_{\tilde\nu_l}^2}\,\Im\mathrm{m}[(g_{R\,i}^{\tilde\chi^\pm l\tilde\nu})^*\, g_{L\,i}^{\tilde\chi^\pm l\tilde\nu}]\; Q_{\tilde\chi^-}\, A(m_{\tilde\chi_i^\pm}^2/m_{\tilde\nu_l}^2)$$

$$\left(\frac{d_u^E}{e}\right)^{\tilde\chi^\pm} = \frac{1}{16\pi^2}\sum_{i,j} \frac{m_{\tilde\chi_i^\pm}}{m_{\tilde d_j}^2}\,\Im\mathrm{m}[(g_{R\,ij}^{\tilde\chi^\pm u\tilde d})^*\, g_{L\,ij}^{\tilde\chi^\pm u\tilde d}]\,[Q_{\tilde\chi^+}\, A(m_{\tilde\chi_i^\pm}^2/m_{\tilde d_j}^2) \;+\; Q_{\tilde d} B(m_{\tilde\chi_i^\pm}^2/m_{\tilde d_j}^2)]$$

$$\left(\frac{d_d^E}{e}\right)^{\tilde\chi^\pm} = \frac{1}{16\pi^2}\sum_{i,j} \frac{m_{\tilde\chi_i^\pm}}{m_{\tilde u_j}^2}\,\Im\mathrm{m}[(g_{R\,ij}^{\tilde\chi^\pm d\tilde u})^*\, g_{L\,ij}^{\tilde\chi^\pm d\tilde u}]\,[Q_{\tilde\chi^-}\, A(m_{\tilde\chi_i^\pm}^2/m_{\tilde u_j}^2) \;+\; Q_{\tilde u} B(m_{\tilde\chi_i^\pm}^2/m_{\tilde u_j}^2)]$$

where $Q_{\tilde\chi^\pm} = \pm 1$, $Q_{\tilde u} = 2/3$, $Q_{\tilde d} = -1/3$, and

$$g_{L\,i}^{\tilde\chi^\pm l\tilde\nu} = -g(C_R)_{i1}\,, \qquad g_{R\,i}^{\tilde\chi^\pm l\tilde\nu} = h_l^*(C_L)_{i2}\,,$$

$$g_{L\,ij}^{\tilde\chi^\pm u\tilde d} = -g(C_L)_{i1}^*(U^{\tilde d})_{1j}^* + h_d(C_L)_{i2}^*(U^{\tilde d})_{2j}^*\,, \qquad g_{R\,ij}^{\tilde\chi^\pm u\tilde d} = h_u^*(C_R)_{i2}^*(U^{\tilde d})_{1j}^*\,,$$

$$g_{L\,ij}^{\tilde\chi^\pm d\tilde u} = -g(C_R)_{i1}(U^{\tilde u})_{1j}^* + h_u(C_R)_{i2}(U^{\tilde u})_{2j}^*\,, \qquad g_{R\,ij}^{\tilde\chi^\pm d\tilde u} = h_d^*(C_L)_{i2}(U^{\tilde u})_{1j}^*$$

- The neutralino-mediated one-loop EDMs of charged leptons and quarks:

$$\left(\frac{d_f^E}{e}\right)^{\tilde{\chi}^0} = \frac{1}{16\pi^2}\sum_{i,j}\frac{m_{\tilde{\chi}_i^0}}{m^2_{\tilde{f}_j}}\Im\mathrm{m}[(g^{\tilde{\chi}^0 f\tilde{f}}_{R\,ij})^*\, g^{\tilde{\chi}^0 f\tilde{f}}_{L\,ij}]\, Q_{\tilde{f}}\, B(m^2_{\tilde{\chi}_i^0}/m^2_{\tilde{f}_j})$$

with $f = l, u, d$. The neutralino-fermion-sfermion couplings are

$$g^{\tilde{\chi}^0 f\tilde{f}}_{L\,ij} = -\sqrt{2}\, g\, T_3^f\, N^*_{i2}(U^{\tilde{f}})^*_{1j} - \sqrt{2}\, g\, t_W\,(Q_f - T_3^f) N^*_{i1}(U^{\tilde{f}})^*_{1j} - h_f N^*_{i\alpha}(U^{\tilde{f}})^*_{2j}\,,$$

$$g^{\tilde{\chi}^0 f\tilde{f}}_{R\,ij} = \sqrt{2}\, g\, t_W\, Q_f\, N_{i1}(U^{\tilde{f}})^*_{2j} - h^*_f N_{i\alpha}(U^{\tilde{f}})^*_{1j}$$

where the Higgsino index $\alpha = 3\,(f = l, d)$ or $4\,(f = u)$

- The gluino-mediated one-loop EDMs of quarks:

$$\left(\frac{d_q^E}{e}\right)^{\tilde{g}} = \frac{1}{3\pi^2}\sum_{j}\frac{|M_3|}{m^2_{\tilde{q}_j}}\Im\mathrm{m}[(g^{\tilde{g}q\tilde{q}}_{R\,j})^*\, g^{\tilde{g}q\tilde{q}}_{L\,j}]\, Q_{\tilde{q}} B(|M_3|^2/m^2_{\tilde{q}_j})$$

$$g^{\tilde{g}q\tilde{q}}_{L\,j} = -\frac{g_s}{\sqrt{2}}\,\mathrm{e}^{-i\Phi_3/2}(U^{\tilde{q}})^*_{1j}\,, \qquad g^{\tilde{g}q\tilde{q}}_{R\,j} = +\frac{g_s}{\sqrt{2}}\,\mathrm{e}^{+i\Phi_3/2}(U^{\tilde{q}})^*_{2j}$$

♠ *One-loop EDMs* $(4/5)$

- The chargino-, neutralino-, and gluino-mediated one-loop CEDMs of quarks:

$$\left(d_u^C\right)^{\tilde{\chi}^\pm} = \frac{g_s}{16\pi^2}\sum_{i,j}\frac{m_{\tilde{\chi}_i^\pm}}{m^2_{\tilde{d}_j}}\,\Im\mathrm{m}[(g^{\tilde{\chi}^\pm u\tilde{d}}_{R\,ij})^*\,g^{\tilde{\chi}^\pm u\tilde{d}}_{L\,ij}]\,B(m^2_{\tilde{\chi}_i^\pm}/m^2_{\tilde{d}_j})\,,$$

$$\left(d_d^C\right)^{\tilde{\chi}^\pm} = \frac{g_s}{16\pi^2}\sum_{i,j}\frac{m_{\tilde{\chi}_i^\pm}}{m^2_{\tilde{u}_j}}\,\Im\mathrm{m}[(g^{\tilde{\chi}^\pm d\tilde{u}}_{R\,ij})^*\,g^{\tilde{\chi}^\pm d\tilde{u}}_{L\,ij}]\,B(m^2_{\tilde{\chi}_i^\pm}/m^2_{\tilde{u}_j})\,,$$

$$\left(d_{q=u,d}^C\right)^{\tilde{\chi}^0} = \frac{g_s}{16\pi^2}\sum_{i,j}\frac{m_{\tilde{\chi}_i^0}}{m^2_{\tilde{q}_j}}\,\Im\mathrm{m}[(g^{\tilde{\chi}^0 q\tilde{q}}_{R\,ij})^*\,g^{\tilde{\chi}^0 q\tilde{q}}_{L\,ij}]\,B(m^2_{\tilde{\chi}_i^0}/m^2_{\tilde{q}_j})\,,$$

$$(d_{q=u,d}^C)^{\tilde{g}} = -\frac{g_s}{8\pi^2}\sum_{j}\frac{|M_3|}{m^2_{\tilde{q}_j}}\,\Im\mathrm{m}[(g^{\tilde{g}q\tilde{q}}_{R\,j})^*g^{\tilde{g}q\tilde{q}}_{L\,j}]\,C(|M_3|^2/m^2_{\tilde{q}_j})$$

where $C(r) \equiv \frac{1}{6(1-r)^2}\left(10r - 26 + \frac{2r\ln r}{1-r} - \frac{18\ln r}{1-r}\right)$, with $C(1) = 19/18$

♠ *One-loop EDMs* (5/5)

- Complex Yukawa couplings; effects of Φ_3 via resummed non-holomorphic threshold corrections:

$$h_u = \frac{\sqrt{2}m_u}{vs_\beta}\frac{1}{1+\Delta_u/t_\beta}, \quad h_c = \frac{\sqrt{2}m_c}{vs_\beta}\frac{1}{1+\Delta_c/t_\beta},$$

$$h_d = \frac{\sqrt{2}m_d}{vc_\beta}\frac{1}{1+\Delta_d t_\beta}, \quad h_s = \frac{\sqrt{2}m_s}{vc_\beta}\frac{1}{1+\Delta_s t_\beta}$$

where

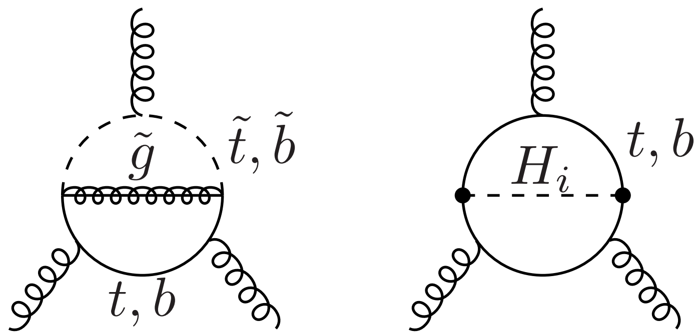
$$\Delta_u = \frac{2\alpha_s}{3\pi}\mu^* M_3^*\, I(M^2_{\tilde{U}_1}, M^2_{\tilde{Q}_1}, |M_3|^2)\,, \quad \Delta_c = \frac{2\alpha_s}{3\pi}\mu^* M_3^*\, I(M^2_{\tilde{U}_2}, M^2_{\tilde{Q}_2}, |M_3|^2)\,,$$

$$\Delta_d = \frac{2\alpha_s}{3\pi}\mu^* M_3^*\, I(M^2_{\tilde{D}_1}, M^2_{\tilde{Q}_1}, |M_3|^2)\,, \quad \Delta_s = \frac{2\alpha_s}{3\pi}\mu^* M_3^*\, I(M^2_{\tilde{D}_2}, M^2_{\tilde{Q}_2}, |M_3|^2)$$

where $I(x,y,z) \equiv \frac{xy\,\ln(x/y) + yz\,\ln(y/z) + xz\,\ln(z/x)}{(x-y)\,(y-z)\,(x-z)}$

