Electric Dipole Moments in Supersymmetric Theories

Apostolos Pilaftsis
Department of Physics and Astronomy, Manchester University,
Manchester M13 9PL, United Kingdom

- CP-violating phases in the MSSM

- One-loop contribution to EDMs and
  CP crisis in the MSSM

- Higgs-mediated EDMs in the MSSM:
  Applications to Baryogenesis and Higgs Searches

- **Conclusions**

*Talk based on A.P., hep-ph/0207277.

• Introduction – Motivation

Strict experimental limits on EDMs:

$$|d_{Tl}| \lesssim 1.3 \times 10^{-24}\ \text{e.cm}, \quad \text{at } 2\sigma \text{ CL.}$$

(Regan et al.

$$d_{Tl}[\text{e.cm}] \approx -585 \times d_e[\text{e.cm}]$$

$$+\ 8.5 \times 10^{-19}\,[\text{e.cm}] \times C_S\,[\text{TeV}^{-2}]$$

$$+$$

$$\rightsquigarrow \quad |d_e|^{2\sigma} \lesssim 2.2 \times 10^{-27}\ \text{e.cm}, \quad |C_S| \lesssim 1.5 \times 10^{-6}\ [\text{TeV}^{-2}]$$

(Smith et al. '90
Harris et al. '99)

$$\rightsquigarrow \quad |d_n|^{2\sigma} \lesssim 1.2 \times 10^{-25}\ (\underbrace{6 \times 10^{-26}}_{\text{criticized}})\ \text{e.cm}$$

criticized by Lamoreaux & Golub (2000)

$$\rightsquigarrow \quad |d_{Hg}|^{2\sigma} \lesssim 2.33 \times 10^{-28}\ \text{e.cm}$$

(Romalis et al '01)

Falk, Olive, Pospelov, Roiban, NPB60 (1999) 3;

➡ But, many theoretical uncertainties, such as modelling of nuclear Schiff moment, neglect of 3-gluon operator, higher dim. operators, etc.

- <u>Counting **CP**-violating phases in the MSSM</u>

$$W_F = \varepsilon_{ij}\left[h_l \hat{H}_1^i \hat{L}^j \hat{E} + h_d \hat{H}_1^i \hat{Q}^j \hat{D} + h_u \hat{H}_2^j \hat{Q}^i \hat{U} - \mu \hat{H}_1^i \hat{H}_2^j \right]$$

$$W_{soft} = \sum_{\lambda}^{\tilde{g},\tilde{B},\tilde{W}} m_\lambda (\lambda\lambda + \bar{\lambda}\bar{\lambda}) + \varepsilon_{ij}\left[m_{12}^2 \Phi_1^i \Phi_2^j + h_l A_l \tilde{\Phi}_1^i \tilde{L}^j \tilde{E} \right.$$

$$\left. h_d A_d \tilde{\Phi}_1^i \tilde{Q}^j \tilde{D} + h_u A_u \Phi_2^j \tilde{Q}^i \tilde{U} + \text{H.c.} \right] +$$

Universal condition at the unification point

m_λ common phase , $A_f = A$

Complex parameters : $\{ \underline{\mu}, \underline{m_{12}^2}, \underline{m_\lambda}, \underline{A} \}$ not all $\underline{4}$ phases are physical

$\underline{2}$ phases may be removed by employing $\underline{2}$ global $U(1)$ symmetries governing the conformal-invariant part of the MSSM Lagrangian:

<u>$U(1)_Q$</u> : $Q(\hat{H}_1) = 1$, $Q(\hat{H}_2) = -2$, $Q(\hat{Q}) = Q(\hat{L}) = 0$

$Q(\hat{U}) = 2$, $Q(\hat{D}) = Q(\hat{E}) = -1$

$\underline{\mu}$, $\underline{m_{12}^2}$ break $U(1)_Q$

<u>$U(1)_R$</u> : $\theta \mapsto e^{i\alpha}\theta$, $\bar{\theta} \mapsto e^{-i\alpha}\bar{\theta}$

$R(\hat{Q}) = R(\hat{L}) = R(\hat{U}) = R(\hat{D}) = R(\hat{E}) = +1$

$R(\hat{H}_1) = R(\hat{H}_2) = 0$

$\underline{m_\lambda}$, $\underline{\mu}$, $\underline{A}$ break $U(1)_R$

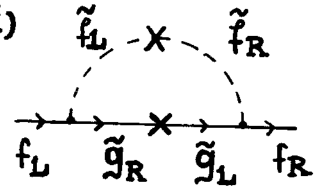
$\Longrightarrow$ $\arg(\mu)$, $\arg(A)$ physical CP-odd phases

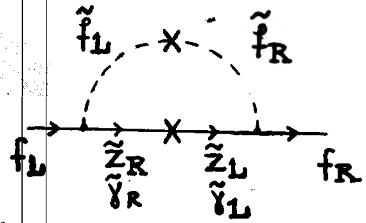
One-loop contribution to EDMs and CP crisis

Type of contributions: $\mathcal{L}_{edm} = -\frac{i}{2} d_f \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu}$

$f = e, d, u$ or μ

(i)



