Electric Dipole Moments

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PERIMETER INSTITUTE

Fermilab Academic Lectures
"The Allure of Ultrasensitive Experiments"
April 1, 2014

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Electric dipole moments as probes of new physics
Annals Phys. **318**, 119 (2005) [hep-ph/0504231]

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JHEP **0810**, 049 (2008) [arXiv:0808.1819 [hep-ph]]

Outline of the Lectures

1. Electric Dipole Moments as Probes of New Physics
   - Introduction
   - EDMs in the Standard Model
   - EDMs Beyond the Standard Model
     - Model Independent Sensitivity to New Physics
     - The SUSY CP Problem

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2. EDMs, Flavor Physics, and the Higgs
   - Interplay of EDMs with Flavor Physics
     - Minimal Flavor Violation
     - Generic Flavor Violation
   - Interplay of EDMs with Higgs Physics
     - Higgs CP Properties at the LHC
     - Higgs CP Properties and EDMs

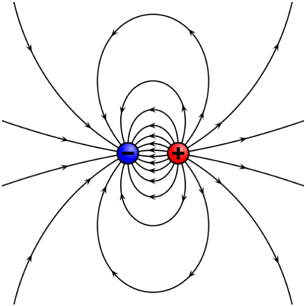
Part I

Electric Dipole Moments as Probes of New Physics

Electric and Magnetic Dipole Moments

interactions of a particle with spin $\vec{S}$
with an electric and magnetic field

$$\mathcal{H} = -\mu \frac{\vec{S}}{|S|} \cdot \vec{B} - d \frac{\vec{S}}{|S|} \cdot \vec{E}$$



electric dipole moment d
magnetic dipole moment μ

Properties under C, P, T

Properties under Charge Conjugation C, Parity P, and Time Reversal T

$$T: \quad \vec{E} \to +\vec{E} \qquad \vec{B} \to -\vec{B} \qquad \vec{S} \to -\vec{S}$$

$$P: \quad \vec{E} \to -\vec{E} \qquad \vec{B} \to +\vec{B} \qquad \vec{S} \to +\vec{S}$$

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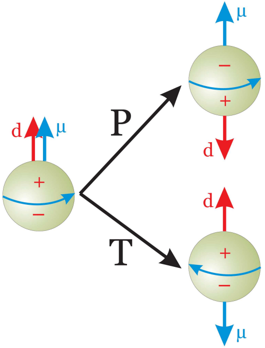
$$\mathcal{H} = -\mu \frac{\vec{S}}{|S|} \cdot \vec{B} - d \frac{\vec{S}}{|S|} \cdot \vec{E}$$

MDMs are P even and T even
EDMs are P odd and T odd

assuming CPT invariance
(= pretty safe assumption):

MDMs are CP conserving
EDMs are CP violating



Relevance for Fundamental Particle Physics

Are EDM measurements accurate enough to probe scales that are relevant for high energy physics? (electro-weak scale, TeV scale)

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$$\Delta \text{Energy} \sim 10^{-6}\text{Hz} \sim 10^{-21} eV$$

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translates into sensitivities of EDMs at the order of

$$d \lesssim \frac{\Delta\text{Energy}}{\text{electric field}} \sim 10^{-25} ecm \quad , \quad \text{electric field} \sim 10^{4} V/cm$$

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Theoretically inferred scaling of EDMs (see later)

$$d \sim \frac{1}{16\pi^2} \times \frac{1MeV}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 1TeV$$

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EDM experiments are relevant for fundamental particle physics

Relativistic Generalization of EDMs and MDMs

Interaction of a fermion f with the photon field A_μ, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

$$-d_f \frac{\vec{S}}{|S|} \cdot \vec{E} \quad \rightarrow$$

$$-\mu_f \frac{\vec{S}}{|S|} \cdot \vec{B} \quad \rightarrow \quad e(\bar{f}\gamma_\mu f)A^\mu$$

the usual minimal coupling of fermions with the photon give rise to a magnetic moment with gyromagnetic factor $g = 2$

$$\mu_f = g_f \frac{e}{2m_f}$$

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$$-d_f \frac{\vec{S}}{|S|} \cdot \vec{E} \quad \rightarrow \quad d_f \frac{i}{2} (\bar{f} \sigma_{\mu\nu} \gamma_5 f) F^{\mu\nu}$$

$$-\mu_f \frac{\vec{S}}{|S|} \cdot \vec{B} \quad \rightarrow \quad e(\bar{f} \gamma_\mu f) A^\mu + a_f \frac{e}{4 m_f} (\bar{f} \sigma_{\mu\nu} f) F^{\mu\nu}$$

the usual minimal coupling of fermions with the photon give rise to a magnetic moment with gyromagnetic factor $g = 2$

the dimension 5 operators induce an electric dipole moment d_f and an anomalous magnetic moment a_f