♠ *Higher-order Contributions* (1/4)

- Weinberg operator;S. Weinberg,Phys. Rev. Lett. **63** (1989) 2333; J. Dai, H. Dykstra, R. G. Leigh, S. Paban and D. Dicus,Phys. Lett. B **237** (1990) 216 [Erratum-ibid. B **242** (1990) 547]; D. A. Dicus,Phys. Rev. D **41** (1990) 999



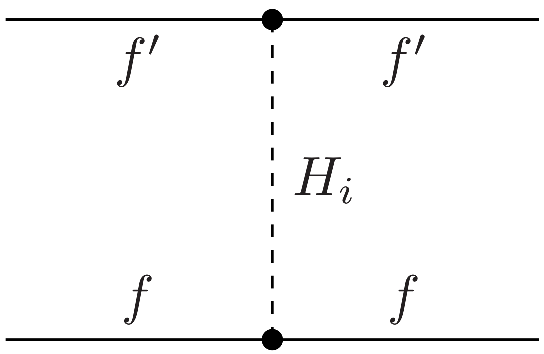
$$\mathcal{L}_{\rm Weinberg} \;=\; -\frac{1}{6}\,d^{\,G}\,f_{abc}\,G^{a}_{\mu\rho}\,G^{b\,\rho}_{\ \ \nu}\,G^{c}_{\lambda\sigma}\,\epsilon^{\mu\nu\lambda\sigma} = \frac{1}{3}\,d^{\,G}\,f_{abc}\,G^{a}_{\rho\mu}\,\tilde{G}^{b\,\mu\nu}\,G^{c}_{\ \ \nu}{}^{\rho}$$

where

$$d^{\,G} \;=\; (d^{\,G})^{\tilde{g}} \,+\, (d^{\,G})^{H}$$

♠ *Higher-order Contributions* (2/4)

- Higgs-mediated Four-fermion interactions;



$$\mathcal{L}_{4\mathrm{f}} \;=\; \sum_{f,f'} C_{ff'}(\bar{f}f)(\bar{f}' i\gamma_5 f')$$

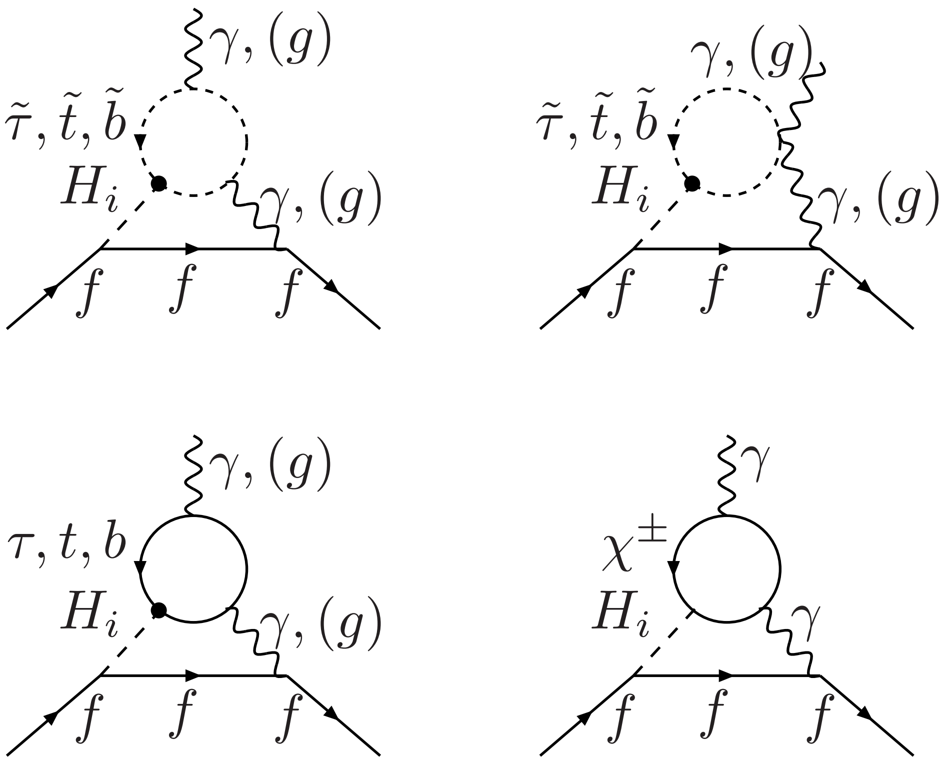
where

$$(C_{ff'})^H \;=\; g_f\, g_{f'} \sum_i \frac{g^S_{H_i\bar{f}f}\, g^P_{H_i\bar{f}'f'}}{M^2_{H_i}}$$

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

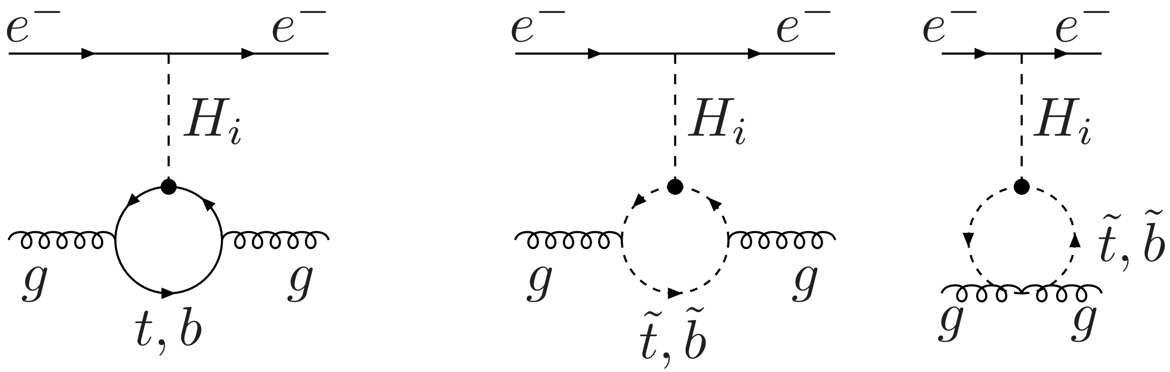
♠ *Higher-order Contributions* (3/4)

- Higgs-mediated Barr-Zee graphs; D. Chang, W. Y. Keung and A. Pilaftsis,Phys. Rev. Lett. **82** (1999) 900 [Erratum-ibid. **83** (1999) 3972], [arXiv:hep-ph/9811202]; A. Pilaftsis,A. Pilaftsis, Nucl. Phys. B **644** (2002) 263, [arXiv:hep-ph/0207277]; J. R. Ellis, JSL and A. Pilaftsis, Phys. Rev. D **72** (2005) 095006 [arXiv:hep-ph/0507046] $(d_f^{E,C})^H \Rightarrow (d_e^E)^H,\ (d_{u,d}^C)^H$



♠ *Higher-order Contributions* $(4/4)$

- The gluon-gluon-Higgs contribution to C_S, $\mathcal{L}_{C_S} = C_S\, \bar{e} i\gamma_5 e\, \bar{N} N$;



$$(C_S)^g = (0.1\,\mathrm{GeV})\, \frac{m_e}{v^2} \sum_{i=1}^{3} \frac{g^S_{H_i gg}\, g^P_{H_i \bar{e} e}}{M^2_{H_i}}$$

$$g^S_{H_i gg} = \sum_{q=t,b} \left\{ \frac{2\,x_q}{3}\, g^S_{H_i \bar{q} q} - \frac{v^2}{12} \sum_{j=1,2} \frac{g_{H_i \tilde{q}^*_j \tilde{q}_j}}{m^2_{\tilde{q}_j}} \right\}$$

♠ *Observable EDMs* (1/9)

- Thallium EDM; I.B. Khriplovich and S.K. Lamoreaux, *CP Violation Without Strangeness* (Springer, New York, 1997); M. Pospelov and A. Ritz, Annals Phys. **318** (2005) 119,[arXiv:hep-ph/0504231]

$$d_{\rm Tl}\,[e\,{\rm cm}] \;=\; -585\cdot d^E_e\,[e\,{\rm cm}] \;-\; 8.5\times 10^{-19}\,[e\,{\rm cm}]\cdot (C_S\,{\rm TeV}^2) \;+\;\cdots$$

$$\begin{aligned} d^E_e &= (d^E_e)^{\tilde\chi^\pm} + (d^E_e)^{\tilde\chi^0} + (d^E_e)^H \\ C_S &= (C_S)^{4f} + (C_S)^g \end{aligned}$$

where $(C_S)^{4f} \;=\; C_{de}\frac{29\,{\rm MeV}}{m_d} + C_{se}\frac{\kappa\times 220\,{\rm MeV}}{m_s}$ with $\kappa \equiv \langle N|m_s\bar{s}s|N\rangle/220~{\rm MeV} \simeq 0.50\pm 0.25$

♠ *Observable EDMs* $(2/9)$

- Neutron EDM [Chiral Quark Model (CQM)];A. Manohar and H. Georgi, Nucl. Phys. B **234** (1984) 189; R. Arnowitt, J. L. Lopez and D. V. Nanopoulos, Phys. Rev. D **42** (1990) 2423; R. Arnowitt, M. J. Duff and K. S. Stelle, Phys. Rev. D **43** (1991) 3085; T. Ibrahim and P. Nath, Phys. Rev. D **57** (1998) 478 [Erratum-ibid. D **58** (1998 ERRAT,D60,079903.1999 ERRAT,D60,119901.1999) 019901] [arXiv:hep-ph/9708456]

$$d_n = \frac{4}{3}\, d_d^{\rm NDA} - \frac{1}{3}\, d_u^{\rm NDA},$$

$$\begin{aligned} d_{q=u,d}^{\rm NDA} &= \eta^E\, d_q^E + \eta^C\, \frac{e}{4\pi}\, d_q^C + \eta^G\, \frac{e\Lambda}{4\pi}\, d^G, \\ d_{q=u,d}^{E\,(C)} &= (d_q^{E\,(C)})^{\tilde{\chi}^\pm} + (d_q^{E\,(C)})^{\tilde{\chi}^0} + (d_q^{E\,(C)})^{\tilde{g}} + (d_q^{E\,(C)})^{H} \end{aligned}$$

where $\eta^E \simeq 1.53\,, \quad \eta^C \simeq \eta^G \simeq 3.4$ and the chiral symmetry breaking scale $\Lambda \simeq 1.19$ GeV

♠ *Observable EDMs* (3/9)

- Neutron EDM [Parton Quark Model (PQM)]; J. R. Ellis and R. A. Flores, Phys. Lett. B **377** (1996) 83, [arXiv:hep-ph/9602211]

$$d_n = \eta^E \, (\Delta_d^{\rm PQM} \, d_d^E \; + \; \Delta_u^{\rm PQM} \, d_u^E + \Delta_s^{\rm PQM} \, d_s^E) \; ,$$

with

$$\Delta_d^{\rm PQM} = 0.746 \, , \qquad \Delta_u^{\rm PQM} = -0.508 \, , \qquad \Delta_s^{\rm PQM} = -0.226$$

The isospin symmetry between the neutron n and the proton p implies that $\Delta_d = (\Delta_u)_p = 4/3$, $\Delta_u = (\Delta_d)_p = -1/3$. Furthermore, in the relativistic Naive Quark Model (NQM), one has $\Delta_s = (\Delta_s)_p = 0$.

