



Electric Dipole Moments in the **MSSM**

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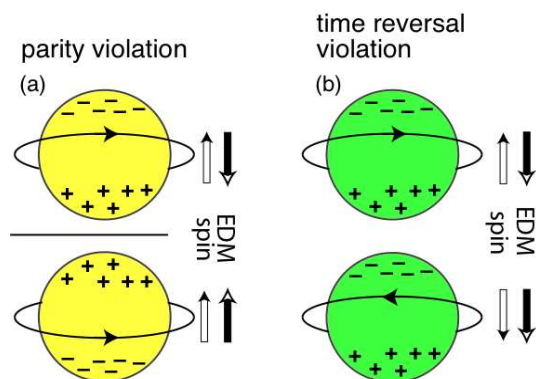
PPP8@NCKU, Tainan, Taiwan, May 20–23, 2009



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

♠ Preliminary

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



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

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

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

- ♠ *CP phases in the MSSM*
- ♠ *One-loop EDMs of leptons and quarks*
- ♠ *Higher-order contributions*
- ♠ *Observable EDMs*
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- ♠ *Summary*

♠ Introduction (1/3)

- CP phases in the MSSM:

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

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

- $\text{Arg} \left(\mathbf{M}_{\tilde{Q}, \tilde{L}, \tilde{u}, \tilde{d}, \tilde{e}}^2 \right)_{i < j}$ [$5 \times 3 \rightarrow 0_{\text{NFV}}$]:

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

- $\text{Arg} (\mathbf{A}_{u,d,e})_{i,j}$ [$3 \times 9 \rightarrow (3 \times 3)_{\text{NFV}}$]:

$$-\mathcal{L}_{\text{soft}} \supset +(\tilde{u}_R^* \mathbf{A}_u \tilde{Q} H_2 - \tilde{d}_R^* \mathbf{A}_d \tilde{Q} H_1 - \tilde{e}_R^* \mathbf{A}_e \tilde{L} H_1 + \text{h.c.})$$

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

♠ Introduction (2/3)

- Physical observables depend on : $\text{Arg}(M_i \mu (m_{12}^2)^*)$ and $\text{Arg}(A_f \mu (m_{12}^2)^*)$ 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**

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

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

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

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

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

♠ Introduction (3/3)

- Our convention for EDMs and CEDMs:

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

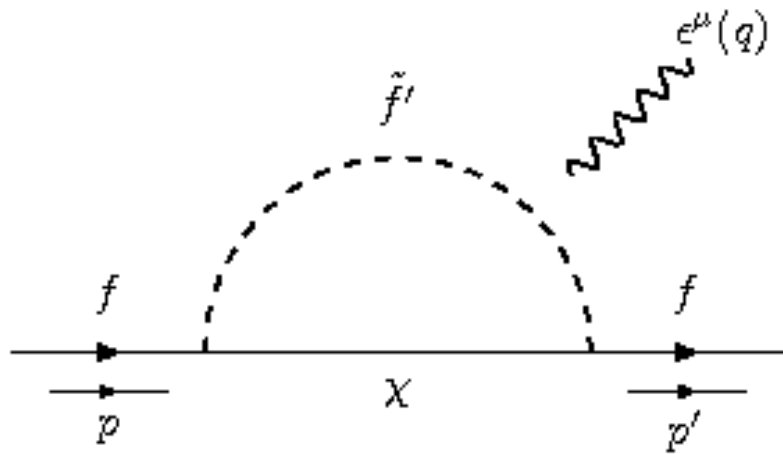
$$d_f^E/e = (d_f^E/e)^{\tilde{x}^\pm} + (d_f^E/e)^{\tilde{x}^0} + (d_f^E/e)^{\tilde{g}} + (d_f^E/e)^H$$

$$d_q^C = (d_q^C)^{\tilde{x}^\pm} + (d_q^C)^{\tilde{x}^0} + (d_q^C)^{\tilde{g}} + (d_q^C)^H$$

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

♠ One-loop EDMs (1/5)

- 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]



$$\mathcal{L}_{\chi\chi A} = -e Q_\chi (\bar{\chi}\gamma_\mu\chi) A^\mu$$

$$\mathcal{L}_{\tilde{f}'\tilde{f}'A} = -ie Q_{\tilde{f}'} \tilde{f}'^* \overleftrightarrow{\partial}_\mu \tilde{f}' A^\mu$$

$$\mathcal{L}_{\chi f \tilde{f}'} = g_{Lij}^{\chi f \tilde{f}'} (\bar{\chi}_i P_L f) \tilde{f}'_j^* + g_{Rij}^{\chi f \tilde{f}'} (\bar{\chi}_i P_R f) \tilde{f}'_j^* + \text{h.c.}$$

$$\left(\frac{d_f^E}{e}\right)^\chi = \frac{m_{\chi_i}}{16\pi^2 m_{\tilde{f}'_j}^2} \Im \left[(g_{Rij}^{\chi f \tilde{f}'})^* g_{Lij}^{\chi f \tilde{f}'} \right] \left[Q_\chi A(m_{\chi_i}^2/m_{\tilde{f}'_j}^2) + Q_{\tilde{f}'} B(m_{\chi_i}^2/m_{\tilde{f}'_j}^2) \right]$$

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

♠ One-loop EDMs (2/5)

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

$$\left(\frac{d_l^E}{e}\right)^{\tilde{\chi}^\pm} = \frac{1}{16\pi^2} \sum_i \frac{m_{\tilde{\chi}_i^\pm}}{m_{\tilde{\nu}_l}^2} \Im[(g_{Ri}^{\tilde{\chi}^\pm l \tilde{\nu}})^* g_{Li}^{\tilde{\chi}^\pm l \tilde{\nu}}] Q_{\tilde{\chi}^-} A(m_{\tilde{\chi}_i^\pm}^2/m_{\tilde{\nu}_l}^2)$$

$$\left(\frac{d_u^E}{e}\right)^{\tilde{\chi}^\pm} = \frac{1}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}_i^\pm}}{m_{\tilde{d}_j}^2} \Im[(g_{Rij}^{\tilde{\chi}^\pm u \tilde{d}})^* g_{Lij}^{\tilde{\chi}^\pm u \tilde{d}}] [Q_{\tilde{\chi}^+} A(m_{\tilde{\chi}_i^\pm}^2/m_{\tilde{d}_j}^2) + Q_{\tilde{d}} B(m_{\tilde{\chi}_i^\pm}^2/m_{\tilde{d}_j}^2)]$$

$$\left(\frac{d_d^E}{e}\right)^{\tilde{\chi}^\pm} = \frac{1}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}_i^\pm}}{m_{\tilde{u}_j}^2} \Im[(g_{Rij}^{\tilde{\chi}^\pm d \tilde{u}})^* g_{Lij}^{\tilde{\chi}^\pm d \tilde{u}}] [Q_{\tilde{\chi}^-} A(m_{\tilde{\chi}_i^\pm}^2/m_{\tilde{u}_j}^2) + Q_{\tilde{u}} B(m_{\tilde{\chi}_i^\pm}^2/m_{\tilde{u}_j}^2)]$$

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

$$\begin{aligned} g_{Li}^{\tilde{\chi}^\pm l \tilde{\nu}} &= -g(C_R)_{i1}, & g_{Ri}^{\tilde{\chi}^\pm l \tilde{\nu}} &= h_l^*(C_L)_{i2}, \\ g_{Lij}^{\tilde{\chi}^\pm u \tilde{d}} &= -g(C_L)_{i1}^*(U^{\tilde{d}})_{1j}^* + h_d(C_L)_{i2}^*(U^{\tilde{d}})_{2j}^*, & g_{Rij}^{\tilde{\chi}^\pm u \tilde{d}} &= h_u^*(C_R)_{i2}^*(U^{\tilde{d}})_{1j}^*, \\ g_{Lij}^{\tilde{\chi}^\pm d \tilde{u}} &= -g(C_R)_{i1}(U^{\tilde{u}})_{1j}^* + h_u(C_R)_{i2}(U^{\tilde{u}})_{2j}^*, & g_{Rij}^{\tilde{\chi}^\pm d \tilde{u}} &= h_d^*(C_L)_{i2}(U^{\tilde{u}})_{1j}^* \end{aligned}$$

♠ One-loop EDMs (3/5)

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

$$\left(\frac{d_f^E}{e}\right)^{\tilde{\chi}^0} = \frac{1}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}_i^0}}{m_{\tilde{f}_j}^2} \Im\text{m}[(g_{Rij}^{\tilde{\chi}^0 f \tilde{f}})^* g_{Lij}^{\tilde{\chi}^0 f \tilde{f}}] Q_{\tilde{f}} B(m_{\tilde{\chi}_i^0}^2/m_{\tilde{f}_j}^2)$$

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

$$\begin{aligned} g_{Lij}^{\tilde{\chi}^0 f \tilde{f}} &= -\sqrt{2} g T_3^f N_{i2}^* (U^{\tilde{f}})_{1j}^* - \sqrt{2} g t_W (Q_f - T_3^f) N_{i1}^* (U^{\tilde{f}})_{1j}^* - h_f N_{i\alpha}^* (U^{\tilde{f}})_{2j}^*, \\ g_{Rij}^{\tilde{\chi}^0 f \tilde{f}} &= \sqrt{2} g t_W Q_f N_{i1} (U^{\tilde{f}})_{2j}^* - h_f^* N_{i\alpha} (U^{\tilde{f}})_{1j}^* \end{aligned}$$