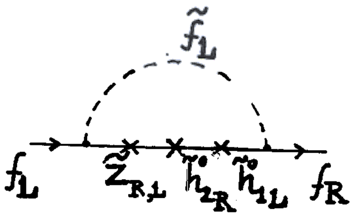


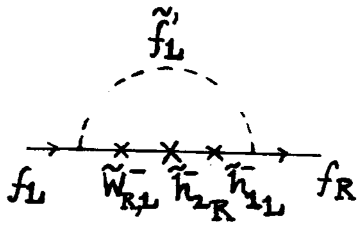
gauge-gauge interactions:

$$\left(\frac{d_f}{e}\right)^{\tilde{g}} \sim Q_f \frac{\alpha_s}{4\pi} \frac{m_f}{M^2_{\tilde{f}}} \frac{\mathrm{Im}(A_f + R_f \mu^*)}{M_{\tilde{f}}} \frac{m_{\tilde{g}}}{M_{\tilde{f}}} \quad ; R_d = \tan\beta,\ R_u = \cot\beta$$

$$\left(\frac{d_f}{e}\right)^{\tilde{\chi}^0} \sim Q_f \frac{\alpha_W}{16\pi} \frac{m_f}{M^2_{\tilde{f}}} \frac{\mathrm{Im}(A_f + R_f \mu^*)}{M_{\tilde{f}}} \frac{\{m_{\tilde{W}} ; m_{\tilde{B}}\}}{M_{\tilde{f}}}$$

gauge-Higgs interactions:

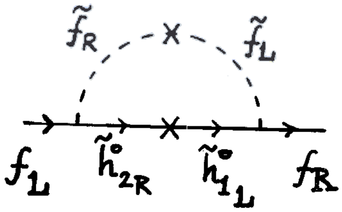


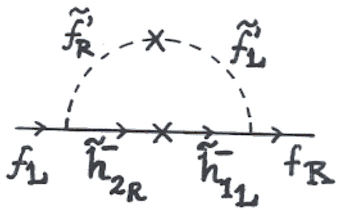


$\tilde{\chi}^- \sim \{\tilde{W}^-, \tilde{h}^-_{1,2}\}$

$$\left(\frac{d_f}{e}\right)^{\tilde{\chi}^-} \sim \frac{\alpha_W}{4\pi} \frac{m_f}{M^2_{\tilde{f}'}} \frac{m_{\tilde{W}}\, \mathrm{Im}\mu}{\max(M^2_{\tilde{f}'}, M^2_{\tilde{\chi}^+_2})}$$

Higgs-Higgs interactions:

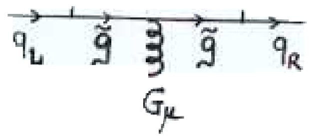


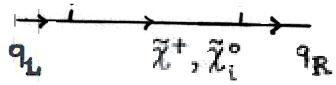


$$\left(\frac{d_f}{e}\right)^{\chi^-} \sim \frac{\alpha_W}{4\pi} \frac{m_f}{M^2_{f'}} \frac{m_f m_{f'} \mathrm{Im}(A_{f'} + R_{f'} \mu^*)}{M^2_{f'}} \sim \text{small}$$

(IV) Chromo EDM contribution $\mathcal{L}_{cedm}$ $\frac{i}{2} d_f^c \bar{f} \sigma^{\mu\nu} \gamma_5 \frac{\lambda^a}{2} f \, G^a_{\mu\nu}$

q $\quad G_\mu$





$\frac{d_f^c}{g_s}$ $\quad \frac{d_f}{e}$

EDM of neutron

$$\frac{d_n}{e} \quad \left(\frac{g_s(M_Z)}{g_s(m_b)}\right)^{32/23} \left(\frac{g_s(m_b)}{g_s(m_c)}\right)^{32/25} \left(\frac{g_s(m_c)}{g_s(\Lambda)}\right)^{32/27}$$

$$\times \left[\; 3 \left(\frac{d_d}{e}\right)_\Lambda \quad \frac{1}{3} \left(\frac{d_u}{e}\right)_\Lambda \right. \qquad NQM$$

$m_u(\Lambda) = 7\,\mathrm{MeV}$ $\quad m_d(\Lambda) = 10\,\mathrm{MeV}$ $\quad g_s(\Lambda$ $\; 4\pi/\sqrt{6}$ $\quad \Lambda$ $\; 1.19\,\mathrm{GeV}$

$$\frac{d_n}{e} \quad \left(\frac{g_s(M_Z)}{g_s(m_b)}\right)^{28/23} \left(\frac{g_s(m_b)}{g_s(m_c)}\right)^{28/25} \left(\frac{g_s(m_c)}{g_s(\Lambda)}\right)^{28/27} \left(\frac{g_s(M_Z)}{g_s(\Lambda)}\right)$$

$$\times \; \frac{4}{9} \quad \frac{d_d}{g_s} \, \Lambda \; + \; \frac{2}{9} \quad \left.\frac{d_u}{g_s}\right)_\Lambda$$

$$\left.\frac{d_f}{e}\right)^{1\text{-loop}} \quad 10^{-25}\mathrm{cm} \times \frac{\{\mathrm{Im}\mu, \mathrm{Im}A_f\}}{\max(M_{\tilde{f}} \; m_{\tilde{\chi}})} \left(\frac{1\,\mathrm{TeV}}{\max(M_{\tilde{f}}, m_{\tilde{\chi}})}\right)^2 \left(\frac{m_f}{10\,\mathrm{MeV}}\right)$$

Schemes of resolving the CP crisis

(i) $\mathrm{Im}\mu/|\mu| \lesssim 10^{-2}$ $\quad \mathrm{Im}A_f/|A_f| \lesssim 10^{\cdot}$ $\quad M_{\tilde{f}}$ $\; m_{\tilde{\chi}} \sim 200\,\mathrm{GeV}$

(ii) CP phases $\sim \mathcal{O}(1)$ but $M_{\tilde{f}} \gtrsim$ TeV $\quad$ for $\tilde{f}$ $\; \tilde{u}, \tilde{d}, \tilde{s}$ $\; \tilde{c}, \tilde{e}$

(iii) $\mathrm{Im}\mu \leq 10$ $\; \mu$ & $A \; \leq 10^{-2}\mu$ $\quad$ for $\tilde{f} = u, \tilde{d}, \tilde{s}, \tilde{c}$ but $\arg A_{t,\bar{b}} \; \frac{\pi}{2}$