♠ *Observable EDMs* (4/9)

- Neutron EDM [QCD sum rule techniques (QCD)];M. Pospelov and A. Ritz, Phys. Rev. Lett. **83** (1999) 2526, [arXiv:hep-ph/9904483]; M. Pospelov and A. Ritz, Nucl. Phys. B **573** (2000) 177, [arXiv:hep-ph/9908508]; M. Pospelov and A. Ritz, Phys. Rev. D **63** (2001) 073015, [arXiv:hep-ph/0010037]; D. A. Demir, M. Pospelov and A. Ritz, Phys. Rev. D **67** (2003) 015007,[arXiv:hep-ph/0208257]; D. A. Demir, O. Lebedev, K. A. Olive, M. Pospelov and A. Ritz, Nucl. Phys. B **680** (2004) 339, [arXiv:hep-ph/0311314]; K. A. Olive, M. Pospelov, A. Ritz and Y. Santoso, Phys. Rev. D **72** (2005) 075001, [arXiv:hep-ph/0506106]

$$d_n \;=\; d_n(d_q^E\,,d_q^C) \;+\; d_n(d^{\,G}) \;+\; d_n(C_{bd}) \;+\; \cdots\,,$$

$$\begin{aligned}
d_n(d_q^E\,,d_q^C) &= (1.4\pm 0.6)\,(d_d^E - 0.25\,d_u^E) \;+\; (1.1\pm 0.5)\,e\,(d_d^C + 0.5\,d_u^C)/g_s\,,\\
d_n(d^{\,G}) &\sim \pm\,e\,(20\pm 10)\ \mathrm{MeV}\,d^{\,G}\,,\\
d_n(C_{bd}) &\sim \pm\,e\,2.6\times 10^{-3}\ \mathrm{GeV}^2\left[\frac{C_{bd}}{m_b} + 0.75\frac{C_{db}}{m_b}\right]
\end{aligned}$$

where $d^G = d^G(1\ \mathrm{GeV}) \simeq 8.5\,d^G(\mathrm{EW})$

♠ Observable EDMs (5/9)

- Mercury EDM; D. A. Demir, O. Lebedev, K. A. Olive, M. Pospelov and A. Ritz, Nucl. Phys. B **680** (2004) 339, [arXiv:hep-ph/0311314]; K. A. Olive, M. Pospelov, A. Ritz and Y. Santoso, Phys. Rev. D **72** (2005) 075001, [arXiv:hep-ph/0506106]

$$\begin{aligned} d_{\rm Hg} &= 7\times 10^{-3}\, e\,(d_u^C - d_d^C)/g_s \;+\; 10^{-2}\, d_e^E \\ &\quad - 1.4\times 10^{-5}\, e\,{\rm GeV}^2 \left[\frac{0.5 C_{dd}}{m_d} + 3.3\kappa\frac{C_{sd}}{m_s} + (1-0.25\kappa)\frac{C_{bd}}{m_b}\right] \\ &\quad + (3.5\times 10^{-3}\ {\rm GeV})\, e\, C_S \\ &\quad + (4\times 10^{-4}\ {\rm GeV})\, e \left[C_P + \left(\frac{Z-N}{A}\right)_{\rm Hg} C_P'\right] \end{aligned}$$

where $\mathcal{L}_{C_P} = C_P\, \bar{e}e\, \bar{N} i\gamma_5 N \;+\; C_P'\, \bar{e}e\, \bar{N} i\gamma_5\tau_3 N$ with

$$\begin{aligned} C_P &= (C_P)^{4f} \simeq -375\ {\rm MeV} \sum_{q=c,s,t,b} \frac{C_{eq}}{m_q}, \\ C_P' &= (C_P')^{4f} \simeq -806\ {\rm MeV}\, \frac{C_{ed}}{m_d} - 181\ {\rm MeV} \sum_{q=c,s,t,b} \frac{C_{eq}}{m_q} \end{aligned}$$

- More on Mercury EDM; M. Pospelov and A. Ritz, Annals Phys. **318** (2005) 119,[arXiv:hep-ph/0504231]

$$d_{\rm Hg} = (1.8 \times 10^{-3}\ {\rm GeV}^{-1})\, e\, \bar{g}^{(1)}_{\pi NN} + 10^{-2} d^E_e + (3.5 \times 10^{-3} {\rm GeV})\, e\, C_S$$
$$+ (4 \times 10^{-4}\ {\rm GeV})\, e \left[C_P + \left(\frac{Z-N}{A} \right)_{\rm Hg} C'_P \right],$$

$$\bar{g}^{(1)}_{\pi NN} = 2^{+4}_{-1} \times 10^{-12} \frac{(d^C_u - d^C_d)/g_s}{10^{-26}{\rm cm}} \frac{|\langle \bar{q}q \rangle|}{(225\,{\rm MeV})^3},$$

$$\bar{g}^{(1)}_{\pi NN} \sim -8 \times 10^{-3} {\rm GeV}^3 \left[\frac{0.5 C_{dd}}{m_d} + 3.3\kappa \frac{C_{sd}}{m_s} + (1 - 0.25\kappa) \frac{C_{bd}}{m_b} \right]$$

where $\mathcal{L}_{\pi NN} \supset \bar{g}^{(1)}_{\pi NN} \bar{N} N \pi^0$. Note that the factors 1.8×10^{-3} GeV^{-1} and 8×10^{-3} GeV^3 are known only up to 50 % accuracy.

- Deuteron EDM; O. Lebedev, K. A. Olive, M. Pospelov and A. Ritz, Phys. Rev. D **70** (2004) 016003,[arXiv:hep-ph/0402023]

$$
\begin{aligned}
d_D \;\simeq\; & -\left[5^{+11}_{-3} + (0.6 \pm 0.3)\right] \, e\,(d_u^C - d_d^C)/g_s \\
& -(0.2 \pm 0.1)\, e\,(d_u^C + d_d^C)/g_s \;+\; (0.5 \pm 0.3)(d_u^E + d_d^E) \\
& +(1 \pm 0.2) \times 10^{-2}\, e\,\mathrm{GeV}^2 \left[\frac{0.5 C_{dd}}{m_d} + 3.3\kappa \frac{C_{sd}}{m_s} + (1 - 0.25\kappa)\frac{C_{bd}}{m_b}\right] \\
& \pm\; e\,(20 \pm 10)\ \mathrm{MeV}\, d^{\,G}
\end{aligned}
$$

The projective sensitivity: Y. K. Semertzidis *et al.* [EDM Collaboration], AIP Conf. Proc. **698** (2004) 200, [arXiv:hep-ex/0308063]; Y. F. Orlov, W. M. Morse and Y. K. Semertzidis, Phys. Rev. Lett. **96** (2006) 214802, [arXiv:hep-ex/0605022]; and also see `http://www.bnl.gov/edm/deuteron_proposal_080423_final.pdf`

$$
|d_D| < 3 \times 10^{-27} - 10^{-29}\ e\,\mathrm{cm}
$$

For our numerical study, we take $3 \times 10^{-27}\ e\,\mathrm{cm}$ as a representative expected value

♠ *Observable EDMs* (8/9)

- To summarize;

$$d_{\rm Tl} = d_{\rm Tl}(d_e^E) + d_{\rm Tl}(C_S)$$

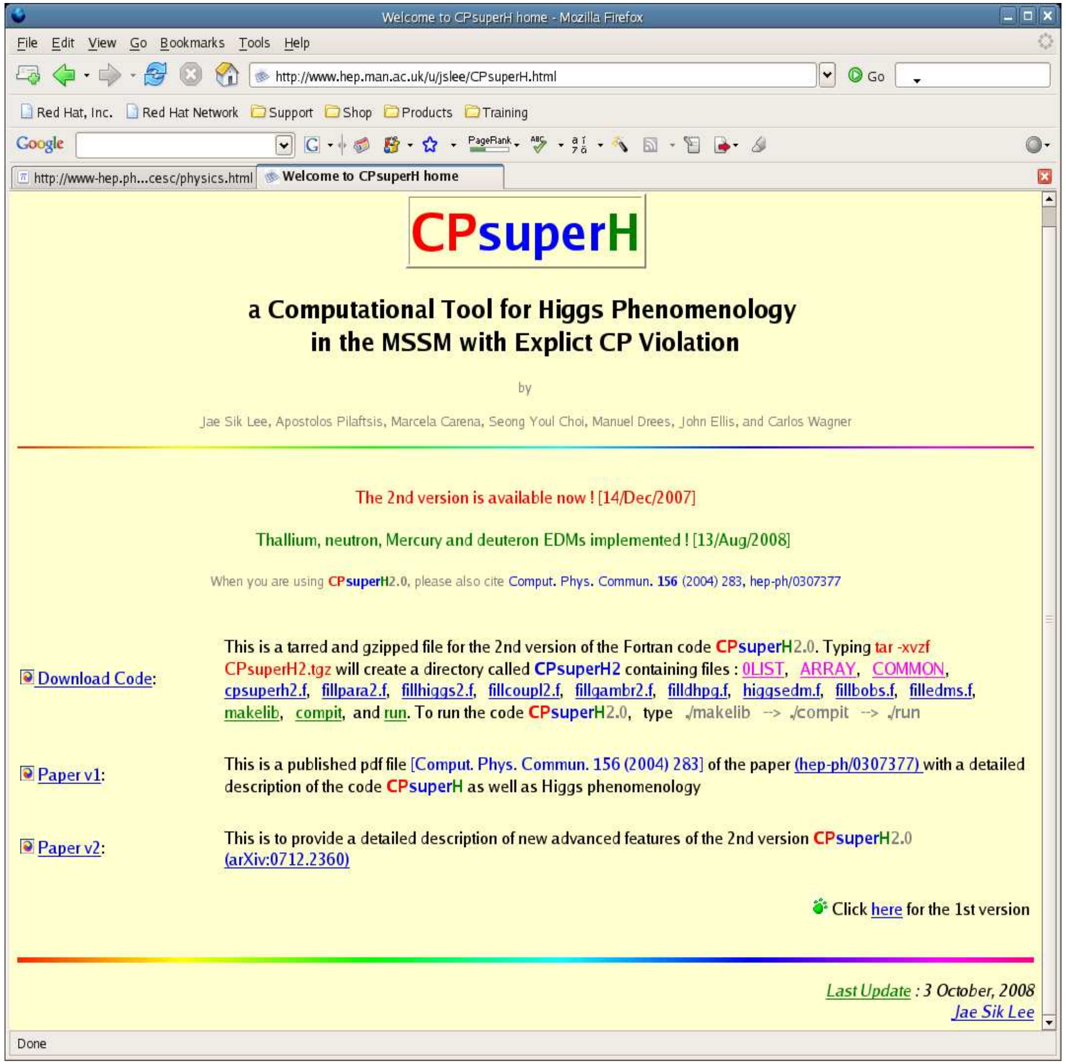
$$\begin{aligned} d_n\,({\rm CQM}) &= d_n(d^E_{u,d}) + d_n(d^C_{u,d}) + d_n(d^G) \\ d_n\,({\rm PQM}) &= d_n(d^E_u) + d_n(d^E_d) + d_n(d^E_s) \\ d_n\,({\rm QCD}) &= d_n(d^E_{u,d}) + d_n(d^C_{u,d}) + d_n(d^G) + d_n(C_{bd,db}) \end{aligned}$$