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

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

$$\left(\frac{d_q^E}{e}\right)^{\tilde{g}} = \frac{1}{3\pi^2} \sum_j \frac{|M_3|}{m_{\tilde{q}_j}^2} \Im\text{m}[(g_{Rj}^{\tilde{g} q \tilde{q}})^* g_{Lj}^{\tilde{g} q \tilde{q}}] Q_{\tilde{q}} B(|M_3|^2/m_{\tilde{q}_j}^2)$$

$$g_{Lj}^{\tilde{g} q \tilde{q}} = -\frac{g_s}{\sqrt{2}} e^{-i\Phi_3/2} (U^{\tilde{q}})_{1j}^*, \quad g_{Rj}^{\tilde{g} q \tilde{q}} = +\frac{g_s}{\sqrt{2}} e^{+i\Phi_3/2} (U^{\tilde{q}})_{2j}^*$$

♠ One-loop EDMs (4/5)

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

$$\left(d_u^C\right)^{\tilde{\chi}^\pm} = \frac{g_s}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}_i^\pm}}{m_{\tilde{d}_j}^2} \Im\left[(g_{Rij}^{\tilde{\chi}^\pm u\tilde{d}})^* g_{Lij}^{\tilde{\chi}^\pm u\tilde{d}}\right] B(m_{\tilde{\chi}_i^\pm}^2/m_{\tilde{d}_j}^2),$$

$$\left(d_d^C\right)^{\tilde{\chi}^\pm} = \frac{g_s}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}_i^\pm}}{m_{\tilde{u}_j}^2} \Im\left[(g_{Rij}^{\tilde{\chi}^\pm d\tilde{u}})^* g_{Lij}^{\tilde{\chi}^\pm d\tilde{u}}\right] B(m_{\tilde{\chi}_i^\pm}^2/m_{\tilde{u}_j}^2),$$

$$\left(d_{q=u,d}^C\right)^{\tilde{\chi}^0} = \frac{g_s}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}_i^0}}{m_{\tilde{q}_j}^2} \Im\left[(g_{Rij}^{\tilde{\chi}^0 q\tilde{q}})^* g_{Lij}^{\tilde{\chi}^0 q\tilde{q}}\right] B(m_{\tilde{\chi}_i^0}^2/m_{\tilde{q}_j}^2),$$

$$\left(d_{q=u,d}^C\right)^{\tilde{g}} = -\frac{g_s}{8\pi^2} \sum_j \frac{|M_3|}{m_{\tilde{q}_j}^2} \Im\left[(g_{Rj}^{\tilde{g}q\tilde{q}})^* g_{Lj}^{\tilde{g}q\tilde{q}}\right] C(|M_3|^2/m_{\tilde{q}_j}^2)$$

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

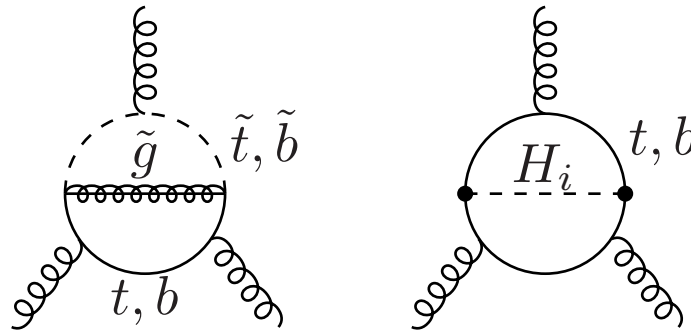
$$\Delta_u = \frac{2\alpha_s}{3\pi} \mu^* M_3^* I(M_{\tilde{U}_1}^2, M_{\tilde{Q}_1}^2, |M_3|^2), \quad \Delta_c = \frac{2\alpha_s}{3\pi} \mu^* M_3^* I(M_{\tilde{U}_2}^2, M_{\tilde{Q}_2}^2, |M_3|^2),$$

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

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



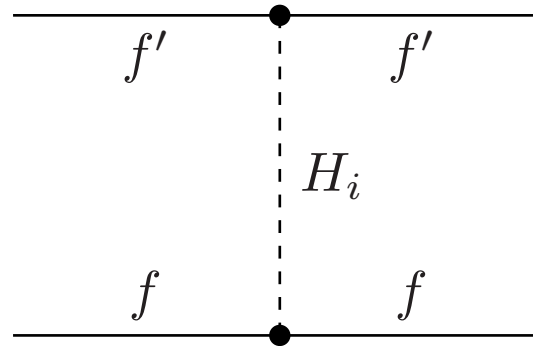
$$\mathcal{L}_{\text{Weinberg}} = -\frac{1}{6} d^G f_{abc} G_{\mu\rho}^a G_{\nu}^{b\rho} G_{\lambda\sigma}^c \epsilon^{\mu\nu\lambda\sigma} = \frac{1}{3} d^G f_{abc} G_{\rho\mu}^a \tilde{G}^{b\mu\nu} G_{\nu}^{c\rho}$$

where

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

♠ Higher-order Contributions (2/4)

- Higgs-mediated Four-fermion interactions;



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

where

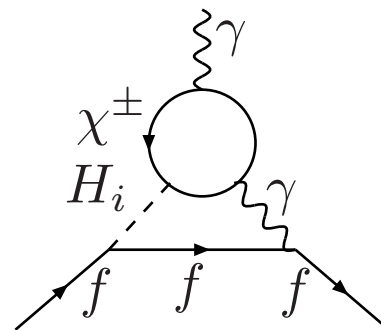
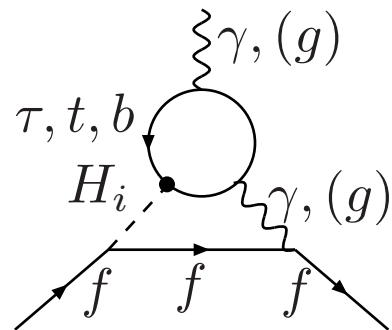
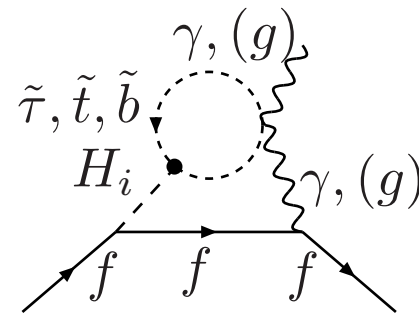
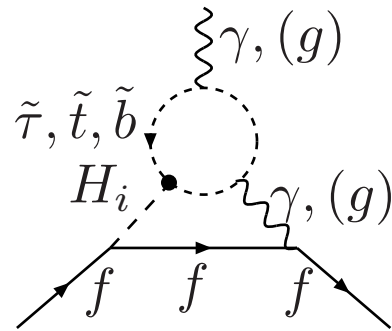
$$(C_{ff'})^H = g_f g_{f'} \sum_i \frac{g_{H_i \bar{f} f}^S g_{H_i \bar{f}' f'}^P}{M_{H_i}^2}$$

$$\mathcal{L}_{Hff} = -g_f H_i \bar{f} (g_{H_i \bar{f} f}^S + i g_{H_i \bar{f} f}^P \gamma_5) f$$

♠ Higher-order Contributions (3/4)

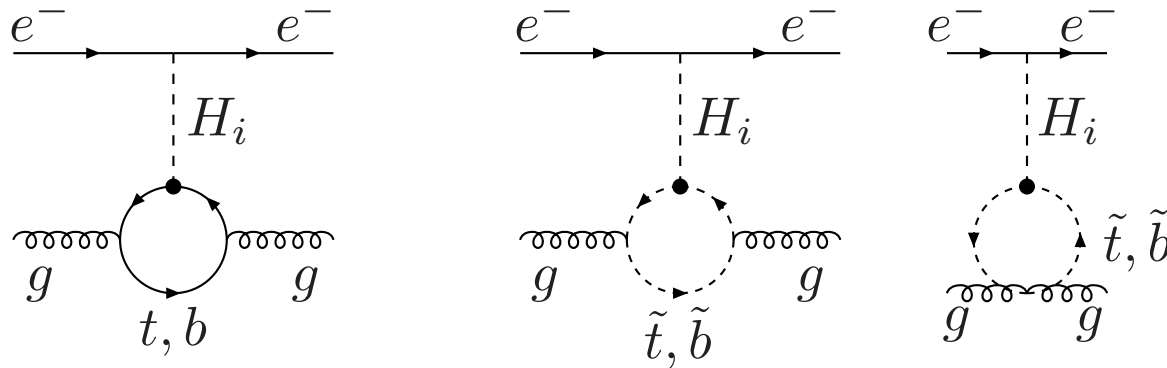
- Higgs-mediated Barr-Zee graphs; D. Chang, W. Y. Keung and A. Pilaftsis, Phys. Rev. Lett. **82** (1999) 900 [Erratum-ibid. **83** (1999) 3972], [arXiv:hep-ph/9811202]; A. Pilaftsis, A. Pilaftsis, Nucl. Phys. B **644** (2002) 263, [arXiv:hep-ph/0207277]; J. R. Ellis, JSL and A. Pilaftsis, Phys. Rev. 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 , $\mathcal{L}_{C_S} = C_S \bar{e} i \gamma_5 e \bar{N} N$;



$$(C_S)^g = (0.1 \text{ GeV}) \frac{m_e}{v^2} \sum_{i=1}^3 \frac{g_{H_i gg}^S g_{H_i \bar{e} e}^P}{M_{H_i}^2}$$