Contributions to e and n EDMs: (MSSM)

- J. Ellis, S. Ferrara and D.V. Nanopoulos, PL**B114** (1982) 231;
  W. Buchmüller and D. Wyler, PL**B121** (1983) 321;
  J. Polchinski and M. Wise, PL**B125** (1983) 393;
  M. Dugan, B. Grinstein and L. Hall, NP**B255** (1985) 413;
  T. Falk, K.A. Olive and M. Srednicki, PL**B354** (1995) 99;
  S. Pokorski, J. Rosiek and C.A. Savoy, hep-ph/9906206;
  E. Accomando, R. Arnowitt and B. Dutta, hep-ph/9907446;
  S. Abel, S. Khalil and O. Lebedev, hep-ph/0103320 · · ·
- P. Nath, PRL**66** (1991) 2565;
  Y. Kizukuri and N. Oshimo, PR**D46** (1992) 3025
- T. Ibrahim and P. Nath, PL**B418** (1998) 98; PR**D58** (1998) 111301;
  M. Brhlik, G.J. Good and G.L. Kane, PR**59** (1999) 115004;
  M. Brhlik, L. Everett, G.L. Kane and J. Lykken, PRL**83** (1999) 2124;
- J. Ellis and R.A. Flores, PL**B377** (1996) 83;
  A. Bartl, T. Gajdosik, W. Porod, P. Stockinger and H. Stremnitzer, PR**D60** (1999) 073003.
- J. Dai, H. Dykstra, R.G. Leigh, S. Paban and D. Dicus, PL**B237** (1990) 216; **B242** (1990) 547 (E).
- D. Chang, W.-Y. Keung and A.P., PRL **82** (1999) 900;
  A.P., PL**B471** (1999) 174.
- A.P., PR**D62** (2000) 016007.

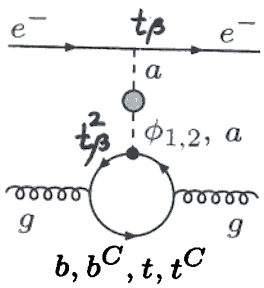
M. Pospelov et al., $d_{Hg} < 2.10^{-28}$ e cm.

$$\Rightarrow \quad e\left|\frac{d_d^c}{g_s} - \frac{d_u^c}{g_s} - 0.012\frac{d_s^c}{g_s}\right| < 2.10^{-26}\,\text{e cm}$$

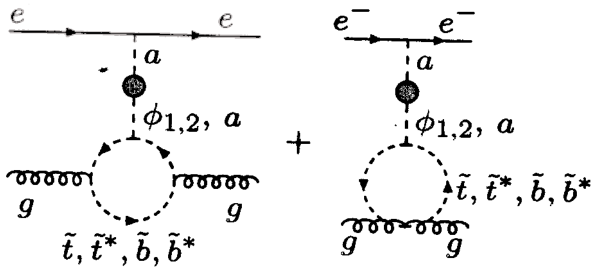
$>25\%$ uncertainties, d_{3g} missing

\+ other uncertainties

C_S operator : [A.P., hep-ph/0207277]



(a)



(b)

$$\mathcal{L}_{\rm EDM} = -\frac{1}{2} d_e\, \bar{e}\, \sigma_{\mu\nu} i\gamma_5\, e\, F^{\mu\nu} + C_S\, \bar{N} N\, \bar{e}\, i\gamma_5\, e + \ldots$$

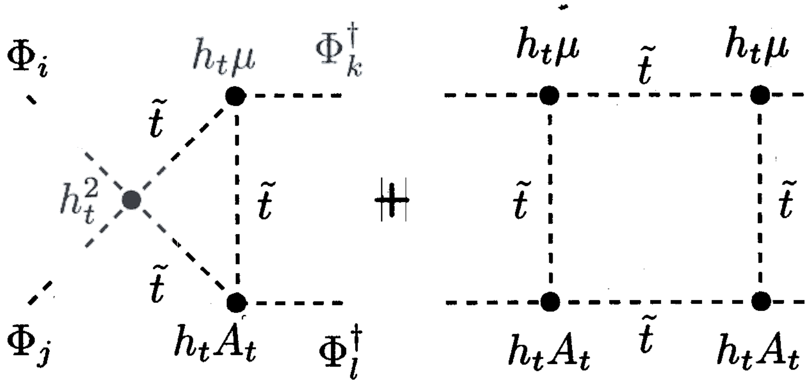
a --- $b\bar{b}$ vertex : $H_i\, \bar{b}\, [\, g^S_{H_i bb} + i\gamma_5\, g^P_{H_i bb}\,]\, b$

$$g^S_{H_i bb} \sim O_{3i}\, {\rm Im} \left[\frac{(\Delta h_b/h_b)\, t_\beta^2}{1 + (\Delta h_b/h_b)\, t_\beta} \right] \xrightarrow{t_\beta \gg 1} O_{3i}\, {\rm Im} \frac{1}{(\Delta h_b/h_b)}$$

FCNC effects at large $\underline{\tan\beta}$: Talks by U. Nierste
C. Kolda

~~CP~~ FCNC effects at large $\underline{\tan\beta}$: A. Dedes & A.P.
in preparation

One-loop CP-violating contributions to the effective Higgs potential:



$$\subset \quad \mathcal{L}_V(\Phi_1, \Phi_2)$$

The one-loop CP-violating effects are proportional to the rephasing-invariant combinations:

$$\boxed{\mathrm{Im}\,(m_{12}^{2*}\,\mu\,A_{t,b})\ \neq\ 0}$$

[A.P., '98
A.P., C.E.M.Wagner '99]
D.Demir
S.Y.Choi, M.Drees
J-S.Lee ....