$$d_{\rm Hg} = d_{\rm Hg}(d_e^E) + d_{\rm Hg}(d^C_{u,d}) + d_{\rm Hg}(C_{4f}) + d_{\rm Hg}(C_S) + d_{\rm Hg}(C_P^{(\prime)})$$

$$d_D = d_D(d^E_{u,d}) + d_D(d^C_{u,d}) + d_n(C_{4f}) + d_n(d^G)$$

♠ *Observable EDMs* (9/9)

- The Thallium, neutron, Mercury and deuteron EDMs are implemented in an updated `CPsuperH2.0`;



♠ EDM Constraints (CPX) (1/14)

- CPX scenario:

Fixed :

$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\rm SUSY}\,,$$
$$|\mu| = 4\,M_{\rm SUSY}\,, \quad |A_{t,b,\tau}| = 2\,M_{\rm SUSY}\,, \quad |M_3| = 1 \ \ {\rm TeV}$$

$$|M_2| = 2|M_1| = 100 \ \ {\rm GeV}\,, M_{H^\pm} = 300 \ \ {\rm GeV}\,, M_{\rm SUSY} = 0.5 \ \ {\rm TeV}$$
$$|A_e| = |A_\tau|, |A_{u,c}| = |A_t|, |A_{d,s}| = |A_b|$$
$$\Phi_\mu = \Phi_{A_\tau} = \Phi_{A_e} = \Phi_{A_u} = \Phi_{A_c} = \Phi_{A_d} = \Phi_{A_s} = 0^\circ$$

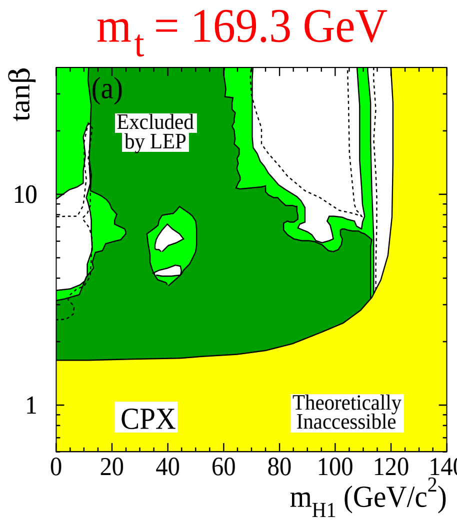
Varying :

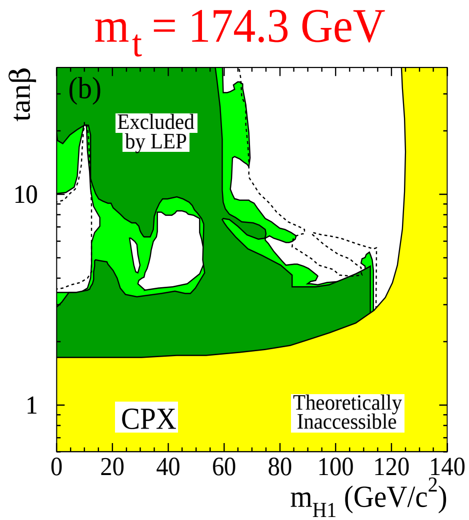
$$\tan\beta\,; \quad \Phi_{A_{t,b}}\,, \ \Phi_3\,; \quad \Phi_1\,, \ \Phi_2\,, \ \rho$$

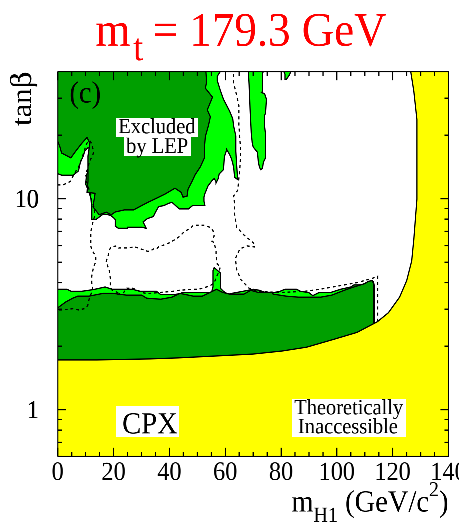
where the ρ parameter is defined as: $M_{\tilde{X}_{1,2}} = \rho\, M_{\tilde{X}_3}$ with $X = Q, U, D, L, E$

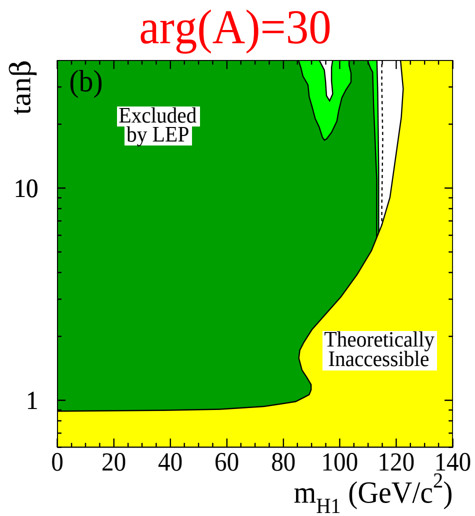
♠ *EDM Constraints (CPX)* (2/14)

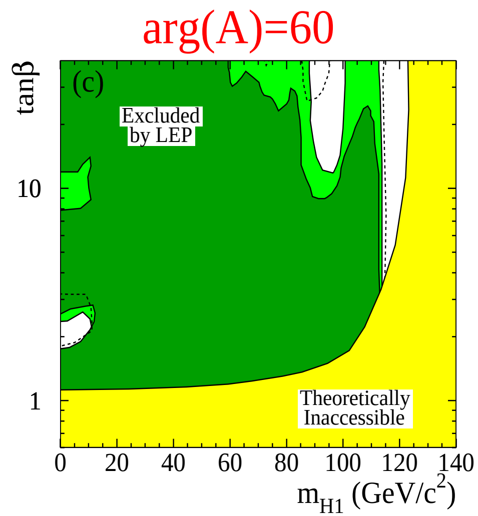
- <u>LEP Limit in the CPX scenario</u> : CPX Scenario with $\Phi_A = \Phi_3 = 90^\circ$ for three values of m_t (LEFT) and with $m_t = 174.3$ GeV for three values of $\Phi_A = \Phi_3$ (RIGHT) P. Bechtle, CPNSH Report, CERN-2006-009, hep-ph/0608079; ADLO, hep-ex/0602042 <u>Combined results with `FeynHiggs`</u>