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

♠ 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]

$$d_{\text{Tl}} [e \text{ cm}] = -585 \cdot d_e^E [e \text{ cm}] - 8.5 \times 10^{-19} [e \text{ cm}] \cdot (C_S \text{ TeV}^2) + \dots$$

$$d_e^E = (d_e^E)^{\tilde{\chi}^\pm} + (d_e^E)^{\tilde{\chi}^0} + (d_e^E)^H$$
$$C_S = (C_S)^{4f} + (C_S)^g$$

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

♠ *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]

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

$$d_{q=u,d}^{\text{NDA}} = \eta^E d_q^E + \eta^C \frac{e}{4\pi} d_q^C + \eta^G \frac{e\Lambda}{4\pi} d^G,$$

$$d_{q=u,d}^{E(C)} = (d_q^{E(C)})^{\tilde{\chi}^\pm} + (d_q^{E(C)})^{\tilde{\chi}^0} + (d_q^{E(C)})^{\tilde{g}} + (d_q^{E(C)})^H$$

where $\eta^E \simeq 1.53$, $\eta^C \simeq \eta^G \simeq 3.4$ 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]

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

with

$$\Delta_d^{\text{PQM}} = 0.746, \quad \Delta_u^{\text{PQM}} = -0.508, \quad \Delta_s^{\text{PQM}} = -0.226$$

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]

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

$$d_n(d_q^E, d_q^C) = (1.4 \pm 0.6) (d_d^E - 0.25 d_u^E) + (1.1 \pm 0.5) e (d_d^C + 0.5 d_u^C) / g_s,$$

$$d_n(d^G) \sim \pm e (20 \pm 10) \text{ MeV } d^G,$$

$$d_n(C_{bd}) \sim \pm e 2.6 \times 10^{-3} \text{ GeV}^2 \left[\frac{C_{bd}}{m_b} + 0.75 \frac{C_{db}}{m_b} \right]$$

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

♠ 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]

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

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

$$C_P = (C_P)^{4f} \simeq -375 \text{ MeV} \sum_{q=c,s,t,b} \frac{C_{eq}}{m_q},$$

$$C'_P = (C'_P)^{4f} \simeq -806 \text{ MeV} \frac{C_{ed}}{m_d} - 181 \text{ MeV} \sum_{q=c,s,t,b} \frac{C_{eq}}{m_q}$$

♠ Observable EDMs (6/9)

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

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

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

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

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

♠ Observable EDMs (7/9)

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

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

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

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

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

♠ Observable EDMs (8/9)

- To summarize;

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

$$d_n(\text{CQM}) = d_n(d_{u,d}^E) + d_n(d_{u,d}^C) + d_n(d^G)$$

$$d_n(\text{PQM}) = d_n(d_u^E) + d_n(d_d^E) + d_n(d_s^E)$$

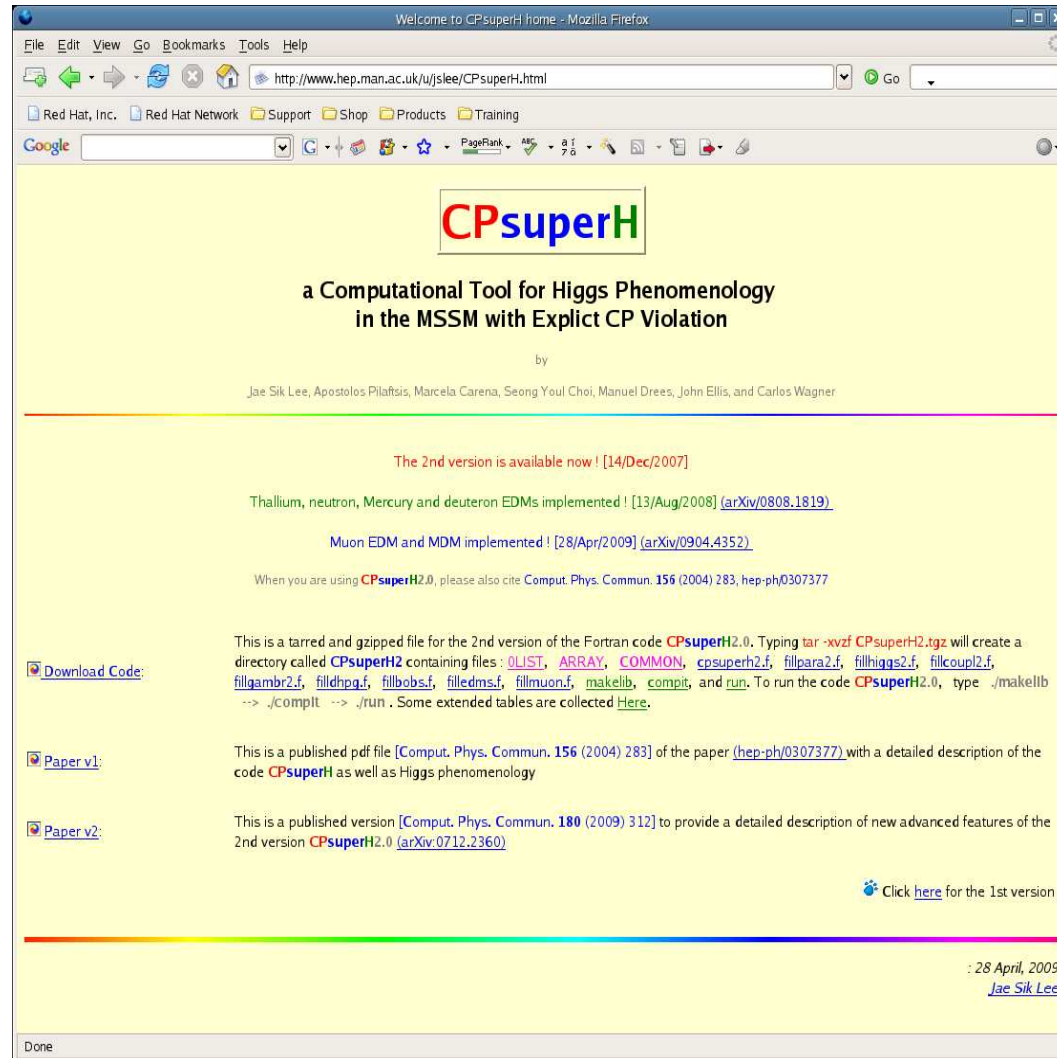
$$d_n(\text{QCD}) = d_n(d_{u,d}^E) + d_n(d_{u,d}^C) + d_n(d^G) + d_n(C_{bd,db})$$

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

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

♠ Observable EDMs (9/9)

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



The screenshot shows a Mozilla Firefox browser window displaying the CPsuperH website. The address bar shows the URL <http://www.hep.man.ac.uk/u/jslee/CPsuperH.html>. The page features the CPsuperH logo and the title "a Computational Tool for Higgs Phenomenology in the MSSM with Explicit CP Violation". The authors listed are Jae Sik Lee, Apostolos Pilaftsis, Marcela Carena, Seong Youl Choi, Manuel Drees, John Ellis, and Carlos Wagner. A red announcement states "The 2nd version is available now! [14/Dec/2007]". Below this, two news items are listed: "Thallium, neutron, Mercury and deuteron EDMs implemented! [13/Aug/2008] (arXiv/0808.1819)." and "Muon EDM and MDM implemented! [28/Apr/2009] (arXiv/0904.4352)". A citation instruction reads: "When you are using CPsuperH2.0, please also cite Comput. Phys. Commun. 156 (2004) 283, hep-ph/0307377". There are three sections with icons: "Download Code:" with instructions on how to use the tar file, "Paper v1:" with a link to the published paper, and "Paper v2:" with a link to a newer version of the paper. A footer at the bottom right says ": 28 April, 2009" and "Jae Sik Lee".

Welcome to CPsuperH home - Mozilla Firefox

File Edit View Go Bookmarks Tools Help

<http://www.hep.man.ac.uk/u/jslee/CPsuperH.html> Go

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CPsuperH

a Computational Tool for Higgs Phenomenology
in the MSSM with Explicit CP Violation

by
Jae Sik Lee, Apostolos Pilaftsis, Marcela Carena, Seong Youl Choi, Manuel Drees, John Ellis, and Carlos Wagner

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When you are using CPsuperH2.0, please also cite *Comput. Phys. Commun.* **156** (2004) 283, [hep-ph/0307377](#)

This is a tarred and gzipped file for the 2nd version of the Fortran code CPsuperH2.0. Typing `tar -xvzf CPsuperH2.tgz` will create a directory called CPsuperH2 containing files: `OLIST`, `ARRAY`, `COMMON`, `cpsuperh2.f`, `fillpara2.f`, `fillhiggs2.f`, `fillcoup2.f`, `fillgambr2.f`, `filldhpq.f`, `fillbobs.f`, `filledms.f`, `fillmuon.f`, `makelib`, `compit`, and `run`. To run the code CPsuperH2.0, type `./makelib --> ./compit --> ./run`. Some extended tables are collected [Here](#).