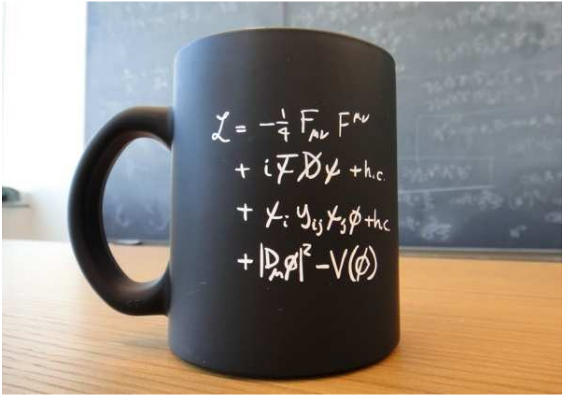
$$\mu_f = g_f \frac{e}{2 m_f} \quad , \qquad (g_f - 2) = 2 a_f$$

d_f and a_f are described by non-renormalizable interactions of fermions with the photon. They are absent for elementary fermions at the classical level, but can be induced by loop corrections.

Electric Dipole Moments in the Standard Model

Sources of CP Violation in the Standard Model

The Standard Model of Particle Physics



CP is violated in nature

$$BR(K_L \to \pi^+\pi^-) \neq 0$$

(Cronin, Fitch 1964)

can be accommodated
in the Standard Model
with 3 generations
$\to$ CKM matrix

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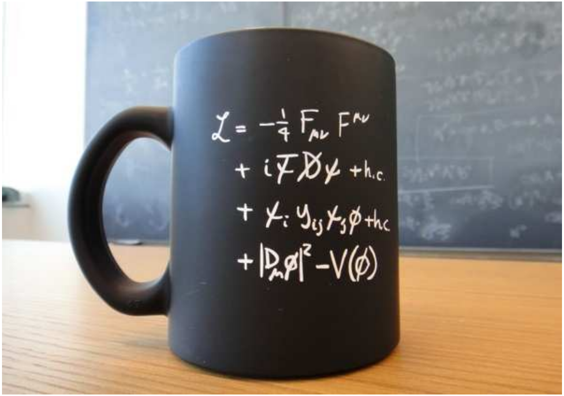

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with 3 generations
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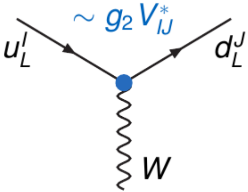
Standard Model
contains another source
of CP violation:
the QCD theta term

more on that later ...

The CKM Matrix

parametrizes the misalignment of up-type quarks and down-type quarks in flavor space

appears in the weak interactions of quarks with the W boson (charged current)



$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

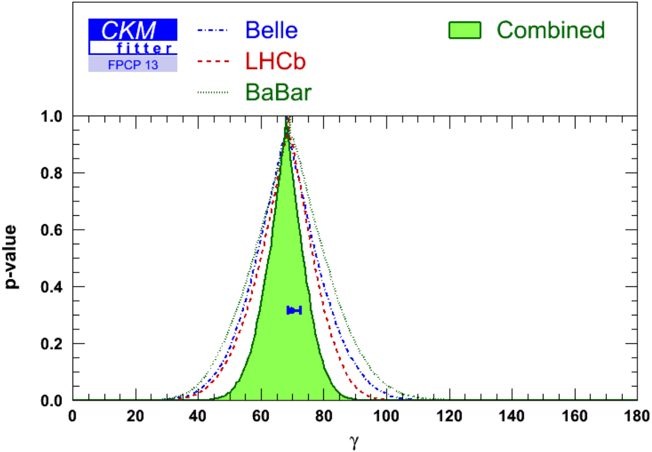
unitary 3×3 matrix $\to$ 3 angles 6 phases