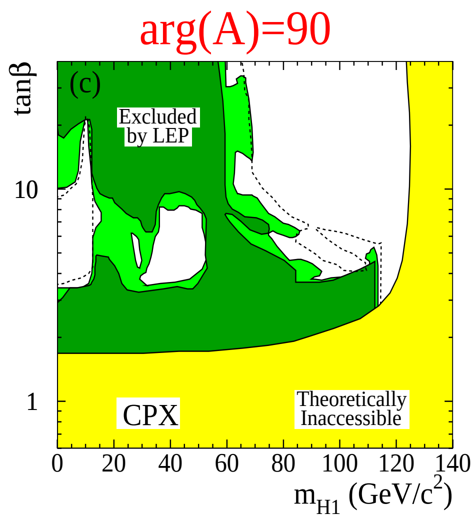










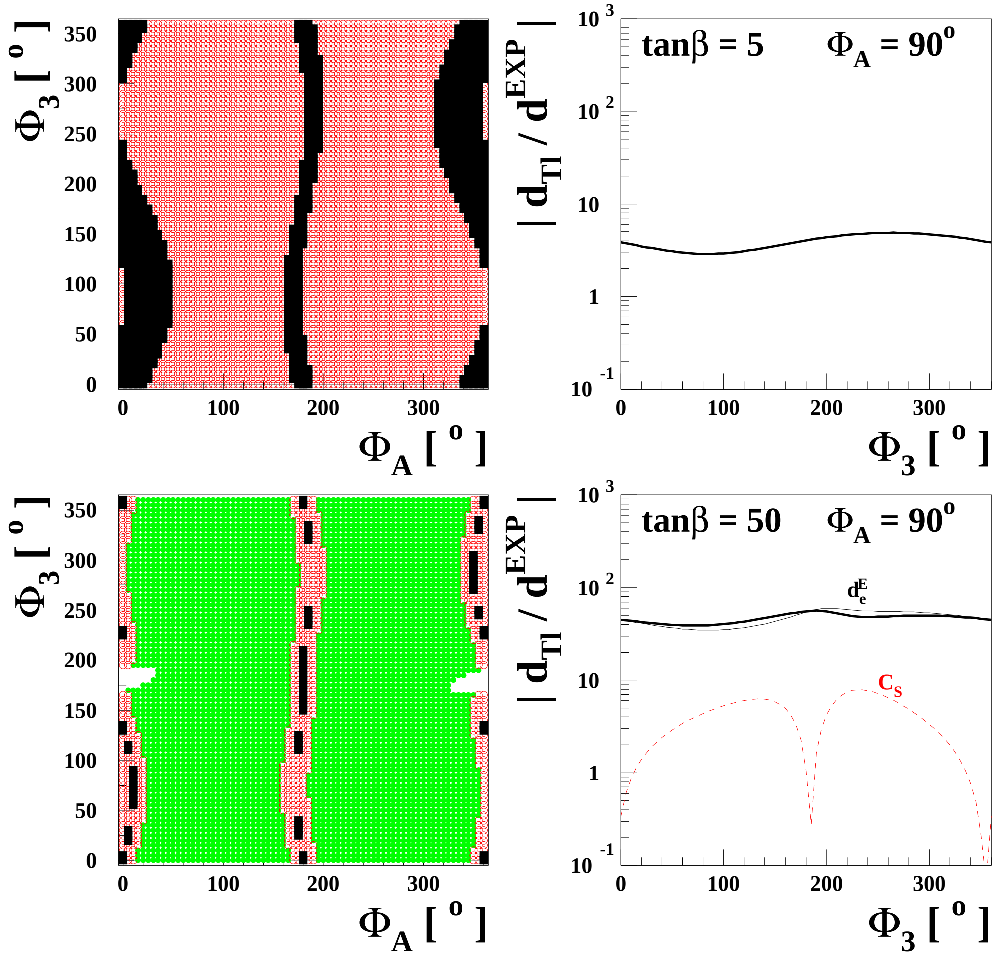


$\mathrm{CL} = 99.7\,\%$

$\mathrm{CL} = 95.0\,\%$

♠ *EDM Constraints (CPX)* (3/14)

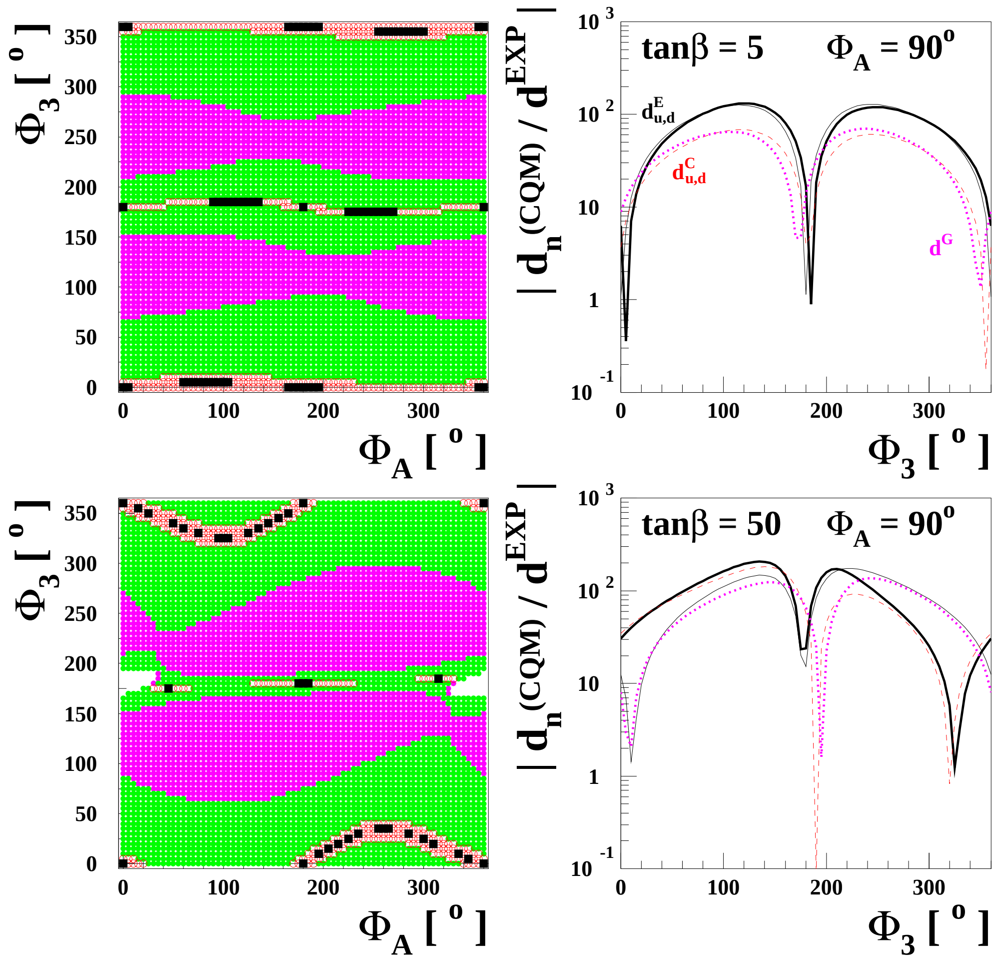
- Thallium EDM: CPX with $\Phi_1 = \Phi_2 = 0^\circ$ and $\rho = 1$;
  $|d/d^{\rm EXP}| = [< 1, 1 - 10, 10 - 100, > 100]$



- $d_{\rm Tl} \sim d_{\rm Tl}(d_e^E)$
- $d_e^E \sim (d_e^E)^H$
  $\rightarrow$ mild dependence on Φ_3
- $d_{\rm Tl}(d_e^E) \propto \tan\beta$
- $d_{\rm Tl}(C_S) \propto \tan^2\beta$

♠ *EDM Constraints (CPX)* (4/14)

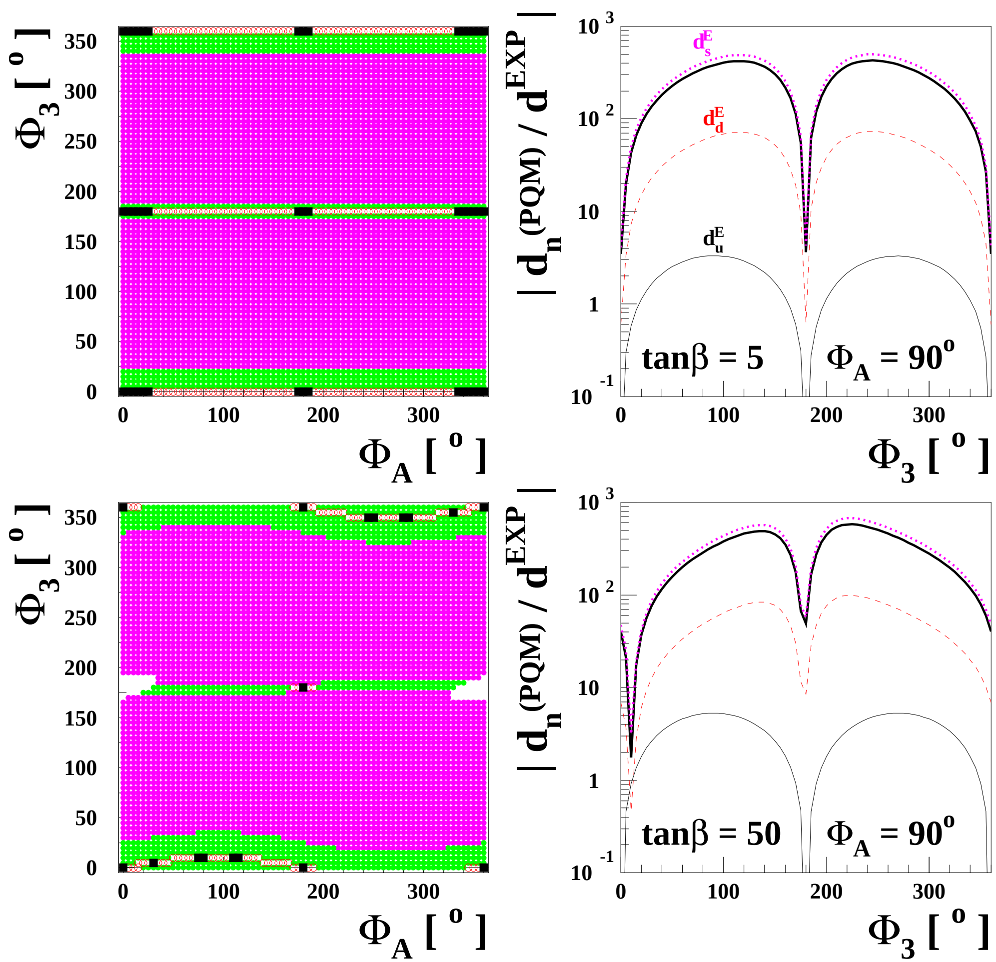
- Neutron EDM (CQM): CPX with $\Phi_1 = \Phi_2 = 0^\circ$ and $\rho = 1$;
  $|d/d^{\mathrm{EXP}}| = [< 1, 1 - 10, 10 - 100, > 100]$



- $d_n(d^E_{u,d}) \sim d_n(d^C_{u,d}) \sim d_n(d^G)$
- $d^{E,C}_d \sim (d^{E,C}_d)^{\tilde{g}}$:
  $\rightarrow$ mild Φ_A dependence
- subdominant $(d^{E,C}_d)^H \uparrow$ and $d^G \uparrow$ as $\tan\beta \uparrow$
- cancellation around $\Phi_3 = 320^\circ$ when $\tan\beta = 50$

♠ *EDM Constraints (CPX)* (5/14)