<u>Other CP-violating contributions:</u>

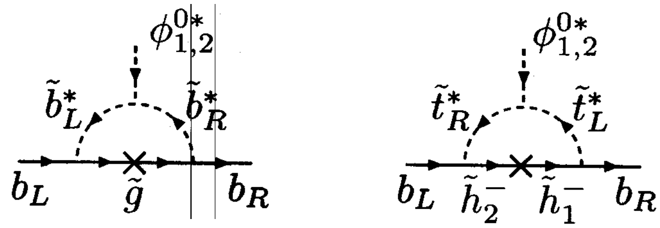
$\mathrm{Im}(m_{12}^{2*}\,\mu\, m_{\tilde{W},\tilde{B}})$: 1-loop chargino/neutralino effects [T.Ibrahim, P.Nath '01]

$\mathrm{Im}(m_{12}^{2*}\,\mu\, m_{\tilde{g}})$: 2-loop gluino effects

[M.Carena, J.Ellis, A.P., C.Wagner] '00

– **CP-violating vertex effects:**

Effective H_1bb-coupling



$$-\mathcal{L}^{\rm eff}_{\phi^0\bar{b}b} = (h_b + \delta h_b)\,\phi_1^{0*}\,\bar{b}_R b_L + \Delta h_b\,\phi_2^{0*}\,\bar{b}_R b_L \;+\; \text{h.c.}$$

with

$$\frac{\delta h_b}{h_b} \sim \frac{2\alpha_s}{\;}\,\frac{m_{\tilde{g}}^* A_b}{\;} - \frac{|h_t|^2}{\;}\,\frac{|\mu|^2}{\;}$$

$$\frac{\Delta h_b}{h_b} \sim$$

and

$$h_b = \frac{g_w m_b}{\sqrt{2} M_W \cos\beta\,[\,1 + \delta h_b/h_b + (\Delta h_b/h_b)\tan\beta\,]}$$

[M. Carena, J. Ellis, A. P., C. Wagner, NPB586 (2000) 92.]

CPX: $\tilde{M}_Q = \tilde{M}_t = \tilde{M}_b = M_{SUSY}$, $|\mu| = 4 M_{SUSY}$
$|A_t| = |A_b| = 2 M_{SUSY}$
$\arg(A_{t,b}) = 90^\circ$
$|m_{\tilde{g}}| = 1$ TeV, $\arg(m_{\tilde{g}}) = 90^\circ$

[M. Carena, J. Ellis, A.P., C. Wagner, PLB495 (2000) 155.]