5 phases can be reabsorbed by redefinition of the quark fields

$$u \to e^{i\phi_u} u \ , \quad d \to e^{i\phi_d} d \ , \quad \dots$$

CKM matrix contains one physical CP violating phase

Tree Level Measurement of the CKM Phase

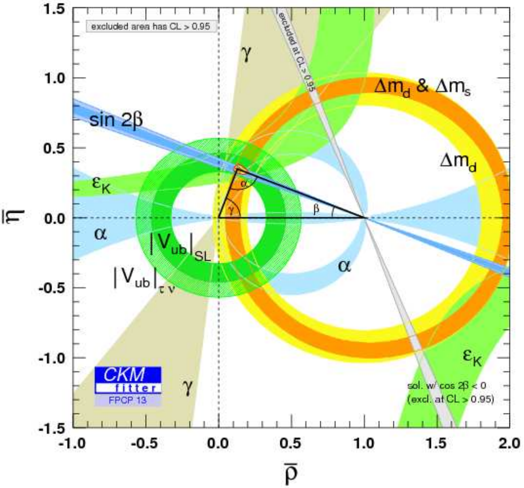


The CKM phase is O(1)

Within the experimental and theoretical uncertainties, the CKM matrix gives a consistent description of all observed flavor and CP violating phenomena

Extraction of the CKM phase from the global fit gives

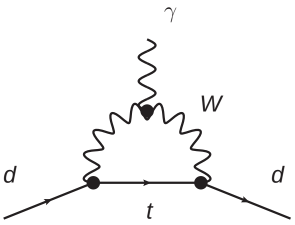
$$\gamma = 69.7^{+1.3}_{-2.8}$$



Quark EDMs from the CKM Matrix

try 1 loop with weak interactions to access the phase of the CKM matrix

$d_d \propto$



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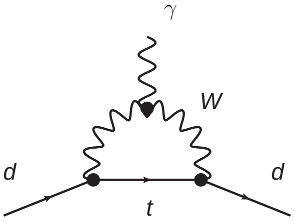

$$d_d \propto \frac{e}{16\pi^2}$$

- loop suppressed

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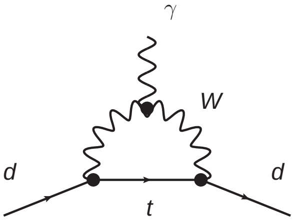
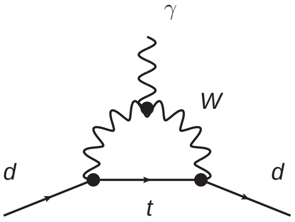


$$d_d \propto \frac{e}{16\pi^2} G_F$$

- loop suppressed
- first order in the weak interactions

Quark EDMs from the CKM Matrix

try 1 loop with weak interactions to access the phase of the CKM matrix

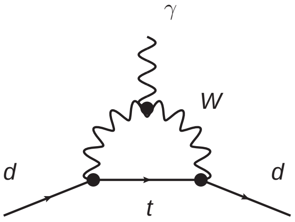


$$d_d \propto \frac{e}{16\pi^2} G_F m_d$$

- loop suppressed
- first order in the weak interactions
- helicity suppressed

try 1 loop with weak interactions to access the phase of the CKM matrix

$$d_d \propto \frac{e}{16\pi^2} G_F m_d \mathrm{Im}(V_{td} \quad)$$



- loop suppressed
- first order in the weak interactions
- helicity suppressed
- pick up a CKM element that contains a CP violating phase

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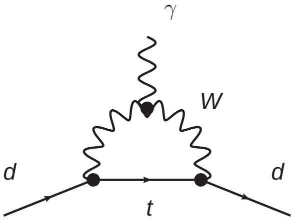


$$d_d \propto \frac{e}{16\pi^2} G_F m_d \mathrm{Im}(V_{td} V_{td}^*) = 0$$

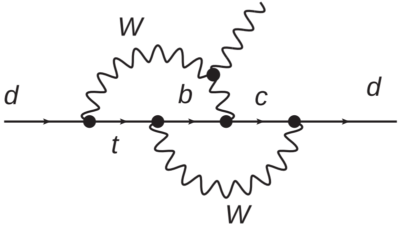
- loop suppressed
- first order in the weak interactions
- helicity suppressed
- pick up a CKM element that contains a CP violating phase
- 1 loop is not sufficient...