[Download Code:](#)

[Paper v1:](#) This is a published pdf file [*Comput. Phys. Commun.* **156** (2004) 283] of the paper ([hep-ph/0307377](#)) with a detailed description of the code CPsuperH as well as Higgs phenomenology

[Paper v2:](#) This is a published version [*Comput. Phys. Commun.* **180** (2009) 312] to provide a detailed description of new advanced features of the 2nd version CPsuperH2.0 ([arXiv:0712.2360](#))

[Click here](#) for the 1st version

: 28 April, 2009
Jae Sik Lee

Done

♠ EDM Constraints (CPX) (1/14)

- CPX scenario:

Fixed :

$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\text{SUSY}},$$

$$|\mu| = 4 M_{\text{SUSY}}, \quad |A_{t,b,\tau}| = 2 M_{\text{SUSY}}, \quad |M_3| = 1 \text{ TeV}$$

$$|M_2| = 2|M_1| = 100 \text{ GeV}, \quad M_{H^\pm} = 300 \text{ GeV}, \quad M_{\text{SUSY}} = 0.5 \text{ TeV}$$

$$|A_e| = |A_\tau|, \quad |A_{u,c}| = |A_t|, \quad |A_{d,s}| = |A_b|$$

$$\Phi_\mu = \Phi_{A_\tau} = \Phi_{A_e} = \Phi_{A_u} = \Phi_{A_c} = \Phi_{A_d} = \Phi_{A_s} = 0^\circ$$

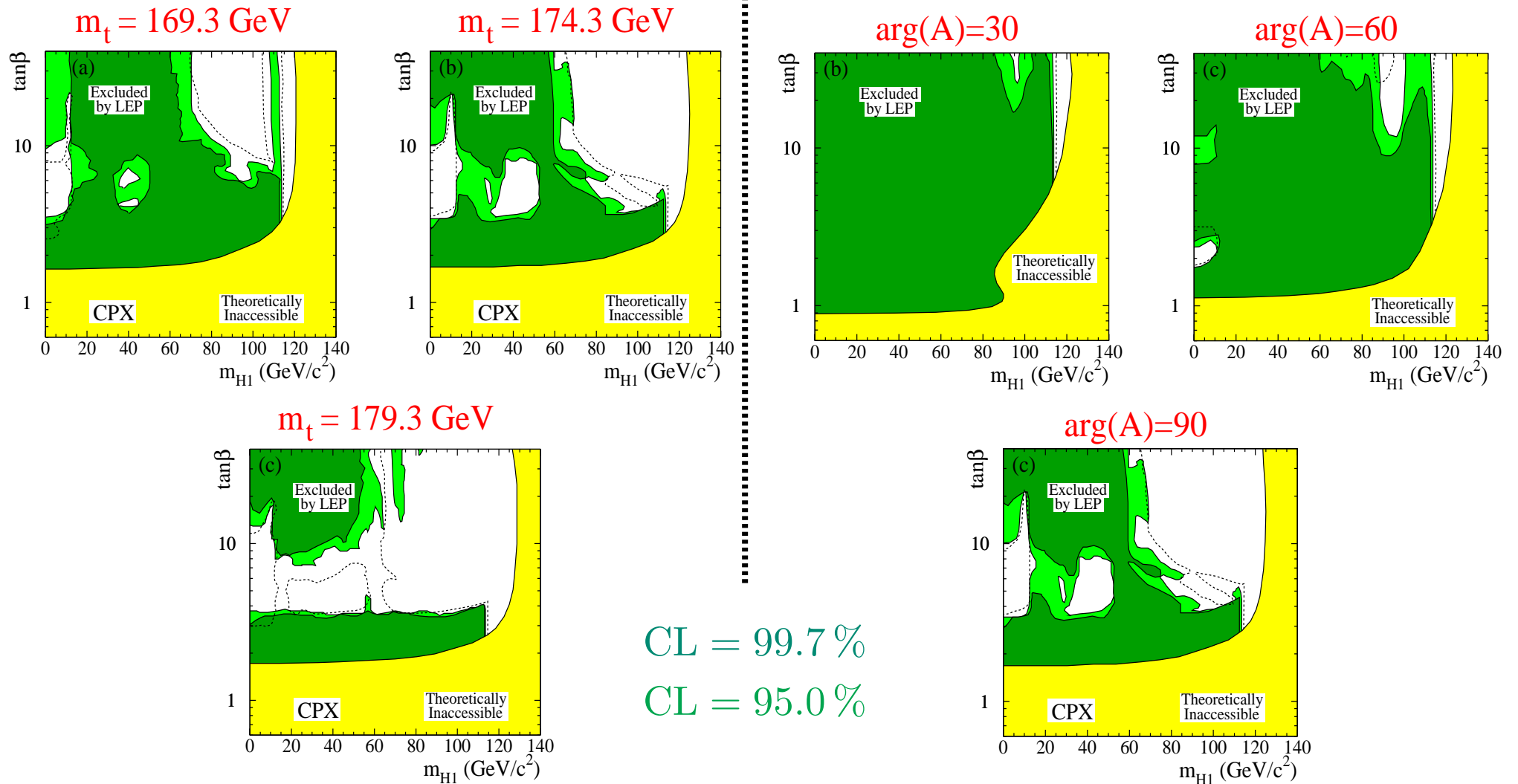
Varying :

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

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

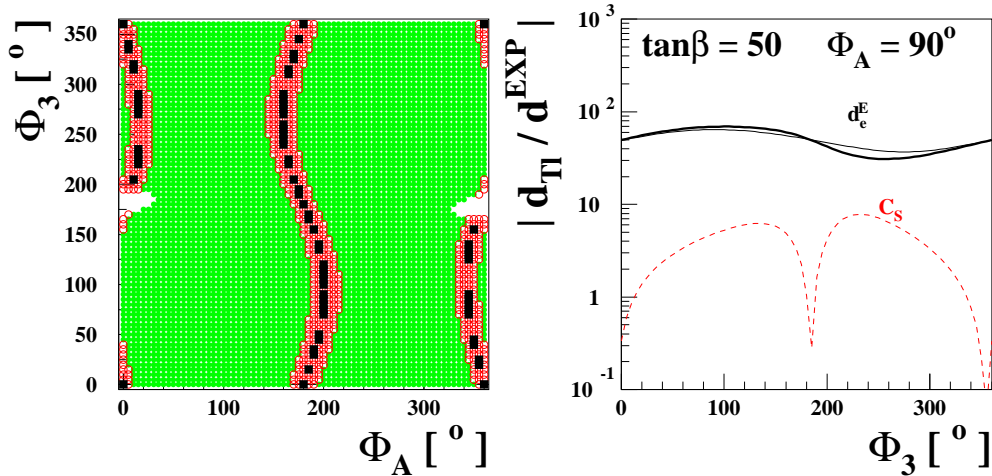
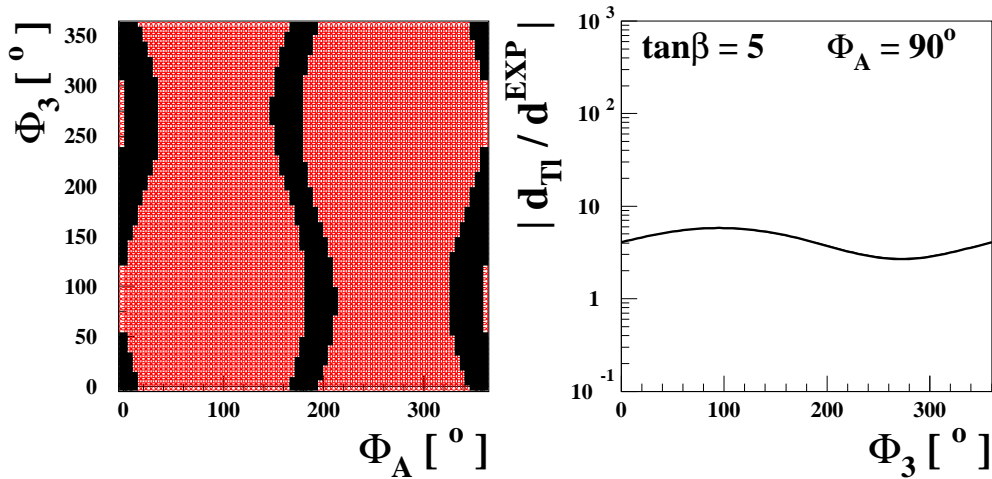
♠ EDM Constraints (CPX) (2/14)

- LEP Limit in the CPX scenario** : 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 Combined results with FeynHiggs



♠ EDM Constraints (CPX) (3/14)