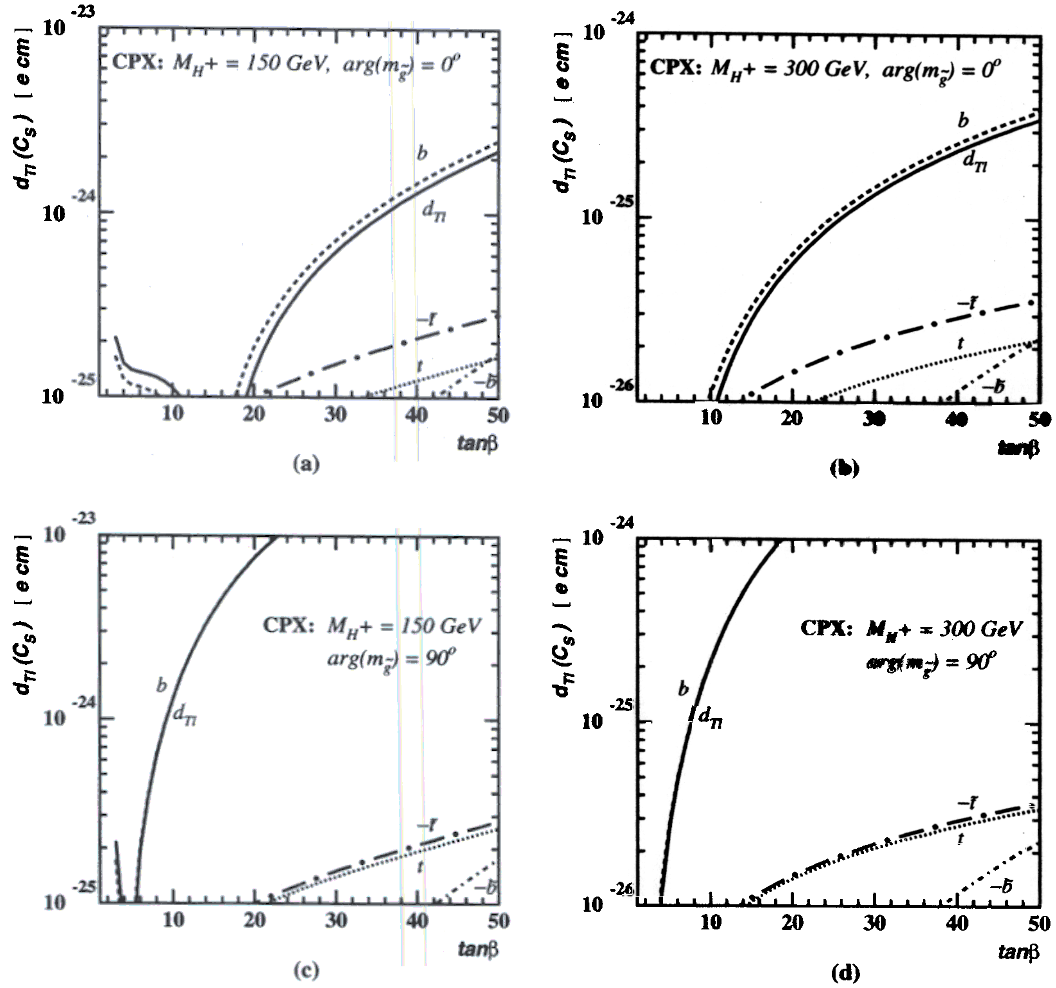
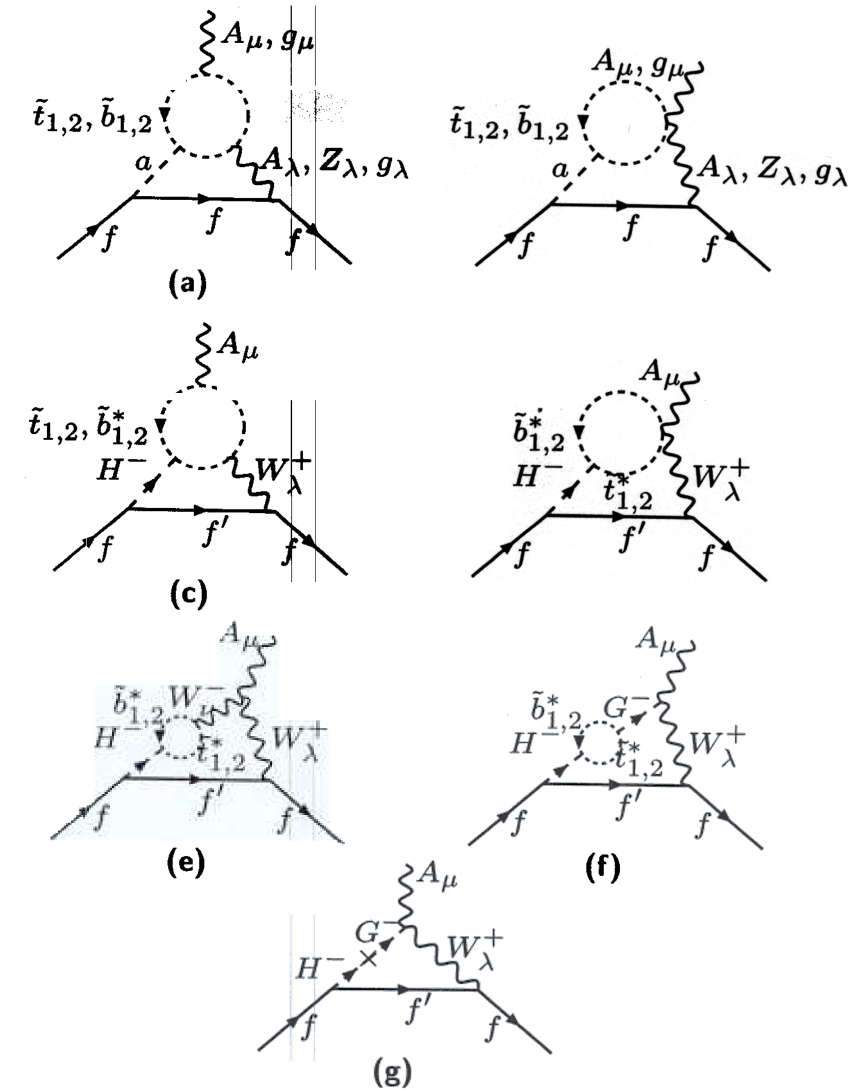
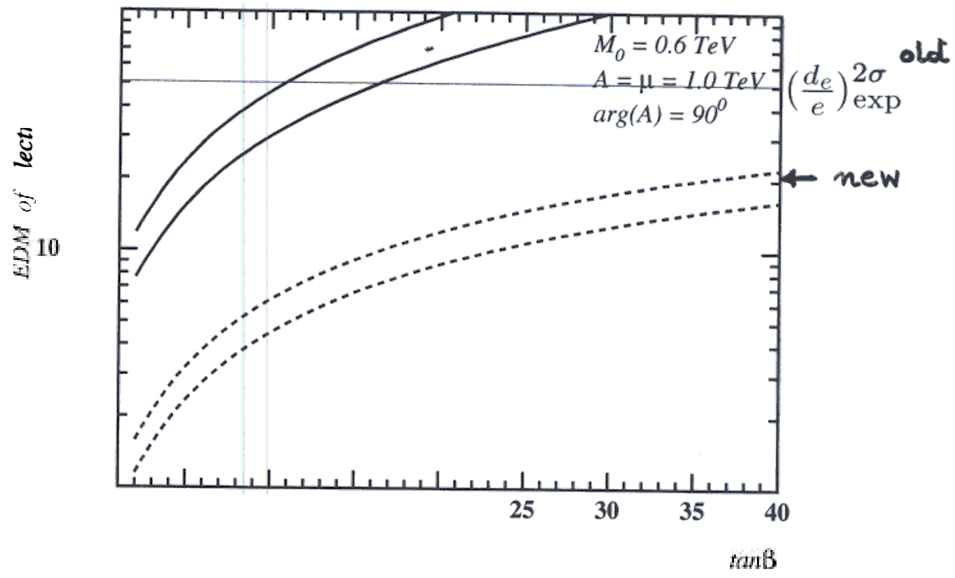