Quark EDMs from the CKM Matrix

try 2 loops with weak interactions to access the phase of the CKM matrix

$$d_d \propto \frac{e}{(16\pi^2)^2} G_F^2 m_c^2 m_d$$

$$\times \mathrm{Im}(V_{td} V_{tb}^* V_{cb} V_{cd}^*) \neq 0$$



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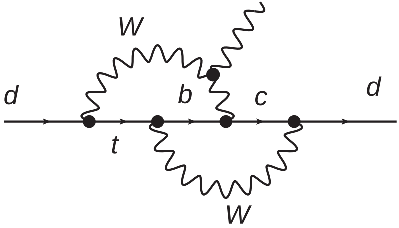

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- 2 loop suppressed

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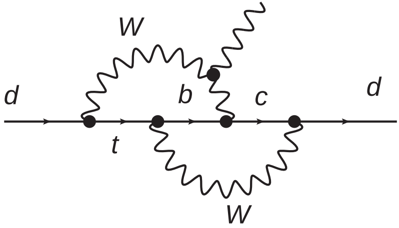

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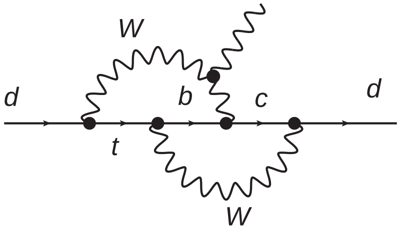
- 2 loop suppressed
- second order in the weak interactions

try 2 loops with weak interactions to access the phase of the CKM matrix



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- pick up CKM combination with non-zero CP phase

Quark EDMs from the CKM Matrix

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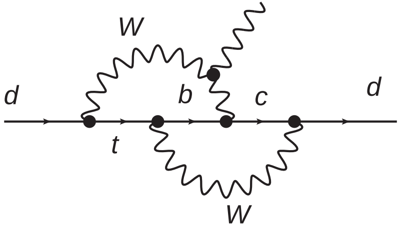

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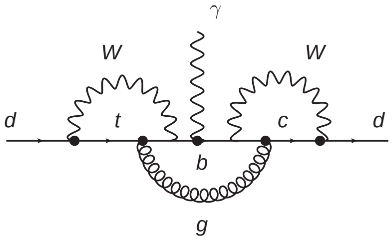
- 2 loop suppressed
- second order in the weak interactions
- pick up CKM combination with non-zero CP phase

seems to work!
however when one adds up all 2-loop diagrams one still gets 0...
(Shabalin, 1981)

Quark EDMs from the CKM Matrix

first non-vanishing contribution to quark EDMs arises at the 3-loop level



$$d_d \propto \frac{e}{(16\pi^2)^2} \frac{g_s^2}{16\pi^2} G_F^2 m_c^2 m_d$$

$$\times \mathrm{Im}(V_{td} V_{tb}^* V_{cb} V_{cd}^*) \neq 0$$

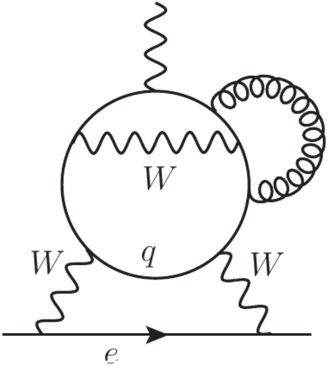
- two electro-weak loops
- one additional gluon loop

$$d_d \simeq 10^{-34} ecm$$

(Khriplovich 1986,
Czarnecki, Krause 1997)

Lepton EDMs from the CKM Matrix

for lepton EDMs one needs at least one additional loop
to switch from leptons to quarks and to access the CKM phase
(Khriplovich, Pospelov 1991)



$$d_e \propto \frac{e}{(16\pi^2)^3} \frac{g_s^2}{16\pi^2} G_F^3 m_c^2 m_s^2 m_e$$

$$\times \mathrm{Im}(V_{td} V_{tb*} V_{cb} V_{cd}^*)$$

- three electro-weak loops
- one additional gluon loop

$$d_e \simeq 10^{-44} ecm$$

(Pospelov, Ritz 2013)

Experimentally Accessible EDMs

- EDMs of paramagnetic systems:
  atoms (Tl, Fr, ...) and molecules (YbF, ThO, ...)

