

Electric Dipole Moments
in
Supersymmetry

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DESY

Outline :

- ① What are EDMs
- ② EDMs in SUSY
- ③ Fundamental sources of ~~CP~~
- ④ Prospects

Introduction to EDMs

Interaction H :

$$H_{\text{nonrel.}} = -d \vec{S} \cdot \vec{E}$$

\vec{E} = el. field , \vec{S} = spin vector

Measurement :

$$\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$



$$\Delta \omega_{\text{Larmor}} \propto |\vec{d} \times \vec{E}|$$

Experimental results:

all negative ...

$$d_{Tl} < 9 \times 10^{-25} \text{ e}\cdot\text{cm} \quad (90\% \text{ CL})$$

$$d_{Hg} < 2 \times 10^{-28} \text{ e}\cdot\text{cm} \quad (95\% \text{ CL})$$

$$d_n < 6 \times 10^{-26} \text{ e}\cdot\text{cm} \quad (90\% \text{ CL})$$

Note:

SM predictions are
very small,

$$d_n \sim 10^{-32} \text{ e}\cdot\text{cm}$$

...

EDMs of complex systems

Schiff theorem:

$$d_{\text{system}} \stackrel{\text{nonrel.}}{=} 0$$



$$\rightarrow \vec{E}_{\text{net}} = 0, \\ \text{no net EDM.}$$

However:

does not apply to
relativistic / non-point-like
particles

$$\text{E.g. } d_{\text{param. atom}} / d_e \sim 10 Z^3 \alpha^2,$$

for d_{T1} the enhancement ~ 585 .

Relativistic EDMs

$$H_{\text{non-rel.}} = -d \vec{S} \cdot \vec{E}$$



$$\mathcal{L}_{\text{rel.}} = -\frac{i}{2} d \bar{\Psi} (F\sigma) \gamma_5 \Psi$$

$$\begin{cases} F_{\mu\nu} = \text{photon field strength} \\ \Psi = \text{fermion} \end{cases}$$

For composite objects (n, atoms, ...) also relevant

$$\mathcal{L} = \frac{g^2}{32\pi^2} \Theta G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{w}{3} f^{abc} G_a \tilde{G}_b G_c$$

$$- \frac{i}{2} \tilde{d} \bar{\Psi} g (G\sigma) \gamma_5 \Psi$$

$$+ \sum_{ij} C_{ij} (\bar{\Psi}_i \Psi_i) (\bar{\Psi}_j i\gamma_5 \Psi_j)$$

$$\begin{cases} G_{\mu\nu} = \text{gluon field strength} \\ \Theta = \text{QCD } \Theta\text{-term} \\ w = \text{Weinberg operator} \\ \tilde{d} = \text{colour EDM} \end{cases}$$

$$\text{EDM} = f(\theta, w, d, \tilde{d}, C_{ij})$$

Example:

Tl atom



$$\mathcal{L} \sim \bar{e} i \gamma_5 e \bar{N} N$$



Deforms the atom \rightarrow EDM

$$d_{\text{Tl}} \approx -585 d_e - C_s \cdot 43 e \cdot \text{GeV}$$

$$\downarrow \mathcal{L} \sim C_s \bar{e} i \gamma_5 e \bar{N} N$$

C_s can be more important than d_e (e.g. heavy superpartners)

Neutron EDM

a) Naive dimensional analysis

$$d_n \approx \frac{4}{3} d_d - \frac{1}{3} d_u$$

$$d_q \equiv \eta d_q^S + \tilde{\eta} \frac{e}{4\pi} \tilde{d}_q^C + \dots$$

Arnovitt, Lopez, '90

$$d_n^{NDA} \sim 2d_d - 0.5d_u + e(0.4\tilde{d}_d - 0.1\tilde{d}_u) + 0.3 \text{ GeV} \cdot eW$$

Here d_q, \tilde{d}_q at EW scale.

b) QCD sum rules

Pospelov, Ritz '01

$$d_n^{SR} \approx 2d_d - 0.5d_u + e(\tilde{d}_d + 0.5\tilde{d}_u) + 0.1 \text{ GeV} \cdot eW$$

4-fermion operators = small

c) ...