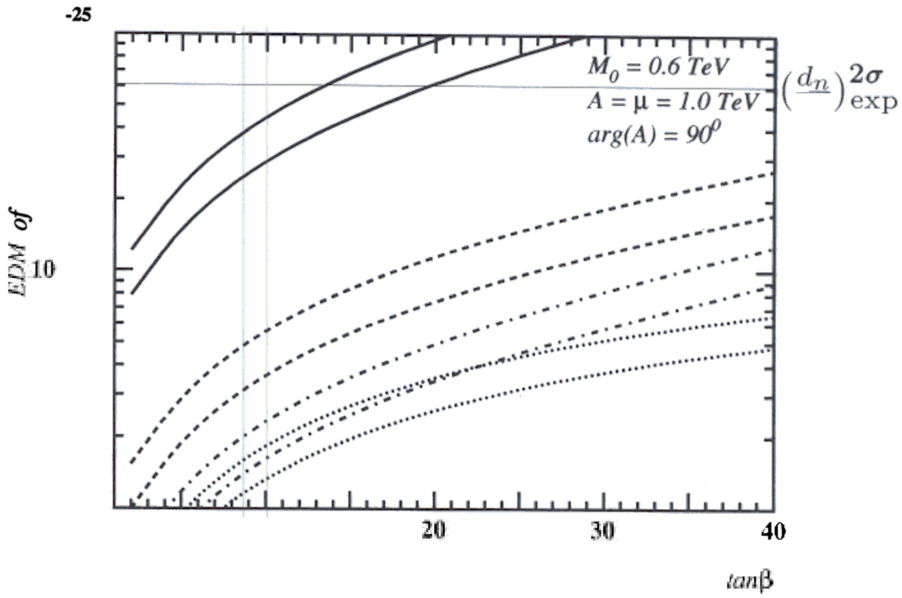
Figure 3: *Numerical estimates of* ^{205}*Tl EDM* $d_{\rm Tl}$ *induced by the CP-odd electron–nucleon operator* C_S *as functions of* $\tan\beta$*, in four selected CPX scenarios with* $M_{\rm SUSY} = 1$ *TeV. The values of the CPX parameters are given in (4.1). The individual* $b, \tilde{t}, t, \tilde{b}$ *contributions to* $d_{\rm Tl}(C_S)$*, along with their relative signs, are also displayed.*

Higgs-boson two-loop contributions to EDM and CEDM of a fermion in the Feynman–'t Hooft gauge; f' represents the conjugate fermion of f under T_z^f [D. Chang, W.-Y. Keung, A.P., Phys. Rev. Lett. **82** (1999) 900; A.P., Phys. Lett. **B471** (1999) 174.]