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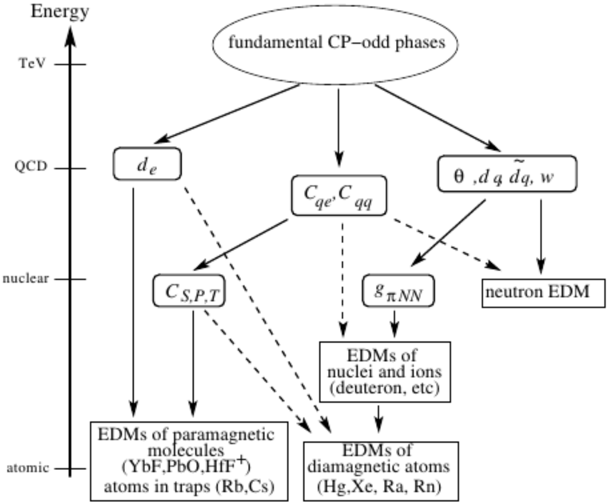
need to predict the EDMs of composite systems
in terms of EDMs of elementary particles

Experimentally Accessible EDMs



CP Violating Interactions

CP-odd Lagrangian at the GeV scale

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CP-odd Lagrangian at the GeV scale

$$\frac{g_s^2}{32\pi^2}\bar{\theta} G^A_{\mu\nu} \tilde{G}^{\mu\nu,\,A}$$

QCD theta term

terms at dimension 4

CP-odd Lagrangian at the GeV scale

$$\frac{g_s^2}{32\pi^2}\bar{\theta} G^A_{\mu\nu}\tilde{G}^{\mu\nu,\,A}$$ QCD theta term

$$d_f \frac{i}{2}(\bar{f}\sigma_{\mu\nu}\gamma_5 f)F^{\mu\nu}$$ EDMs of quarks and leptons

$$d_q^c \frac{i g_s}{2}(\bar{q}_\alpha \sigma^{\mu\nu} T^A_{\alpha\beta}\gamma_5 q_\beta)G^A_{\mu\nu}$$ chromo EDMs (CEDMs) of quarks

terms at dimension 4 , dimension 5

CP Violating Interactions

CP-odd Lagrangian at the GeV scale

$$\frac{g_s^2}{32\pi^2}\bar{\theta}G^A_{\mu\nu}\tilde{G}^{\mu\nu,\,A}$$

QCD theta term

$$d_f\,\frac{i}{2}(\bar{f}\sigma_{\mu\nu}\gamma_5 f)F^{\mu\nu}$$

EDMs of quarks and leptons

$$d_q^c\,\frac{ig_s}{2}(\bar{q}_\alpha\sigma^{\mu\nu}T^A_{\alpha\beta}\gamma_5 q_\beta)G^A_{\mu\nu}$$

chromo EDMs (CEDMs) of quarks

$$\frac{w}{3}f^{ABC}G^A_{\mu\nu}\tilde{G}^{\nu\rho,\,B}G^{\mu,\,C}_{\rho}$$

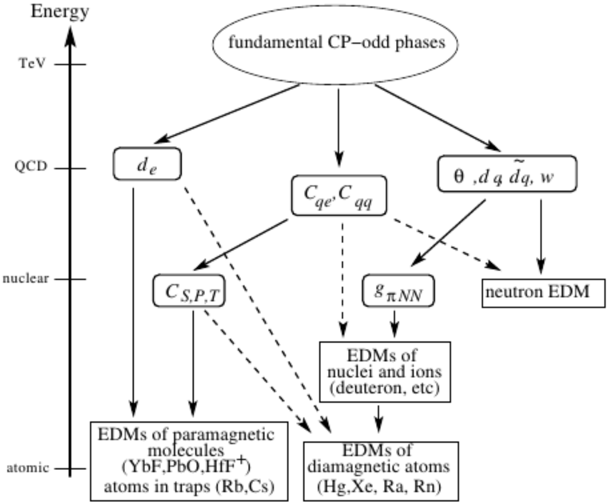
Weinberg three gluon operator

$$C_{ij}(\bar{f}_i f_i)(\bar{f}_j i\gamma_5 f_j)$$

CP violating 4 fermion operators

terms at dimension 4 , dimension 5 , dimension 6, ...