Thallium EDM:

Liu, Kelly '92
Bouchiat '75

$$d_{Tl} = -585 d_e - C_5 \cdot 43 \text{ e} \cdot \text{GeV},$$

$$\mathcal{L} \sim C_5 \bar{e} i \gamma_5 e \bar{N} N$$

Hence, a bound on d_e :

$$d_e < 1.5 \times 10^{-27} \text{ e cm}$$

Mercury EDM

Flambaum, Dmitriev,
Sukhov '03, Pospelov '01

$$d_{Hg} \approx 7 \cdot 10^3 \text{ e} (\tilde{d}_u - \tilde{d}_d) + \dots$$

4-fermion,
...

This is from:



EDMs in SUSY

Induced by new CP phases:

$$\Delta \mathcal{L} = \underbrace{\mu}_{\text{complex}} \bar{\Psi}_{H_1} \Psi_{H_2} + \underbrace{B\mu}_{\text{complex}} H_1 H_2 + \text{h.c.}$$

$$+ \frac{1}{2} \left(\underbrace{m_3}_{\text{complex}} \bar{\lambda}_3 \lambda_3 + \underbrace{m_2}_{\text{complex}} \bar{\lambda}_2 \lambda_2 + \underbrace{m_1}_{\text{complex}} \bar{\lambda}_1 \lambda_1 \right)$$

$$+ \underbrace{A_{ij}^d}_{\text{complex}} H_1 \tilde{q}_{L_i} \tilde{q}_{R_j}^* + \dots$$

$\underbrace{\dots}_{\text{complex}} = \text{complex}$

2 phases eliminated by $U(1)_R$, $U(1)_{PQ}$

Physical phases: $\text{Arg}(m_i^* A)$, $\text{Arg}(B^* A)$, ...

Typical EDM contribution:

Ellis, Ferrara, Nanopoulos '82

$g_{\text{susy}} \sim 10^{-2} \Leftarrow$
(CP problem)



The CP problem appears
already in the minimal SUSY
scenario

m SUGRA :

$\mu, A = \text{complex!}$

(unlike the FCNC problem)

Suppression of EDMs:

1. small phases
2. decoupling
3. off diagonal ~~CP~~

(+ accidental cancellations)

① Small phases

E.g. phase alignment

$$y_M = y_A = -y_\mu$$

↓

$$y(M^* A) = y(\mu A) = \dots = 0 //$$

(dilaton domination + Giudice - Masiero)

② Decoupling

Nath '91
Kikuchi,
Oshimo '92


$$\sim \frac{1}{m_{\tilde{q}_{1,2}}^2} \xrightarrow{\sim 10 \text{ TeV}} 0$$

③ off diagonal CP

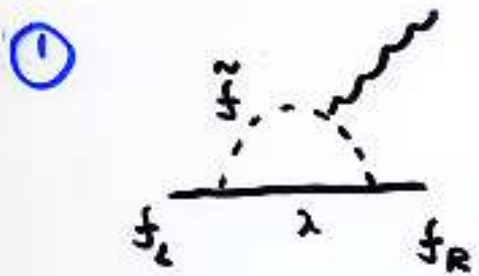
$$\left. \begin{array}{l} A = A^* \\ M = M^* \\ \dots \end{array} \right\} \text{by symmetry} \begin{array}{l} \rightarrow LR \\ \rightarrow \text{flavour} \end{array}$$

Mohapatra,
Senjanovich

Abel, Bailin,
Khalil, DL

Like in the SM, small EDMs.

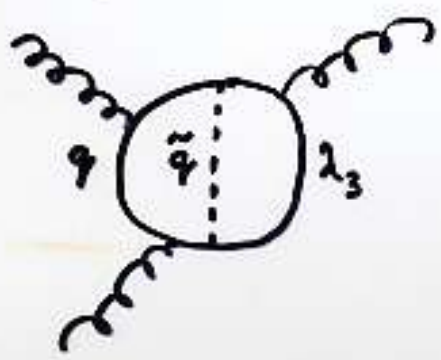
Classes of EDM contributions



→ typically the most important contributions

② Weinberg operator

Weinberg '89
Dai et al. '90



→ $\Delta \tilde{2} \sim G \tilde{G} G$;
non-zero d_n

It dominates when 1, 2^d generation fermions are decoupled:

$$m_{\tilde{q}_{1,2}} \rightarrow \infty$$

Barr, Zele '90

③ Barr-Zee-type contributions

Chang
Keung
Pilat'99



→ subleading to the Weinberg op., induces d_n, d_e, \dots

Chang
Keung '02
Pilat'02

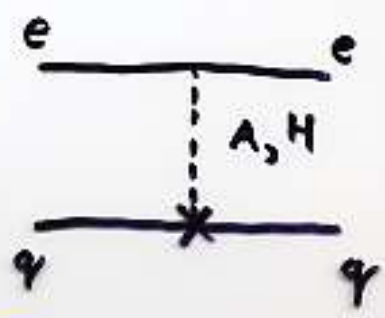
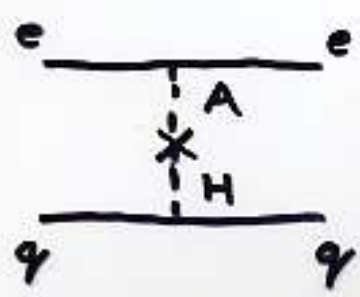


→ survives when sfermions decouple

Dominates in split SUSY.

④ 4-fermion operators

Barr '92
OL, Pospelov '02



→ $\Delta \tilde{2} \sim \bar{e} i \gamma_5 e \cdot \bar{N} N$

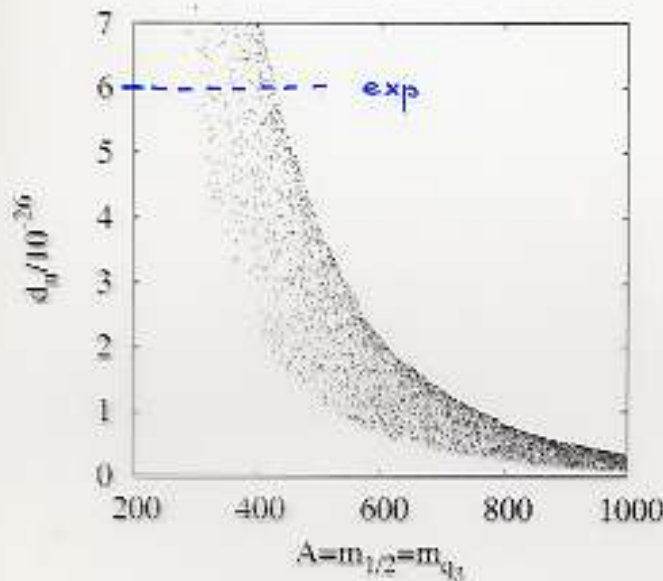
→ d_{TI}, d_{Hg}, \dots

Dominates when all SUSY particles are decoupled. Also at large $\tan\beta$.

nEDM due to the
Weinberg op.

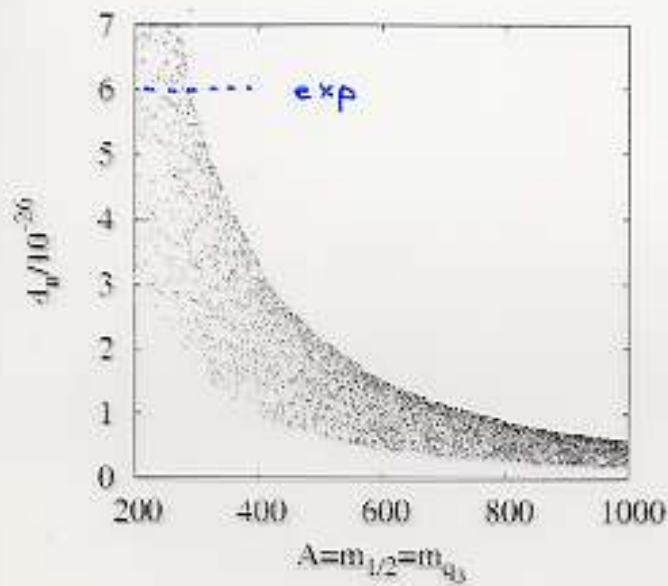
$$m_{1,2} \rightarrow \infty ; \quad A = m_{1/2} = m_3 \quad \Big| \quad \text{GUT}$$
$$\tan\beta = 5$$