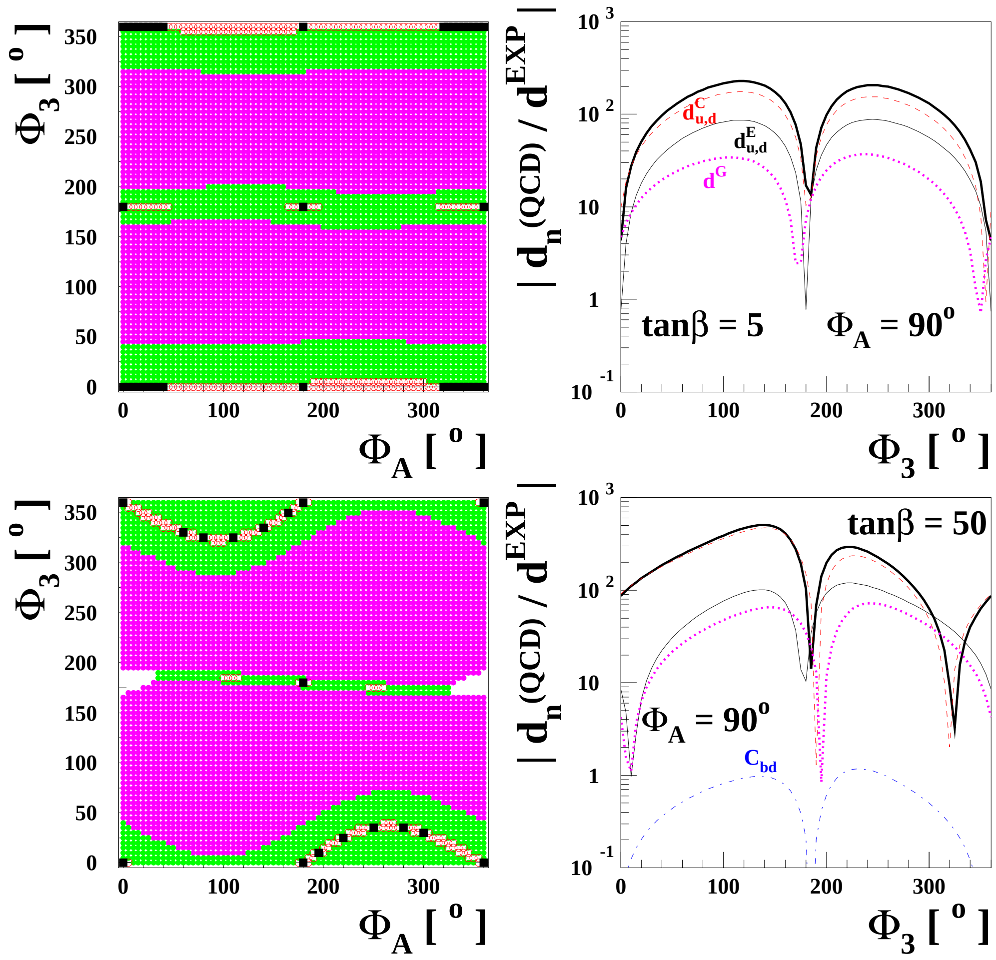
- Neutron EDM (PQM): CPX with $\Phi_1 = \Phi_2 = 0^\circ$ and $\rho = 1$;
  $|d/d^{\rm EXP}| = [< 1, 1 - 10, 10 - 100, > 100]$



- $d_n(d_s^E)$ dominates
- $d_s^E = (d_s^E)^{\tilde g}$ with subdominant $(d_s^E)^H$

♠ *EDM Constraints (CPX)* (6/14)

- Neutron EDM (QCD): CPX with $\Phi_1 = \Phi_2 = 0^\circ$ and $\rho = 1$;
  $|d/d^{\rm EXP}| = [< 1, 1 - 10, 10 - 100, > 100]$

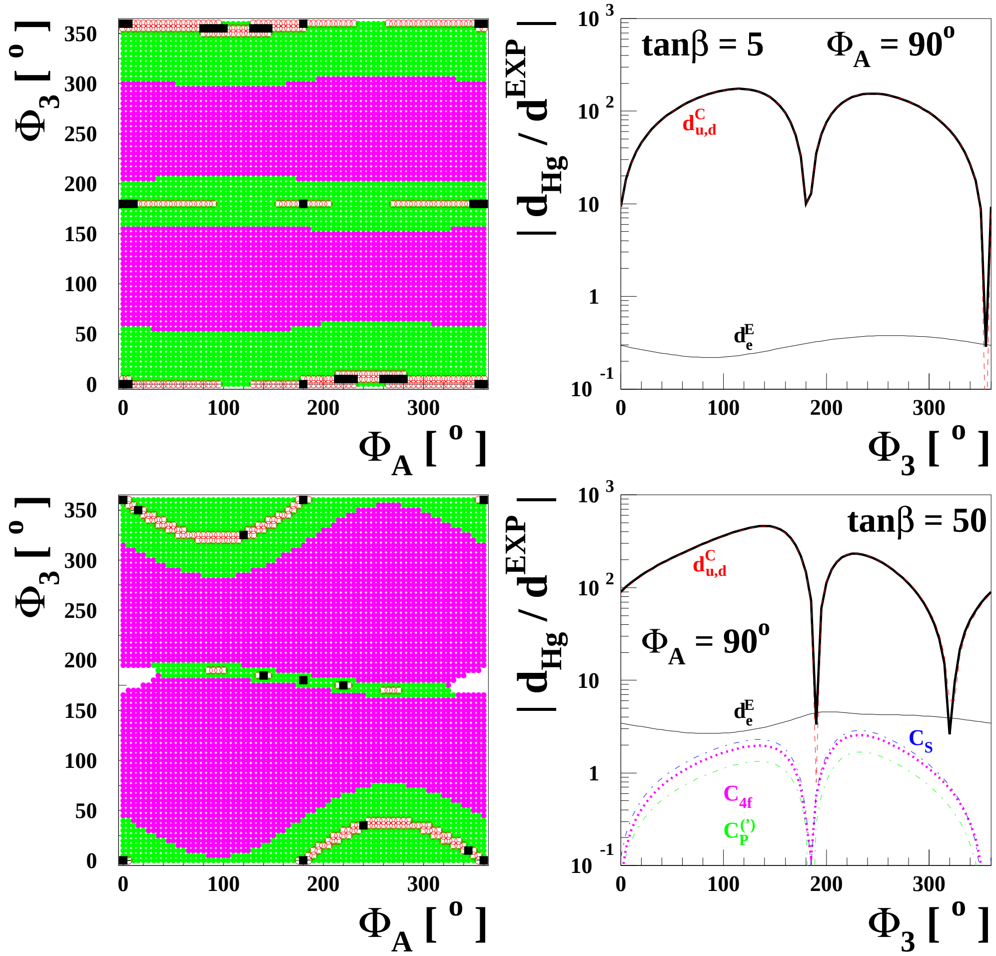


– $d_n(d_d^C)$ dominates with subdominant $d_n(d_d^E)$ and $d_n(d^G)$

– $d_n^{\rm QCD}(d_d^C) \sim 3\, d_n^{\rm CQM}(d_d^C)$
  $d_n^{\rm QCD}(d^G) \sim 0.5\, d_n^{\rm CQM}(d^G)$

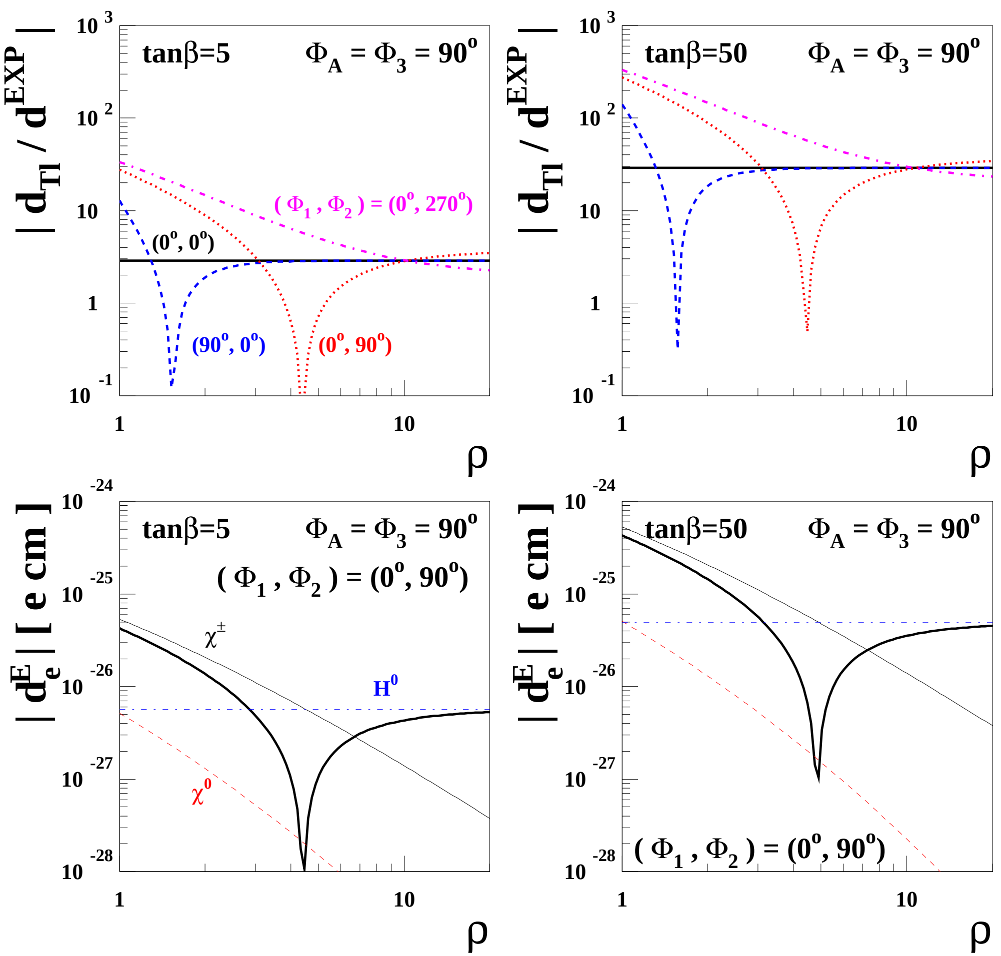
– cancellation around $\Phi_3 = 320^\circ$ when $\tan\beta = 50$

- Mercury EDM: CPX with $\Phi_1 = \Phi_2 = 0^\circ$ and $\rho = 1$;
  $|d/d^{\rm EXP}| = [< 1, 1-10, 10-100, > 100]$



  - $d_{\rm Hg}(d_d^C)$ dominates with subdominant $d_{\rm Hg}(d_e^E)$
  - For large $\tan\beta$, visible contributions from $C_{4f} \equiv C_{dd,sd,bd}$ and $C_{S,P}^{(\prime)}$