CP Violating Interactions



EDMs of paramagnetic systems:
atoms (Tl, Fr, ...) and molecules (YbF, ThO, ...)

e.g. $|d_{Tl}| \simeq$

Calculation of EDMs

EDMs of paramagnetic systems:
atoms (Tl, Fr, ...) and molecules (YbF, ThO, ...)

contain an unpaired electron
$\rightarrow$ mainly sensitive to the electron EDM that sees an enhanced effective electric field inside the atom/molecule

e.g. $|d_{Tl}| \simeq \quad d_e$

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typical enhancement factor for atoms

$$d_{\rm para} \sim \frac{10\, Z^3 \alpha_{\rm em}}{J(J+1/2)(J+1)^2}\, d_e \quad ,$$

J: angular momentum
Z: atomic number

for polar molecules the enhancement can be even larger

e.g. $|d_{Tl}| \simeq 585\, d_e$

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for polar molecules the enhancement can be even larger

additional contributions from CP-odd electron nucleon couplings
(induced by CP-odd 4 fermion contact terms)

e.g. $|d_{Tl}| \simeq 585\, d_e + e\, 43\ \text{GeV} \times (C_S^{(0)} - 0.2 C_S^{(1)}) + \ldots$

Calculation of EDMs

EDMs of diamagnetic atoms (Hg, Ra, Rn, ...)

e.g. $|d_{Hg}| \simeq$

Calculation of EDMs

EDMs of diamagnetic atoms (Hg, Ra, Rn, ...)

all electron spins are paired up
suppressed sensitivity to the electron EDM

e.g. $|d_{Hg}| \simeq 10^{-2}\, d_e$

Calculation of EDMs

EDMs of diamagnetic atoms (Hg, Ra, Rn, ...)

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suppressed sensitivity to the electron EDM

sensitivity to the EDM of the nucleus,
that is mainly induced by CP-odd pion nucleon couplings,
that in turn depend mainly on the quark chromo-EDMs

e.g. $|d_{Hg}| \simeq 10^{-2}\, d_e + 7 \times 10^{-3}\, e\, (\tilde{d}_u - \tilde{d}_d)$

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(induced by CP-odd 4 fermion contact terms)

e.g. $|d_{Hg}| \simeq 10^{-2}\, d_e + 7 \times 10^{-3}\, e\, (\tilde{d}_u - \tilde{d}_d) + O(C_S) + ...$

most of the terms come with uncertainties of $>$ O(1) proton and neutron EDMs

e.g. $d_n \simeq$

Calculation of EDMs

proton and neutron EDMs

high sensitivity to the constituent quark EDMs

e.g. $d_n \simeq 1.4 \left(d_d - \frac{1}{4} d_u\right)$

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additional contributions from CP-odd pion nucleon couplings
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most of the terms have uncertainties of O(1)

Current Experimental Bounds

[Griffith et al. 2009 (Hg); Baker et al. 2006 (neutron);
Regan et al. 2002 (Tl); Hudson et al. 2011 (YbF); ACME 2013 (ThO)]

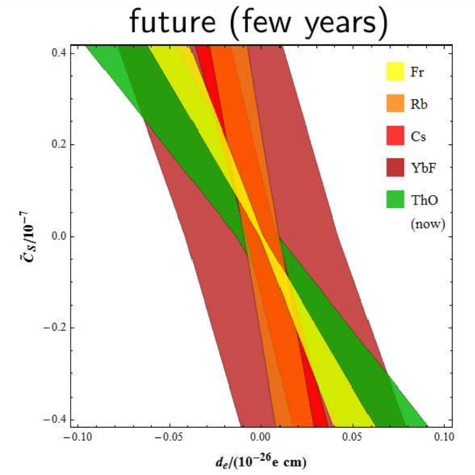
$$d_{Hg} < 3.1 \times 10^{-29}\ ecm$$

$$d_n < 2.9 \times 10^{-26}\ ecm$$

$$|d_e| \leq \left\{ \begin{array}{ll} 1.6 & (Tl) \\ 1.05 & (YbF) \\ 0.089 & (ThO) \end{array} \right\} \times 10^{-27}\, e\,\mathrm{cm}$$

bounds on the electron EDM assume the absence of
contributions from CP-odd electron nucleon couplings

Disentangling Different Contributions



Jung, 2013

different paramagnetic atoms/molecules have different dependence on the electron EDM d_e and the CP-odd electron nucleon interaction C_S.

considering many systems simultaneously allows to bound d_e and C_S separately

SM Predictions for EDMs and the QCD theta term

QCD theta term: $$\frac{g_s^2}{32\pi^2}\bar{\theta}G\tilde{G}$$

the QCD theta term is a dimension 4 operator
$\rightarrow$ not suppressed by any high scale
$\rightarrow$ generically expected to be O(1)