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



$$- d_{\text{Tl}} \sim d_{\text{Tl}}(d_e^E)$$

$$- d_e^E \sim (d_e^E)^H$$

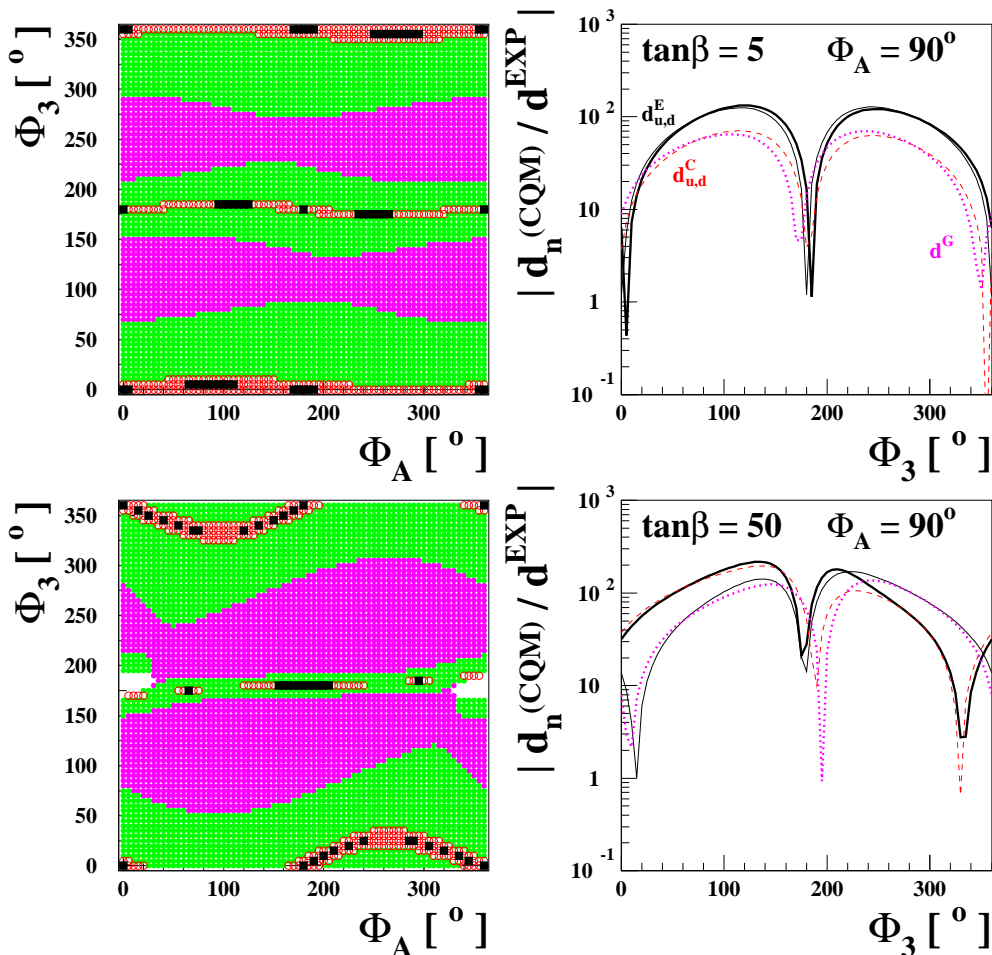
→ mild dependence on Φ_3

$$- d_{\text{Tl}}(d_e^E) \propto \tan \beta$$

$$- d_{\text{Tl}}(C_S) \propto \tan^2 \beta$$

♠ EDM Constraints (CPX) (4/14)

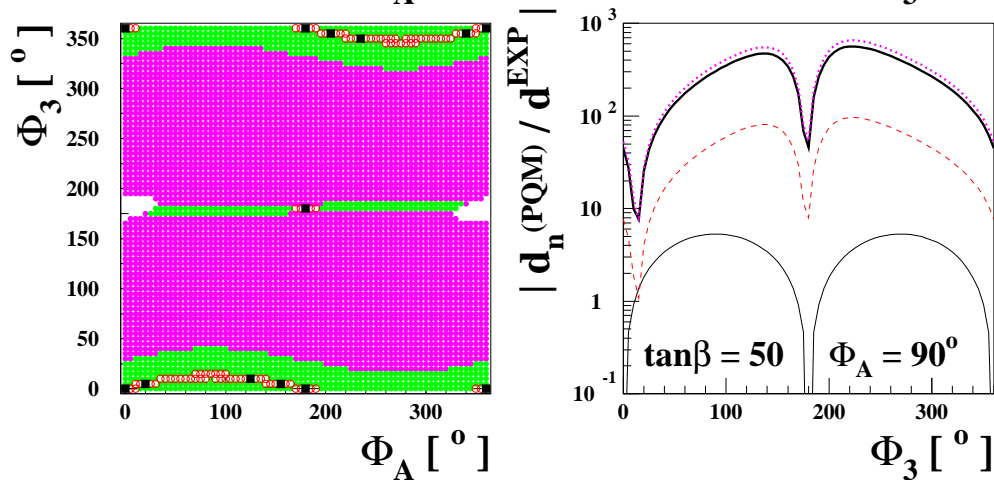
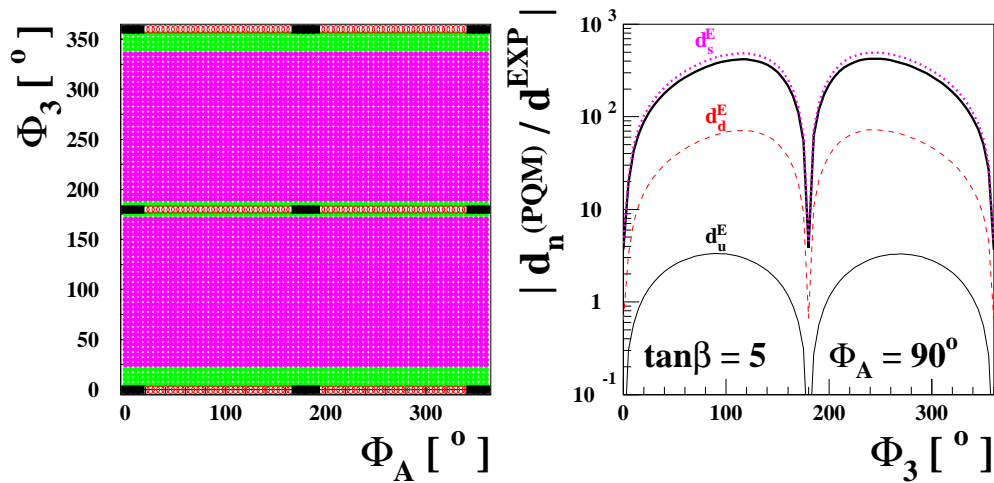
- Neutron EDM (CQM): CPX with $\Phi_1 = \Phi_2 = 0^\circ$ and $\rho = 1$;
 $|d/d^{\text{EXP}}| = [< 1, 1 - 10, 10 - 100, > 100]$



- $d_n(d_{u,d}^E) \sim d_n(d_{u,d}^C) \sim d_n(d^G)$
- $d_d^{E,C} \sim (d_d^{E,C})^{\tilde{g}}$:
 \rightarrow mild Φ_A dependence
- subdominant $(d_d^{E,C})^H \uparrow$ 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 $\rho = 1$;
 $|d/d^{\text{EXP}}| = [< 1, 1 - 10, 10 - 100, > 100]$

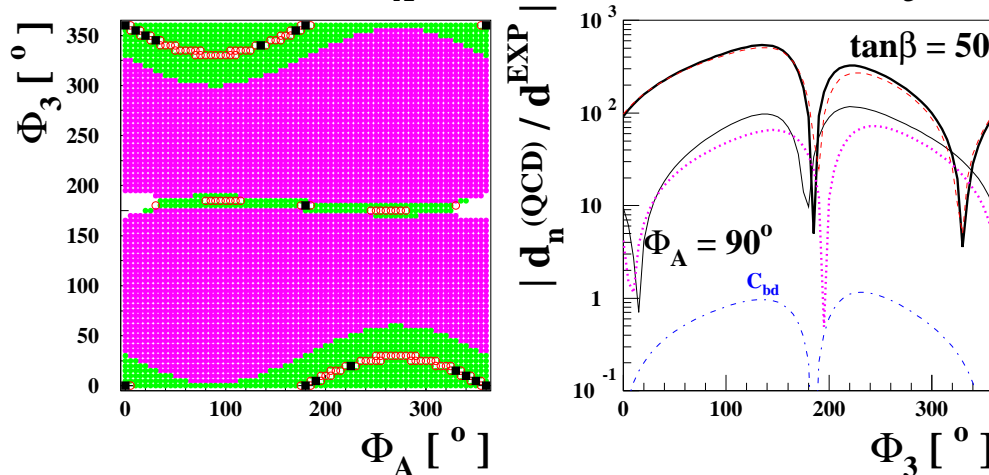
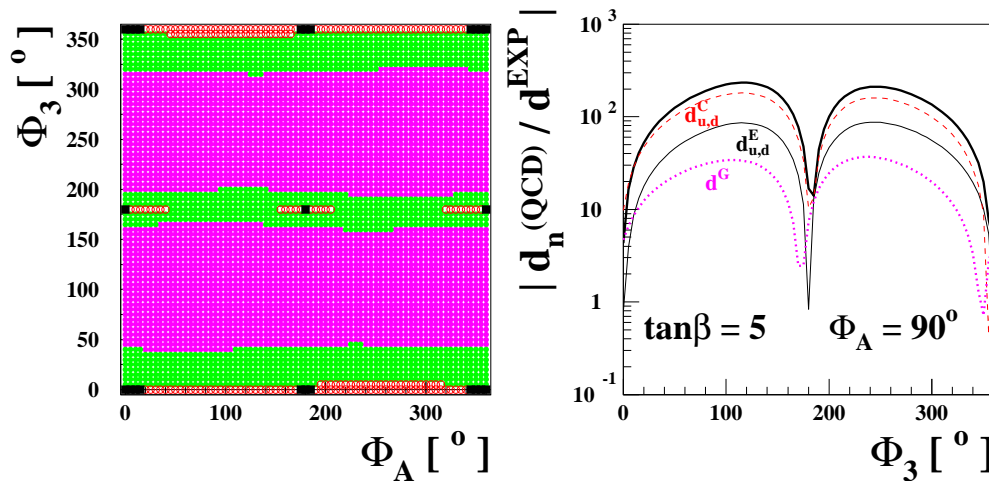