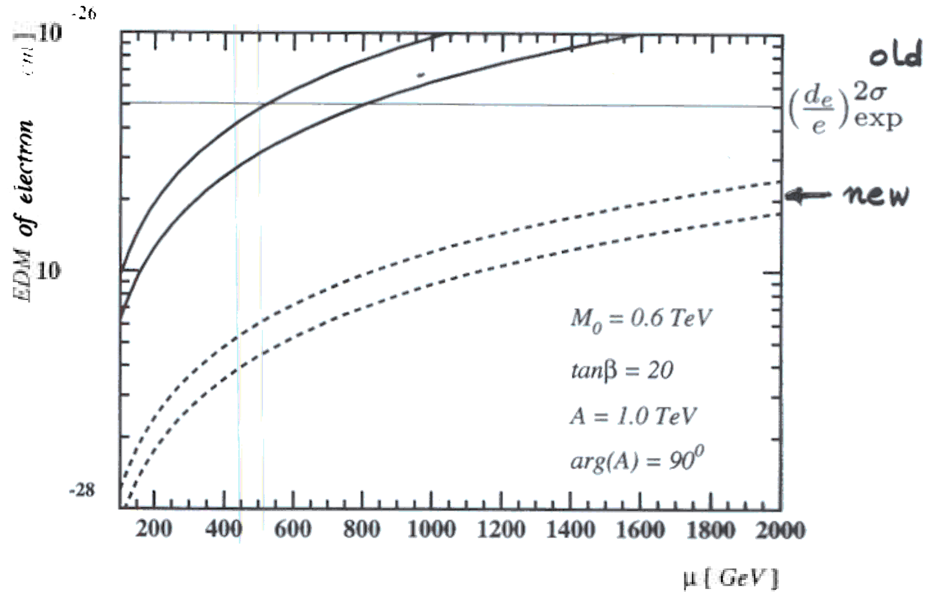


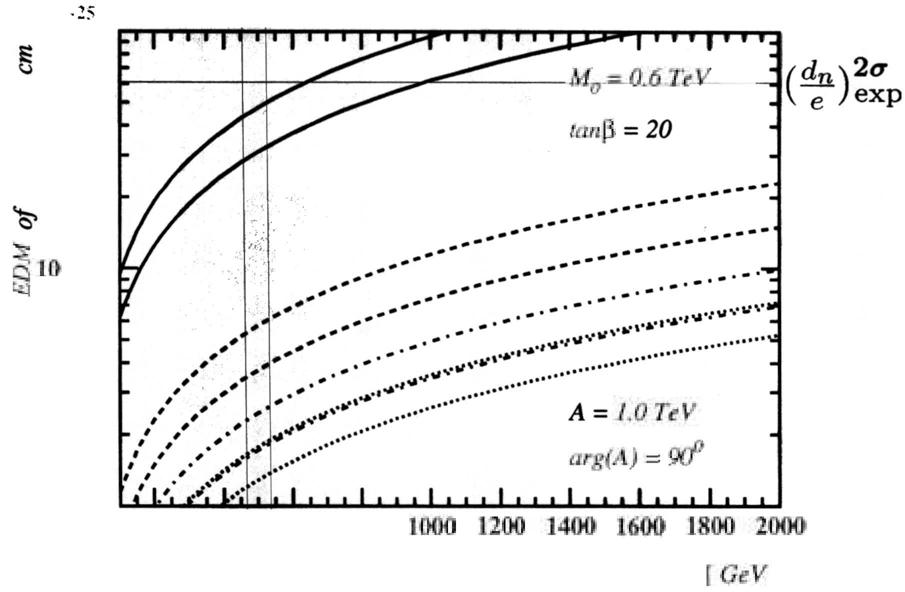
M_a 150 300 GeV





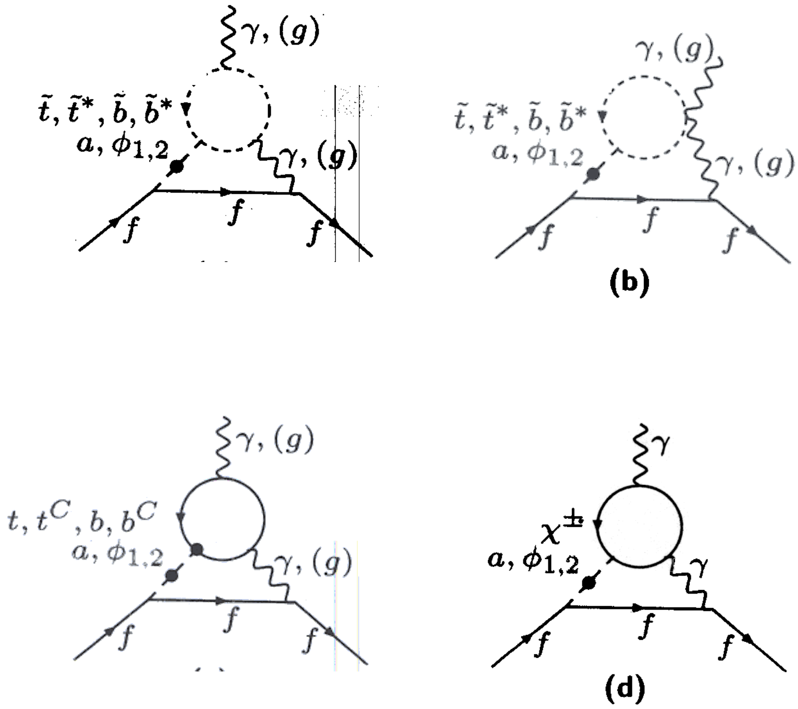
M_α 150 300 GeV



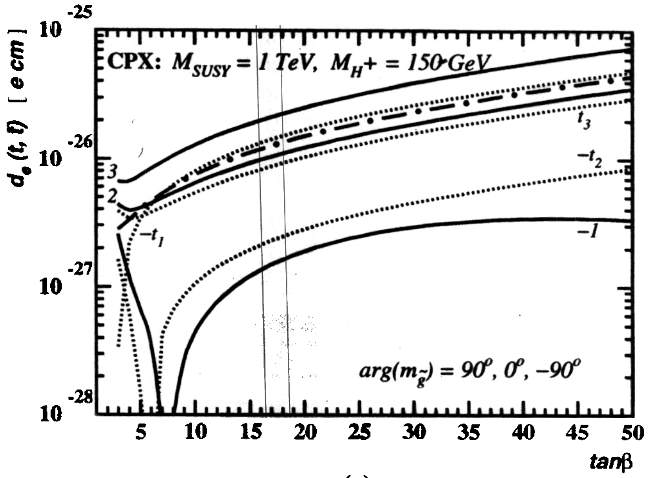


Higgs-mediated EDMs :

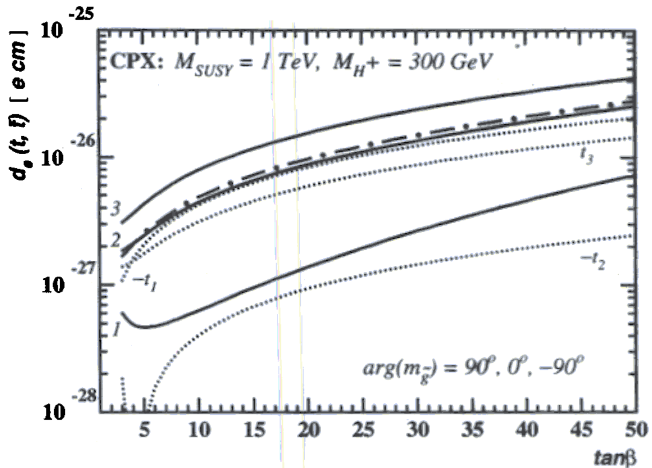
[A.P., hep-ph/0207277]



$$d_e \;\propto\; \not{C}\!\not{P}\ \text{phases},\ \tan\beta,\ \frac{1}{M_a}$$

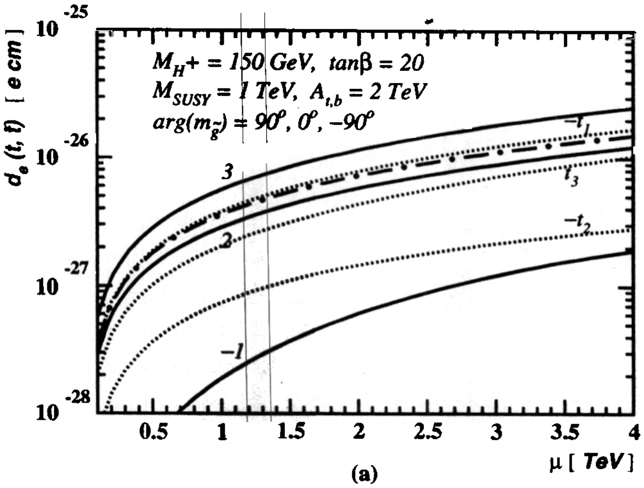


(a)



(b)

Figure 4: *Numerical estimates of resummed Higgs-boson two-loop effects on d_e, induced by t, b- quarks and $\tilde{t}, \tilde{b}$- squarks, as functions of* $\tan\beta$, *in two variants of the CPX scenario, with (a)* $M_{H^+} = 150$ *GeV and (b)* $M_{H^+} = 300$ *GeV. The long-dash-dotted lines indicate the stop/sbottom contributions to d_e. The dotted lines $t_{1,2,3}$ correspond to top/bottom contributions, for* $\arg(m_{\tilde{g}}) = 90°,\ 0°,\ -90°$, *respectively. Likewise, the solid lines* $1, 2, 3$ *give the sum of all the aforementioned contributions to d_e for the same values of gluino phases. Contributions to d_e that are denoted with a minus sign are negative.*