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also contributes to the EDMs of hadronic systems

$$d_n \sim e\bar{\theta}\frac{m_u m_d}{m_u + m_d}\frac{1}{m_n^2} \sim \bar{\theta} \times 6 \times 10^{-17} ecm$$

experimental bound on d_n translates into the limit: $\theta \lesssim 10^{-9}$

$\rightarrow$ strong CP problem

Dynamical Relaxation of $\bar{\theta}$

add an axion: a pseudoscalar that couples to $G\tilde{G}$

$$\mathcal{L} = \bar{\theta} \frac{g_s^2}{32\pi^2} G\tilde{G} + \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{a}{f_a}\frac{g_s^2}{32\pi^2} G\tilde{G}$$

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$$= \left(\bar{\theta} + \frac{a}{f_a}\right)\frac{g_s^2}{32\pi^2}G\tilde{G} + \frac{1}{2}\partial_\mu a \partial^\mu a$$

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below the QCD scale a potential for the axion is induced

$$V(a) \propto \left(\bar{\theta} + \frac{a}{f_a}\right)^2$$

axion acquires a vev: $\langle a \rangle = -\bar{\theta} f_a$

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the $G\tilde{G}$ term vanishes in the vacuum
$\rightarrow$ no contribution anymore to the neutron EDM

The Neutron EDM from the CKM Matrix

with the QCD theta term switched off,
the dominant contributions to the neutron EDM in the SM
are not the EDMs of the constituent quarks

$$d_n \simeq \bar{\theta} \times 2.5 \times 10^{-16} e cm + 1.1 e(\tilde{d}_d + 0.5 \tilde{d}_u) + 1.4(d_d - 0.25 d_u)$$

$+$contributions from the Weinberg operator

$+$contributions from 4 fermion operators

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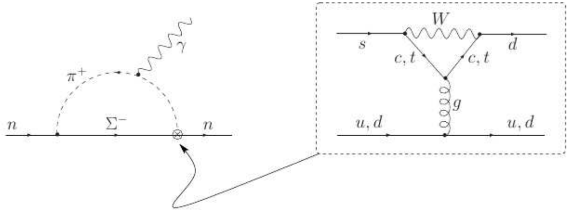
the dominant effect arises from a CP violating pion nucleon coupling that is generated at the one loop level from a 4-fermion operator



can be as large as

$$d_n \sim 10^{-31}\ ecm$$

(Khriplovich, Zhitnitski 1982)
(Mannel, Uraltsev, 2012)

The "Electron EDM" from the CKM Matrix

in the Standard Model, the contribution to EDMs of paramagnetic systems from the electron is absolutely negligible ($d_e^{\rm SM} \sim 10^{-44} ecm$)

$$\text{e.g.} \quad d_{Tl} \simeq -585 d_e - e\, 43\text{GeV} \times (C_S^{(0)} - 0.2 C_S^{(1)})$$

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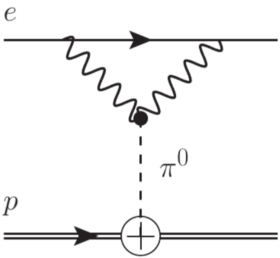
largest SM contribution comes from the
CP violating electron nucleon couplings



“equivalent electron EDM benchmark”

$$d_e^{\rm equiv} \sim 10^{-39}\ ecm$$

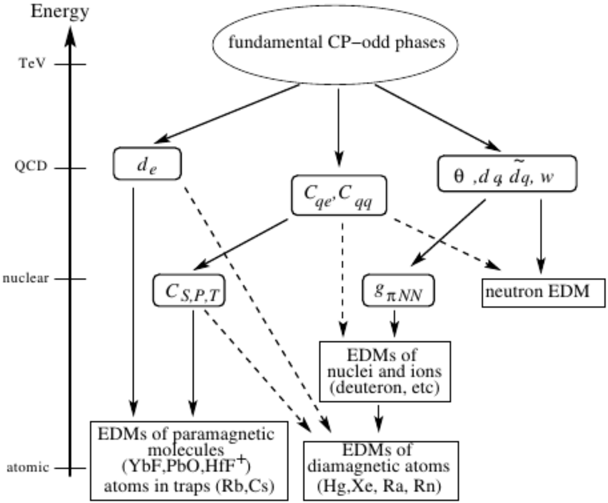
(Pospelov, Ritz 2013)

Standard Model Benchmarks for EDMs are
Many Orders of Magnitude Below
the Current Experimental Sensitivities