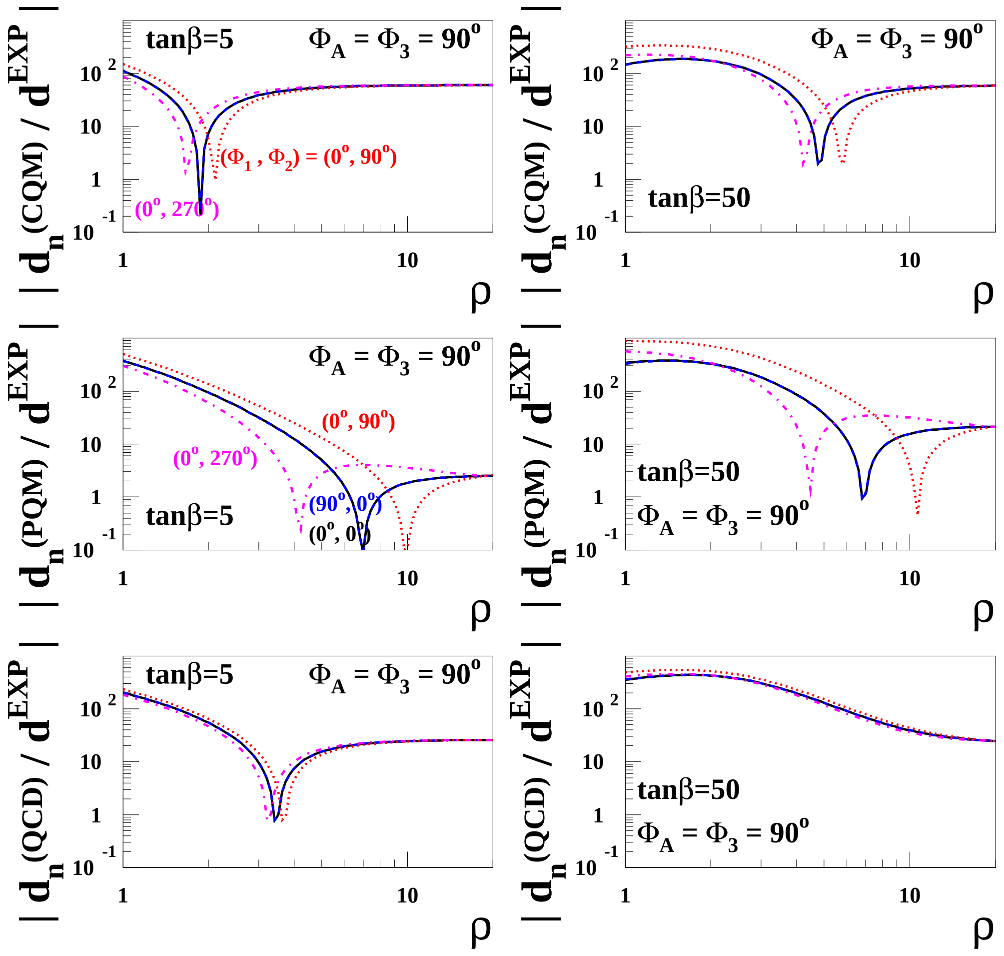
- Thallium EDM: CPX with $\Phi_A = \Phi_3 = 90^\circ$ as functions of ρ;



- When $(\Phi_1, \Phi_2) = (0^\circ, 0^\circ)$, $d_{\rm Tl} = d_{\rm Tl}(d_e^E)$ with $d_e^E = (d_e^E)^H \to \rho$ independence
- As $\rho \uparrow$; 'decrease' $\to$ 'dip' $\to$ 'flat'
- 'decrease': suppressed one-loop contribution
- 'dip': cancellation between one- and two-loop contributions
- 'flat': two-loop (higher-order) contribution dominates

♠ *EDM Constraints (CPX)* (9/14)

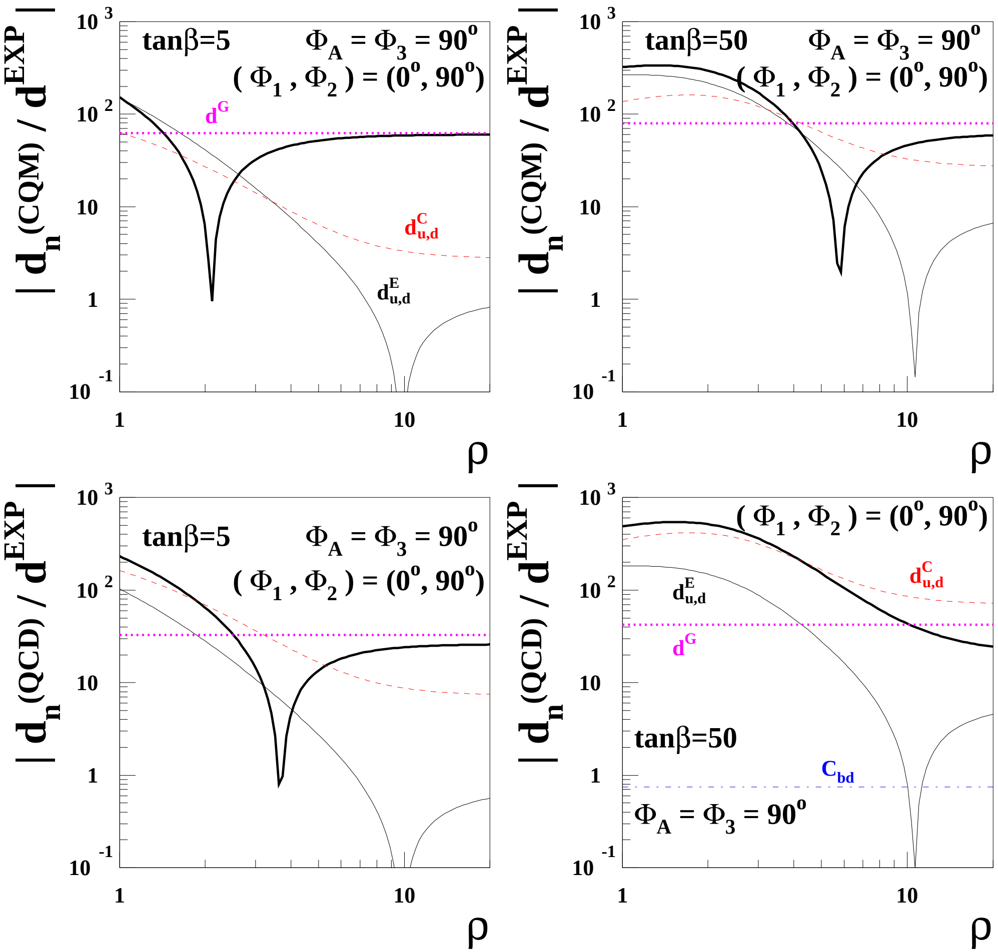
- Neutron EDM: CPX with $\Phi_A = \Phi_3 = 90^\circ$ as functions of ρ;



- no sensitive to Φ_1
- PQM is most sensitive to Φ_2
- QCD least sensitive to Φ_2
- position of dips depends on models/approaches

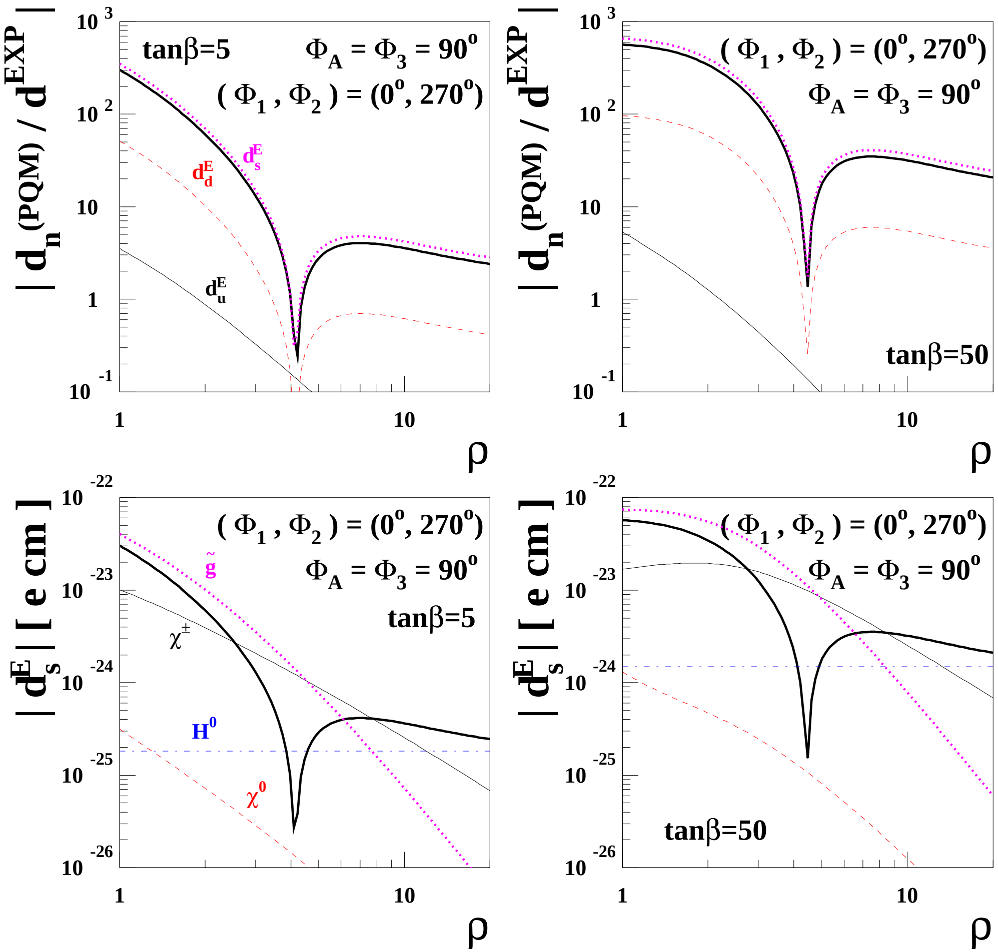
♠ *EDM Constraints (CPX)* (10/14)

- Neutron EDM (CQM and QCD): CPX with $\Phi_A = \Phi_3 = 90^\circ$ as functions of ρ;



- cancellation between $d_n(d_d^C)$ and $d_n(d^G)$
- 'flat': d^G and $(d_d^{E,C})^H$
- $\tan\beta = 5$: CQM dip around $\rho = 2$ and QCD dip around $\rho = 3.6$
- $\pm 50\%$ $d_n(d^G)$ uncertainty: no cancellation and/or dip position $\delta\rho \sim \pm 1$
- more significant $d_n(d_d^E)$ in CQM $\rightarrow$ more sensitive to Φ_2

- Neutron EDM (PQM): CPX with $\Phi_A = \Phi_3 = 90°$ as functions of ρ;