– $d_n(d_s^E)$ dominates

– $d_s^E = (d_s^E)^{\tilde{g}}$ with subdominant $(d_s^E)^H$

♠ EDM Constraints (CPX) (6/14)

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



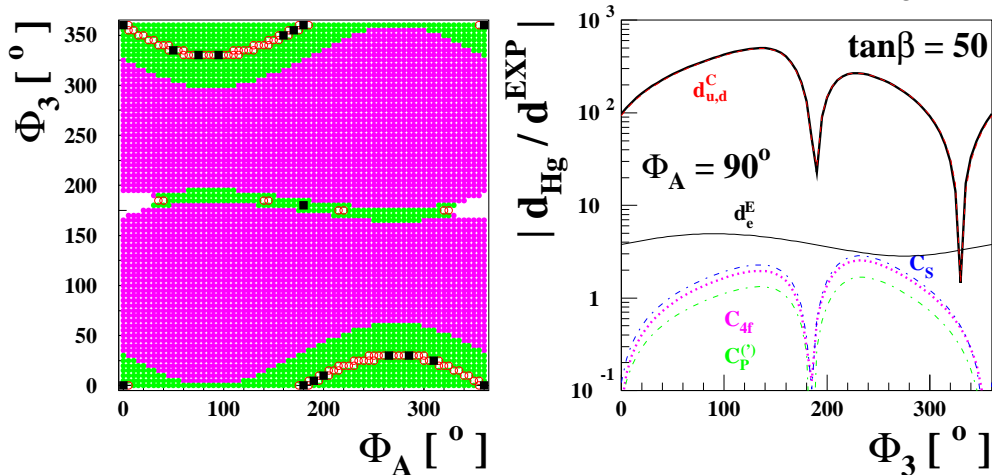
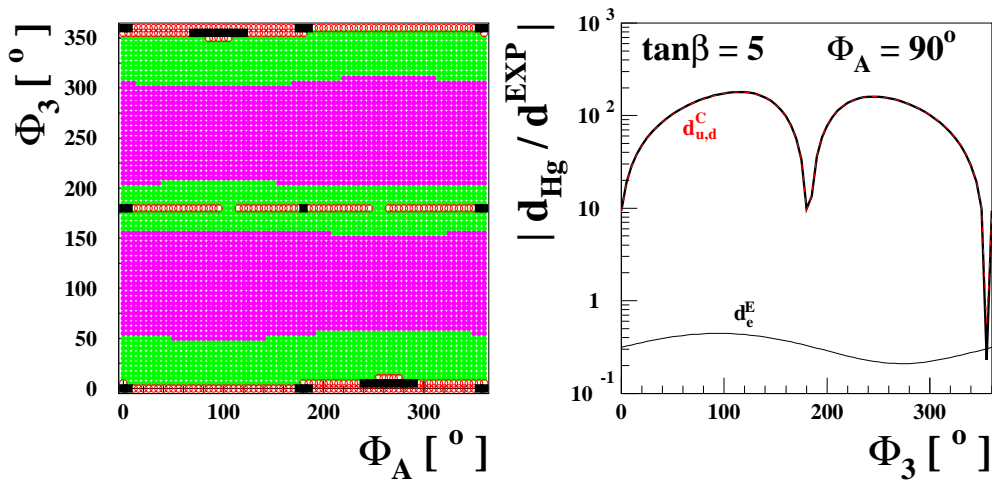
– $d_n(d_d^C)$ dominates with $d_n(d_d^E)$ and $d_n(d^G)$ subdominant

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

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

♠ EDM Constraints (CPX) (7/14)

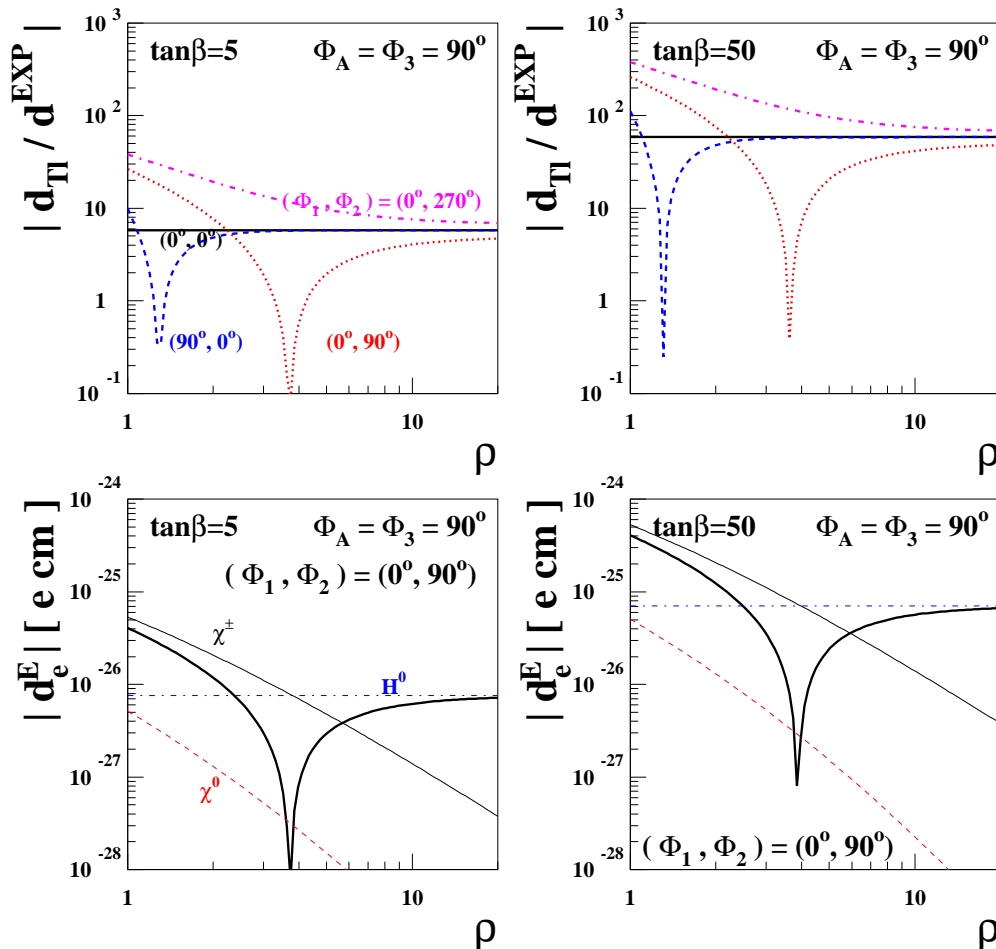
- Mercury EDM: CPX with $\Phi_1 = \Phi_2 = 0^\circ$ and $\rho = 1$;
 $|d/d^{\text{EXP}}| = [< 1, 1 - 10, 10 - 100, > 100]$



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

♠ EDM Constraints (CPX) (8/14)

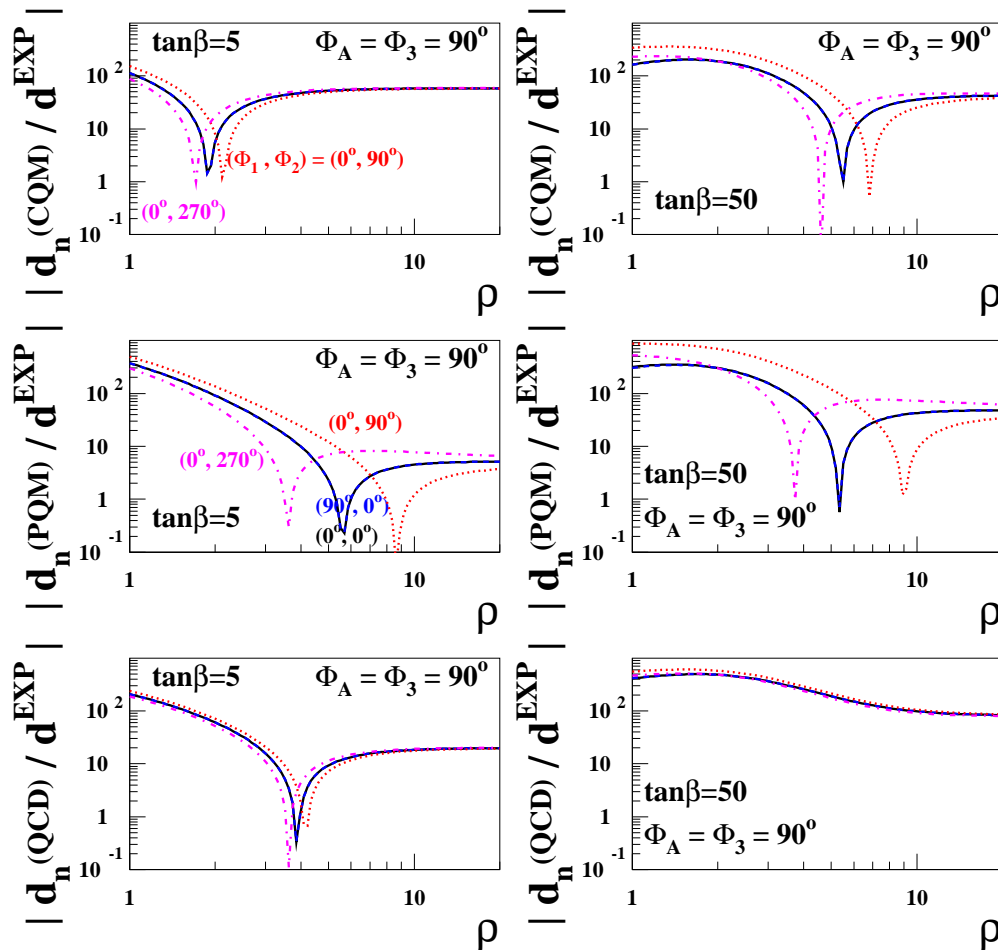
- Thallium EDM: CPX with $\Phi_A = \Phi_3 = 90^\circ$ as functions of ρ ;