$$\begin{cases} \varphi_A = 0 \\ \varphi_\mu \in [\pi/10, \pi/2] \end{cases}$$



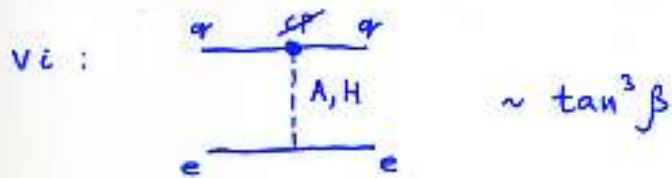
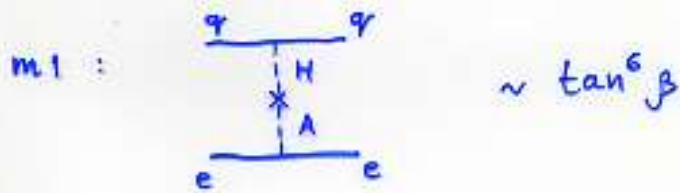
Abel, OL'05

$$\begin{cases} \varphi_A \in [\pi/10, \pi/2] \\ \varphi_\mu = 0 \end{cases}$$

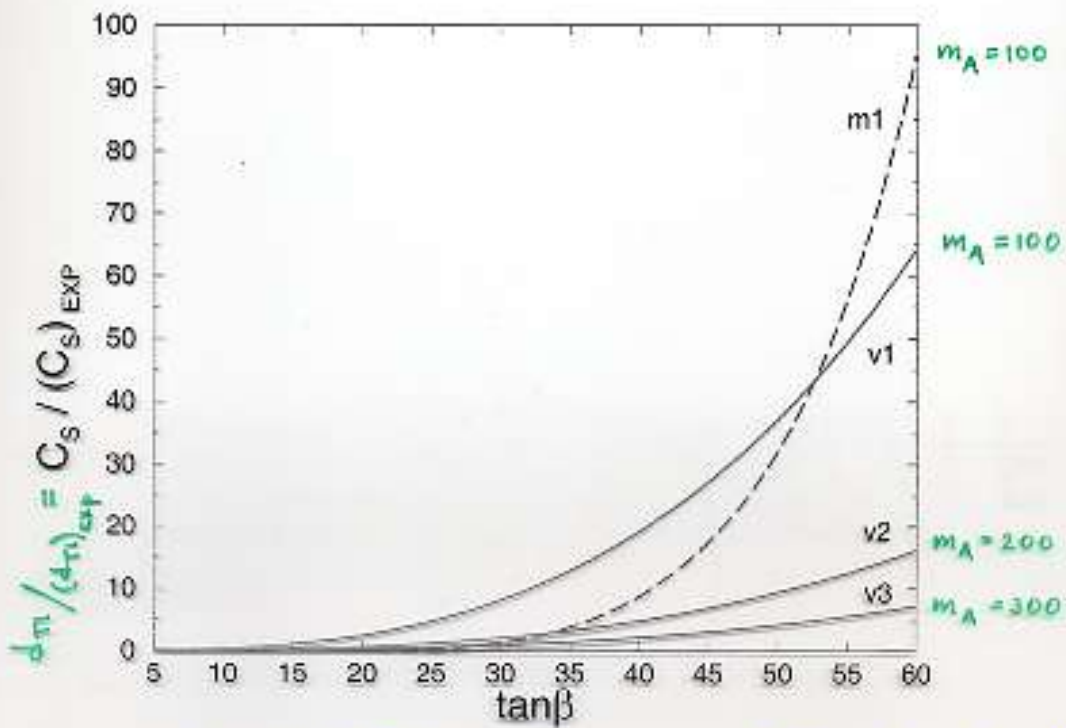


Abel, 02'05

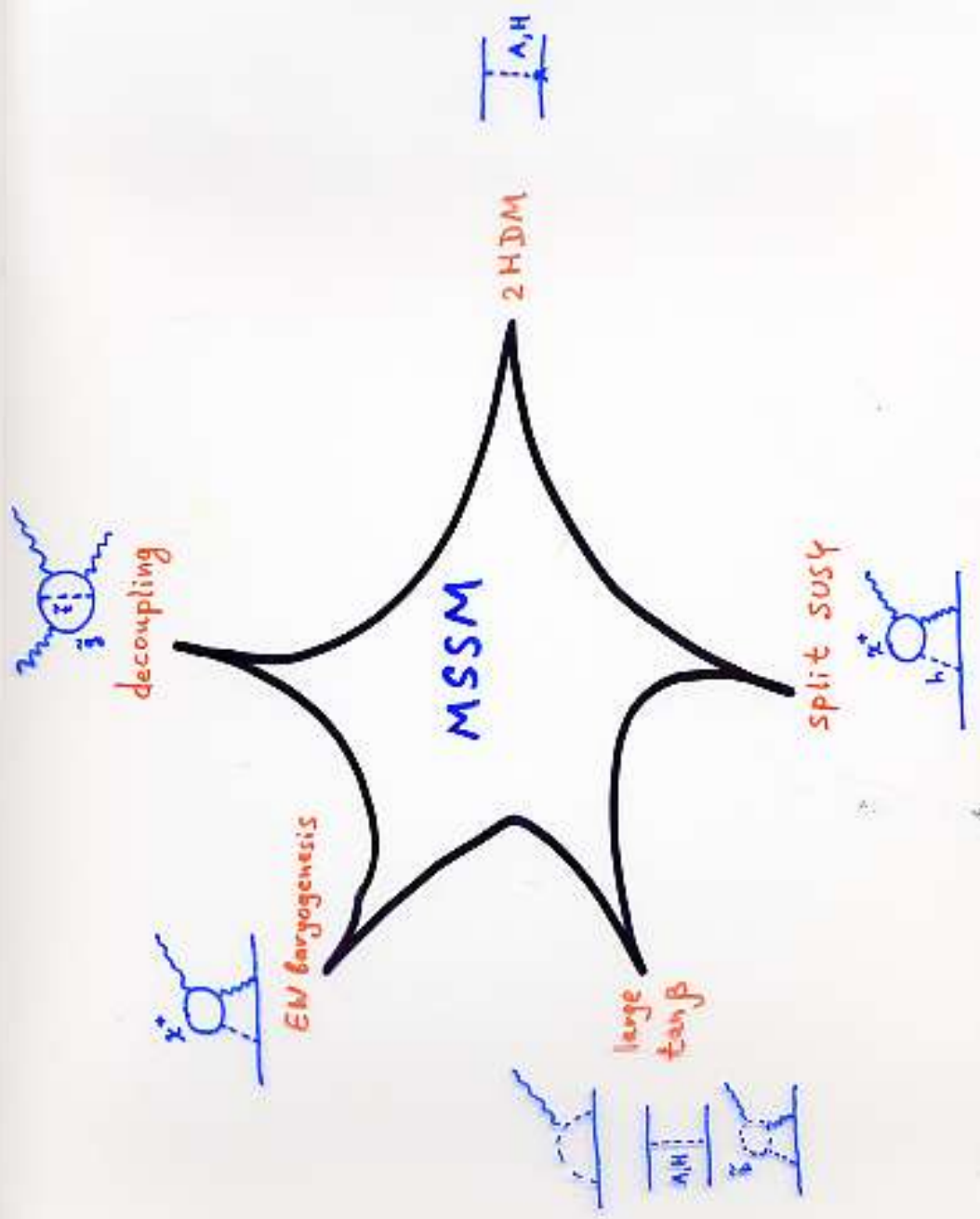
d_{TI} due to 4-fermion interactions



DL, Pospelov 192

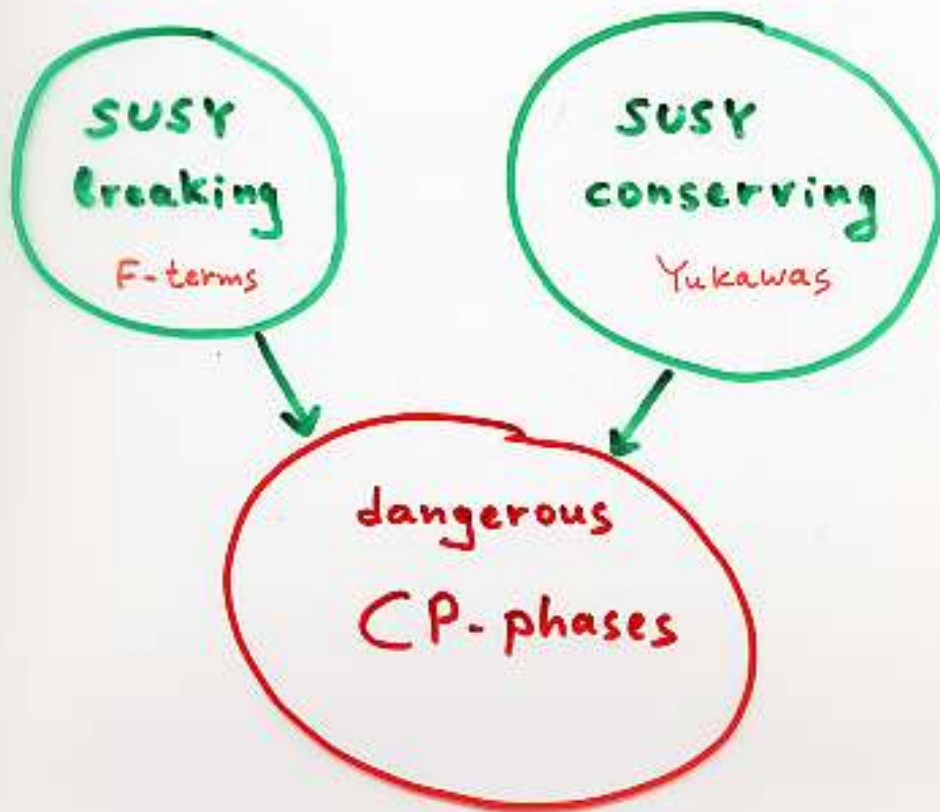


$\text{Arg}(A\mu) = \pi/2$; $A_{t,b} = M = 1 \text{ TeV}$; $m_{\tilde{g}_3} = 600 \text{ GeV}$



Fundamental sources of
SUSY CP

MSSM = low energy limit of
supergravity



① SUSY breaking F-terms

Gaugino masses:

$$m_i \sim F^n \partial_n f_i$$

↑
gauge kinetic
function

μ -term:

$$\mu \sim F^n \partial_n Z + \dots$$

↑
Giudice - Masiero
function

...

Leads to flavour-independent phases

$$\text{Arg}(m_i^* m_j), \text{Arg}(\mu m_i), \dots$$

(+ possibly flavour-dependent phases in the A-terms)