– $d_n \sim d_n(d_s^E)$

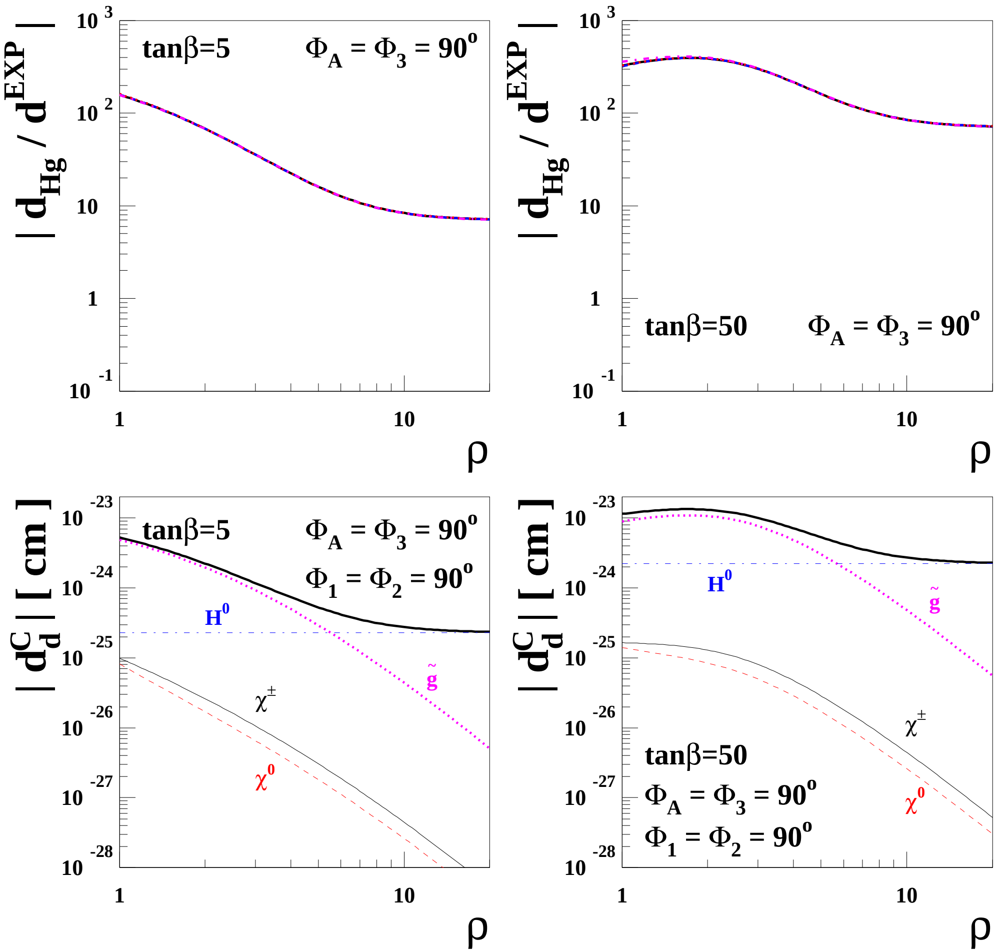
– $d_s^E \sim (d_s^E)^{\tilde{\chi}^\pm} + (d_s^E)^{\tilde{g}}$

– cancellation between the two dominant one-loop EDMs

– large $(d_s^E)^{\tilde{\chi}^\pm} \longrightarrow$ sensitive to Φ_2

♠ *EDM Constraints (CPX)* (12/14)

- Mercury EDM: CPX with $\Phi_A = \Phi_3 = 90^\circ$ as functions of ρ;



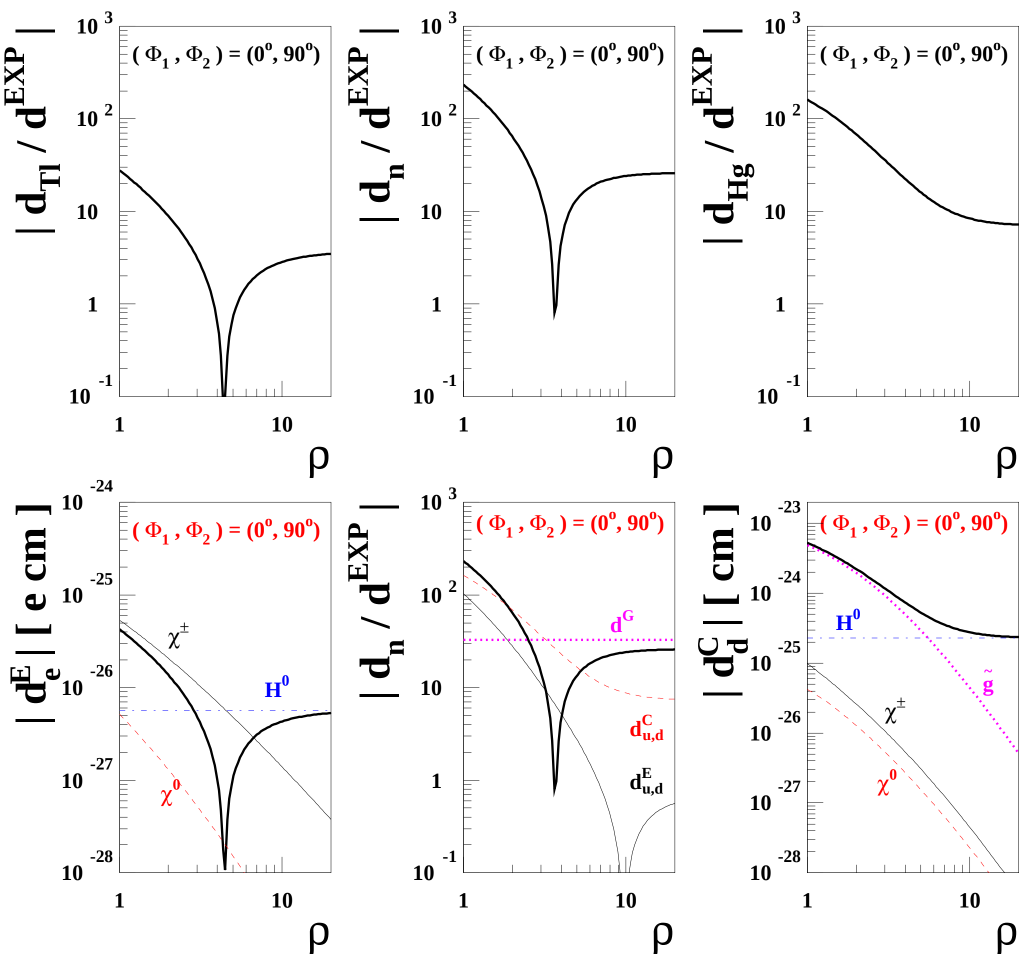
– dominance of $d_{\rm Hg}(d_d^C)$ $\rightarrow$ no sensitive to $\Phi_{1,2}$

– no cancellation between $(d_d^C)^{\tilde g}$ and $(d_d^C)^H$

– 'flat': $(d_d^C)^H$

♠ *EDM Constraints (CPX)* (13/14)

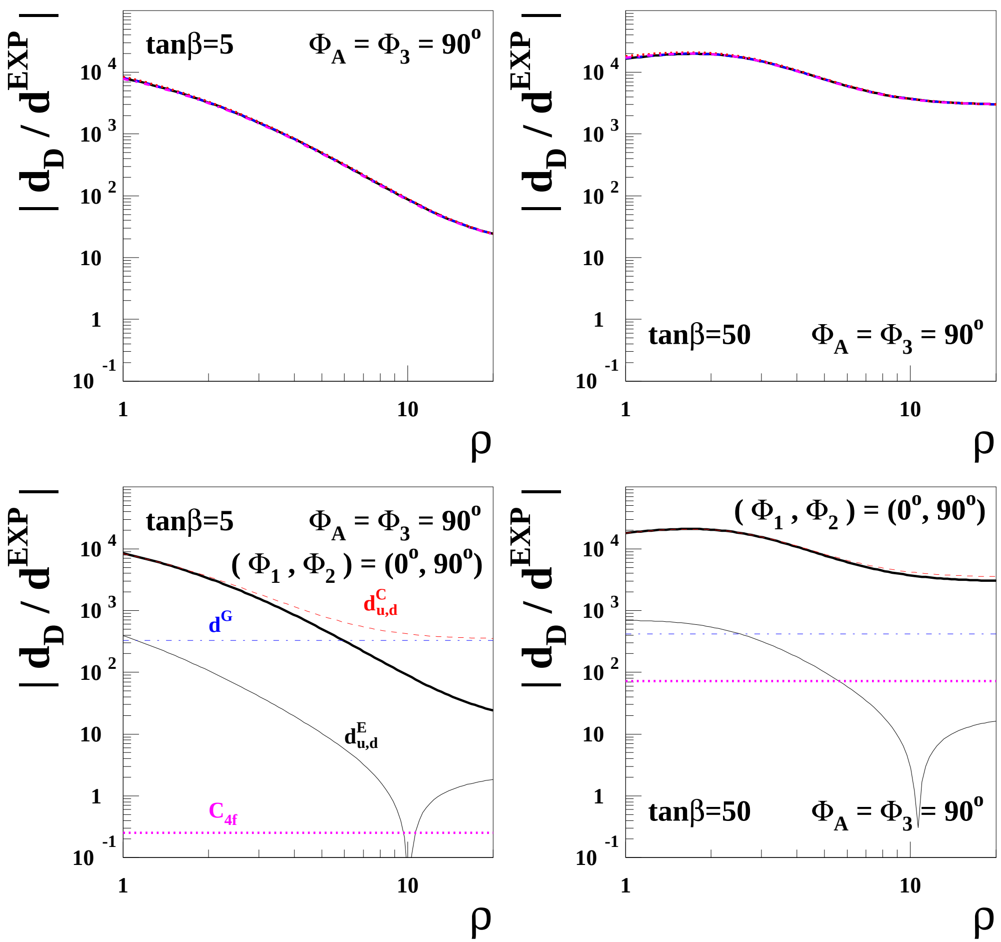
- Thallium, neutron(QCD), and Mercury EDMs: CPX with $\Phi_1 = 0^\circ, \Phi_2 = 90^\circ, \Phi_A = \Phi_3 = 90^\circ$ as functions of ρ when $\tan\beta = 5$;



– $\rho \sim 4$?

♠ *EDM Constraints (CPX)* (14/14)

- Deuteron EDM: CPX with $\Phi_A = \Phi_3 = 90^\circ$ as functions of ρ;



  - no sensitive to $\Phi_{1,2}$
  - Very sensitive even to the higher-order corrections
  - 300 times more sensitive if the projective $10^{-29} e\,cm$ achieved

♠ *Summary*

- We present the most comprehensive study of the Thallium, neutron, Mercury, and deuteron EDMs

- We improve upon earlier calculations by including the resummation effects due to CP-violating Higgs-boson mixing and to threshold corrections

- Large CP phases may be possible avoiding all existing EDM constraints

- The analytic expressions for the EDMs are implemented in an updated version of the code `CPsuperH2.0`