- When $(\Phi_1, \Phi_2) = (0^\circ, 0^\circ)$, $d_{\text{Tl}} = d_{\text{Tl}}(d_e^E)$ with $d_e^E = (d_e^E)^H \rightarrow \rho$ independence
- As $\rho \uparrow$; 'decrease' \rightarrow 'dip' \rightarrow '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)

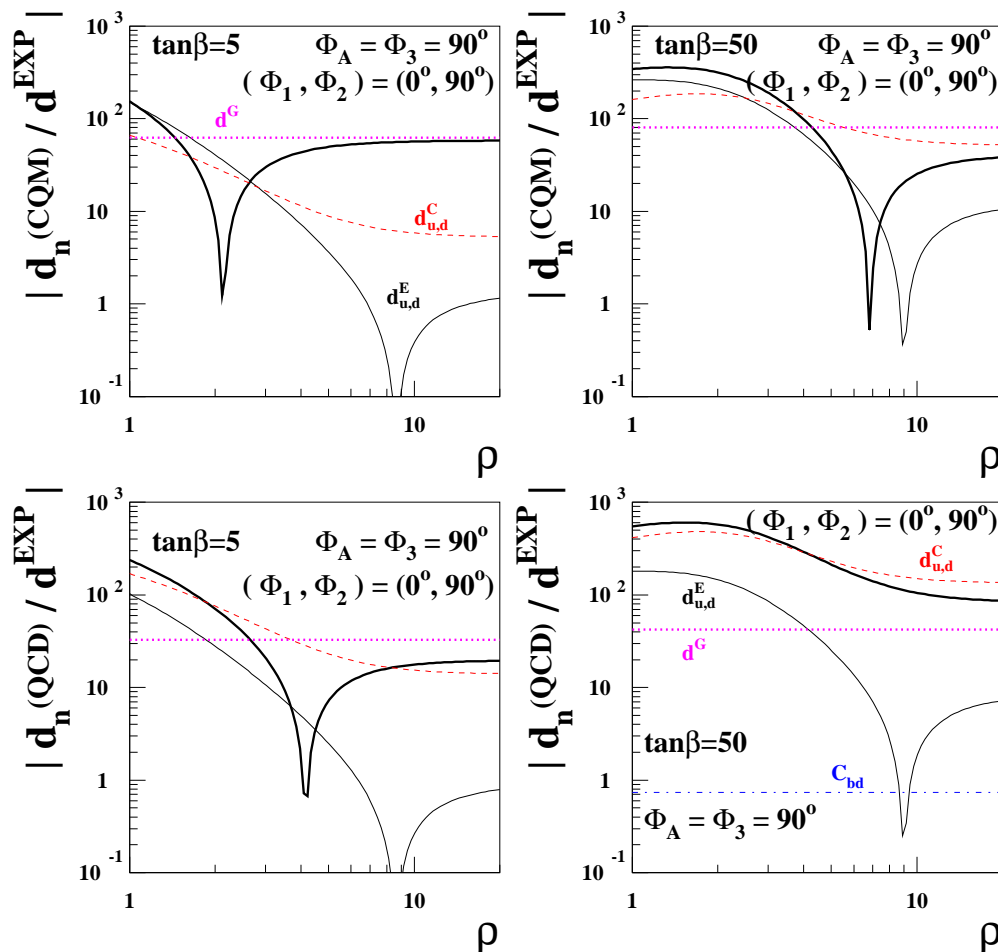
- Neutron EDM: CPX with $\Phi_A = \Phi_3 = 90^\circ$ as functions of ρ ;



- 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)

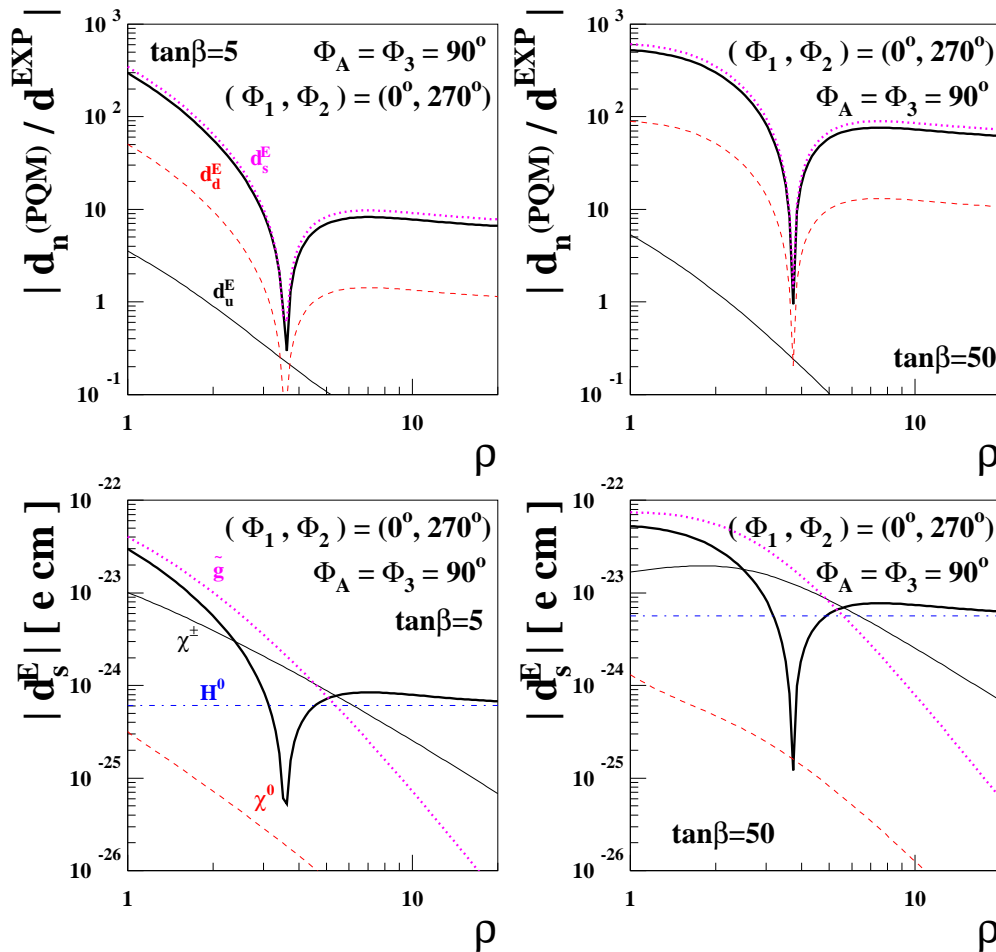
- Neutron EDM (CQM and QCD): CPX with $\Phi_A = \Phi_3 = 90^\circ$ as functions of ρ ;



- 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 $\rho = 4$
- $\pm 50\%$ $d_n(d^G)$ 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

♠ EDM Constraints (CPX) (11/14)