② SUSY conserving quantities

E.g. Yukawas Y_{ij} are complex

Induce large EDMs through
flavour-dependent A-terms.

Abel, Khalil
01'02

$$A_{ij} \sim F^m \left[Y_{ij} + \underline{\underline{\partial_m Y_{ij}}} + \dots \right]$$

$$\Rightarrow A_{ij} \not\propto Y_{ij}$$

$\Rightarrow A_{ij}$ and Y_{ij} are not
diagonalizable simultaneously

$$\begin{cases} Y_{\text{diag}} = V_L^\dagger Y V_R \\ A' = V_L^\dagger A V_R \neq \text{diag} \end{cases}$$

$$A' = \begin{pmatrix} a'_{11} & \dots \\ \dots & \dots \end{pmatrix}; \text{Arg } a'_{11} \sim O(1)$$



\rightarrow large EDMs

What if $\mathcal{L}_{\text{soft}}$ is real?

$$\mathcal{L} = \underbrace{m_i}_{\text{all real}} \bar{\lambda}_i \lambda_i + \underbrace{A_{ij}}_{\text{all real}} \tilde{q}_{Li}^* \tilde{q}_{Rj} H + \dots$$

all real

Does not help. What matters is

$$A|_{\text{SCKM}} = \underbrace{V_L^\dagger}_{\text{order one}} A \underbrace{V_R}_{\text{phases!}}$$