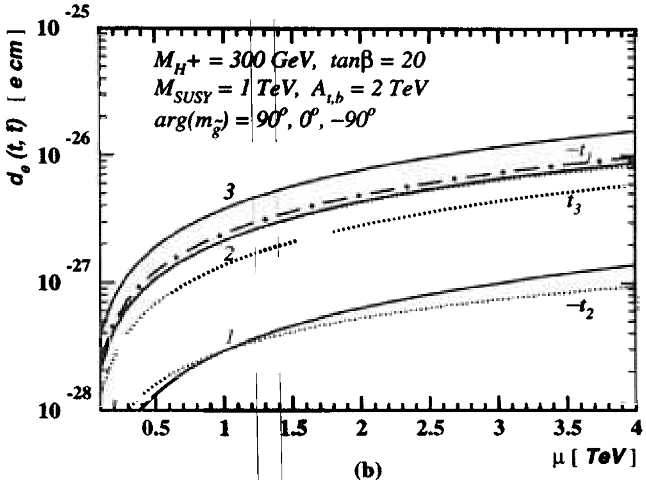


Figure 5: *Numerical values of resummed Higgs-boson two-loop effects on d_e, induced by t, b- quarks and $\tilde{t}, \tilde{b}$- squarks, as functions of μ, in two variants of the CPX scenario, with* $\tan\beta = 20$, *and (a)* $M_{H^+} = 150$ *GeV and (b)* $M_{H^+} = 300$ *GeV. The meaning of the different line types is identical to that of Fig. 4. For* $A_{t,b} = 0$, *the long-dash-dotted line disappears and so the solid lines collapse to the dotted ones.*

EDM constraints on Electroweak Baryogenesis

[A.P., hep-ph/0207277]

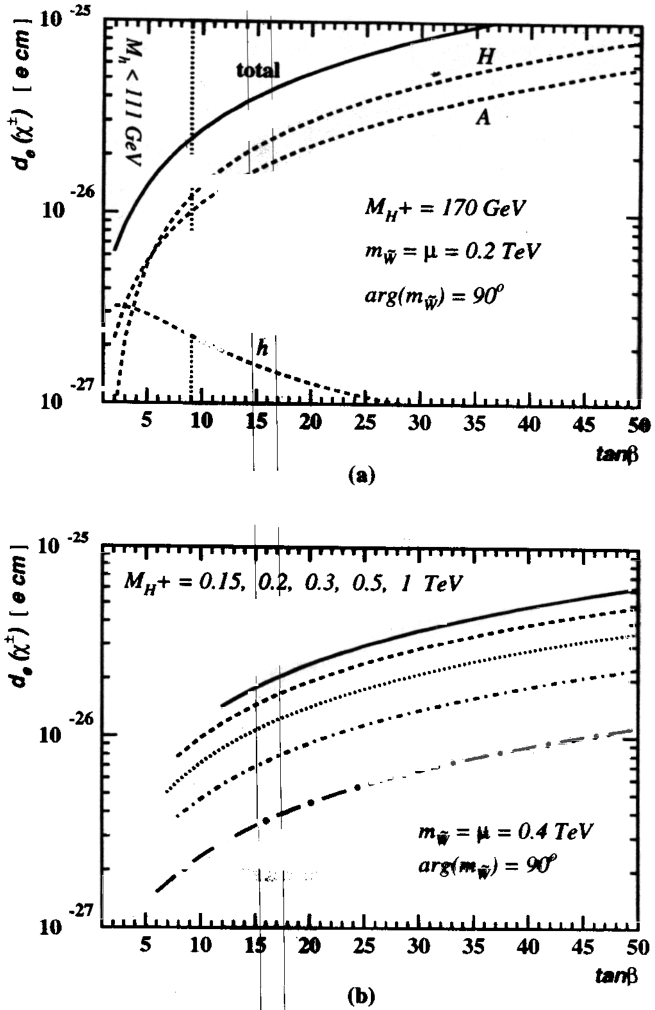


Figure 6: d_e *versus* $\tan\beta$ *in a scenario favoured by electroweak baryogenesis, with MSSM parameters* $\widetilde{M}_Q = \widetilde{M}_D = 3$ *TeV*, $\widetilde{M}_U = 0$, $A_{t,b} = 1.8$ *TeV*, $m_{\tilde{g}} = 3$ *TeV and* $\arg(A_{t,b}) =$ * $\arg(m_{\tilde{g}}) = 0°$. *In (a),* $M_{H^+} = 170$ *GeV is used, corresponding to* $M_A \approx 150$ *GeV, and* $m_{\widetilde{W}} = \mu = 0.2$ *TeV and* $\arg(m_{\widetilde{W}}) = 90°$. *Also displayed are the individual 'h', 'H', 'A' contributions to* d_e *and the LEP excluded region from direct Higgs-boson searches. In (b), numerical values are shown for* $M_{H^+} = 150$ *GeV (solid), 200 GeV (dashed), 300 GeV (dotted), 500 GeV (dash-dotted) and 1 TeV (long-dash-dotted), in a scenario with* $m_{\widetilde{W}} = \mu = 0.4$ *TeV and* $\arg(m_{\widetilde{W}}) = 90°$. [Related study by D. Chang et al., hep-ph/0205084 (v2, 4 June '02)] with different results!]

* Compatible with studies by M. Carena, J. Moreno, M. Quiros, M. Seco, G. Wagner.

New phenomenological structure starts emerging ...