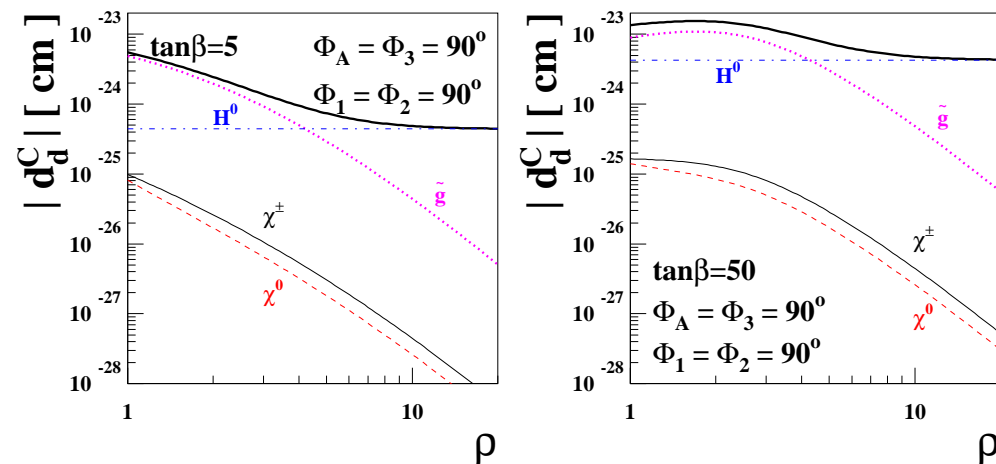
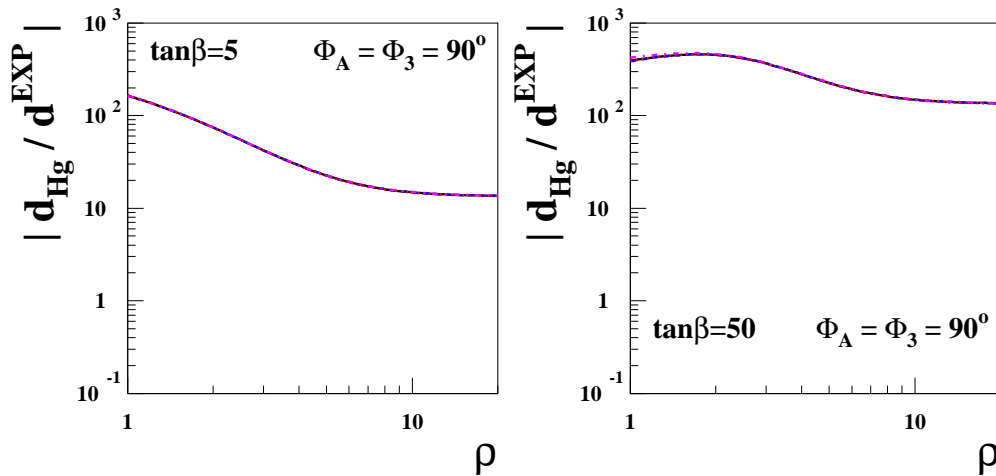
- Neutron EDM (PQM): CPX with $\Phi_A = \Phi_3 = 90^\circ$ as functions of ρ ;



- $d_n \sim d_n(d_s^E)$
- $d_s^E \sim (d_s^E)\tilde{\chi}^\pm + (d_s^E)\tilde{g}$
- cancellation between the two dominant one-loop EDMs
- large $(d_s^E)\tilde{\chi}^\pm \rightarrow$ sensitive to Φ_2

♠ EDM Constraints (CPX) (12/14)

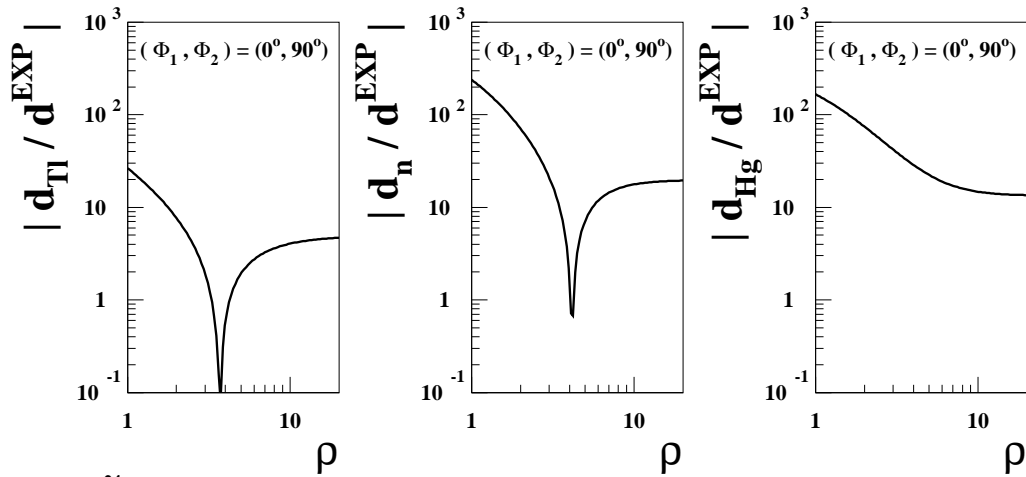
- Mercury EDM: CPX with $\Phi_A = \Phi_3 = 90^\circ$ as functions of ρ ;



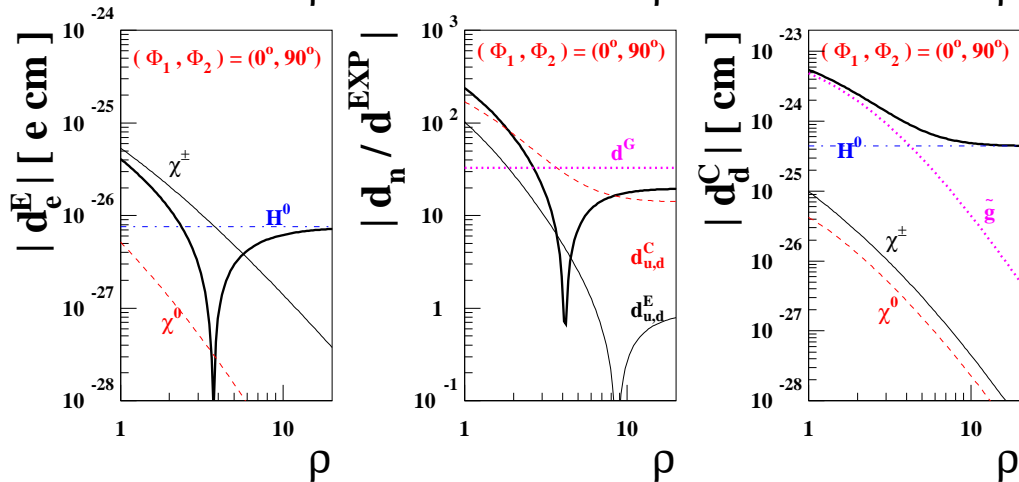
- dominance of $d_{\text{Hg}}(d_d^C) \rightarrow$ no sensitive to $\Phi_{1,2}$
- no cancellation between $(d_d^C)^{\tilde{g}}$ and $(d_d^C)^H$
- 'flat': $(d_d^C)^H$

♠ 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 $\tan \beta = 5$;

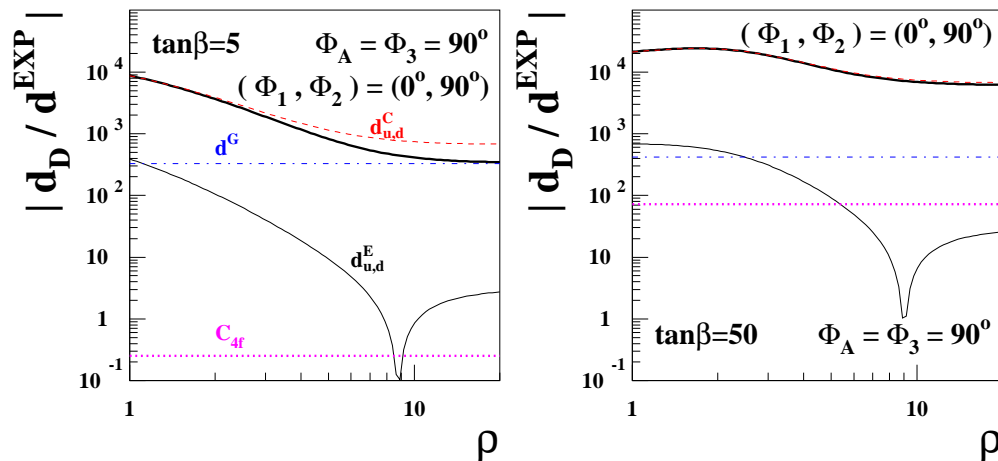
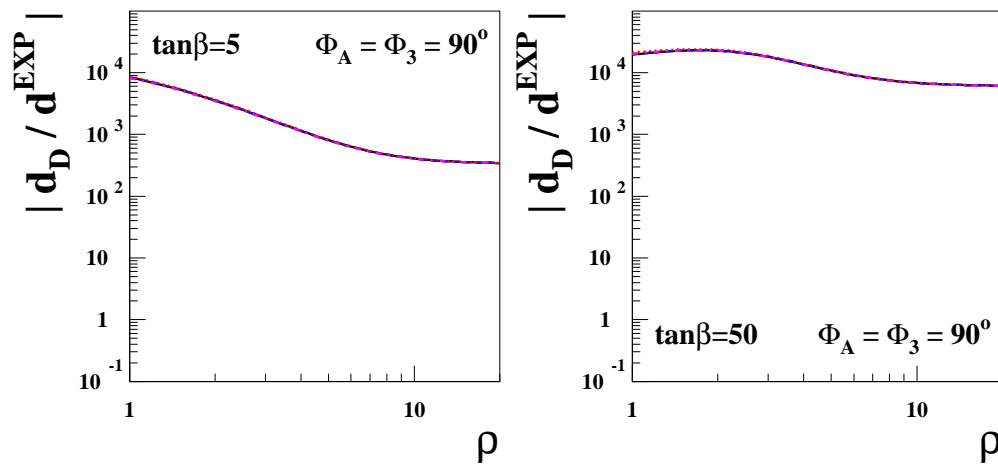


- $\rho \sim 4$?



♠ 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