Another view: real is basis-dependent!

$$\text{SUSY Jarlskog} = \text{Im Tr} \left\{ \begin{array}{l} Y_u Y_u^\dagger, Y_d Y_d^\dagger, A_u A_u^\dagger \\ \vdots \\ \text{antisym.} \end{array} \right\} \quad \text{01'02}$$

Vanishes if $A_u \sim Y_u, \dots$

Prospects

EDM predictions:

① small phases $\rightarrow ?$

② decoupling $\rightarrow \begin{cases} d_n \sim 10^{-26} \text{ ecm} \\ d_e \gtrsim 10^{-28} \text{ ecm} \end{cases}$

split SUSY $\rightarrow \begin{cases} d_n \lesssim 10^{-27} \text{ ecm} \\ d_e \lesssim 10^{-28} \text{ ecm} \end{cases}$

③ off diag. $\cancel{CP} \rightarrow ?$

Imperial, Yale $\rightarrow d_e \sim 10^{-29}, 10^{-30} \text{ ecm}$ } 2006
ILL $\rightarrow d_n \sim 10^{-26} \text{ ecm}$

Los Alamos: much better bounds by 2009

BNL: d_3, d_μ

Conclusions

- ① EDMs probe CP/flavour of fundamental theories (e.g. SUGRA, string, ...)
- ② CP - problem is rather difficult, but possible to avoid
- ③ Probe solutions in the next 1-4 years