$\rightarrow$ EDMs are “Background-Free” Probes
of New Physics

EDMs and New Physics

Fundamental CP-odd Phases



EDM operators and $SU(2)_L$ Invariance

EDMs and CEDMs are helicity flipping

$$d_f \frac{i}{2}(\bar{f}\sigma_{\mu\nu}\gamma_5 f)F^{\mu\nu} = d_f \frac{i}{2}(\bar{f}_L\sigma_{\mu\nu}f_R - \bar{f}_R\sigma_{\mu\nu}f_L)F^{\mu\nu}$$

$\rightarrow$ EDM and CEDM operators are not $SU(2)_L$ invariant

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above the electro-weak scale, need to add a Higgs doublet to the operators to restore $SU(2)_L$ invariance.

$$H(\bar{f}_L\sigma_{\mu\nu}f_R)F^{\mu\nu}$$

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$$\frac{1}{\Lambda^2}H(\bar{f}_L\sigma_{\mu\nu}f_R)F^{\mu\nu} \quad \to \quad \frac{v}{\Lambda^2}(\bar{f}_L\sigma_{\mu\nu}f_R)F^{\mu\nu} \quad , \quad d_f \sim \frac{v}{\Lambda^2}$$

$\to$ EDMs and CEDMs are secretly dimension 6 operators and decouple with the new physics scale Λ squared

Model Independent Sensitivity to New Physics

example 1: down quark EDM

$$\frac{\tilde{C}}{\Lambda^2} H y_d (\bar{d}_L \sigma_{\mu\nu} d_R) F^{\mu\nu} \to \frac{\tilde{C}}{\Lambda^2} m_d \, (\bar{d}_L \sigma_{\mu\nu} d_R) F^{\mu\nu} \quad , \quad d_d \sim \frac{\tilde{C} m_d}{\Lambda^2}$$

- Minimal Flavor Violation implies that the down EDM is proportional to the down Yukawa coupling ($\to$ lecture on Thursday)
- constraint from neutron EDM, assuming $\tilde{C} \sim 1$ with O(1) phase

$$\Lambda \gtrsim 50 \text{ TeV}$$

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example 2: electron EDM

$$\frac{\tilde{C}}{\Lambda^2} H y_e (\bar{e}_L \sigma_{\mu\nu} e_R) F^{\mu\nu} \to \frac{\tilde{C}}{\Lambda^2} m_e \, (\bar{e}_L \sigma_{\mu\nu} e_R) F^{\mu\nu} \quad , \quad d_e \sim \frac{\tilde{C} m_e}{\Lambda^2}$$

- MFV: proportionality to electron Yukawa
- constraint from ThO EDM, assuming $\tilde{C} \sim 1$ with O(1) phase

$$\Lambda \gtrsim 300 \text{ TeV}$$

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- MFV: proportionality to electron Yukawa
- constraint from ThO EDM, assuming $\tilde{C} \sim 1/16\pi^2$ with O(1) phase

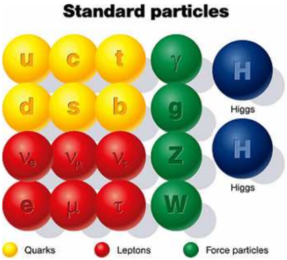
$$\Lambda \gtrsim 30 \text{ TeV}$$

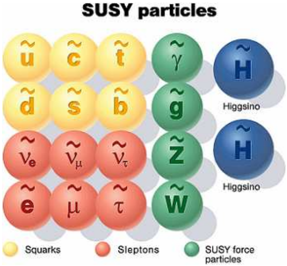
Supersymmetry (SUSY) implies:
every fermion has a bosonic partner
and vice versa

requires 2 Higgs doublets to give mass
to up-type and down-type fermions

$$\tan\beta = \langle H_u \rangle / \langle H_d \rangle$$

expect at least some SUSY particles
(Higgsinos, stops, gluinos)
at or below O(TeV) for a
natural electro-weak scale





CP Violation in the MSSM

The MSSM can contain many new sources of CP violation

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Higgsino and Higgs masses
$\rightarrow$ 2 phases

$$\mu \tilde{H}_u \tilde{H}_d + B\mu H_u H_d + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2$$

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squark and slepton masses
$\rightarrow$ 15 phases

$$m_Q^2 \tilde{Q}_L^\dagger \tilde{Q}_L + m_U^2 \tilde{U}_R^\dagger \tilde{U}_R + m_D^2 \tilde{D}_R^\dagger \tilde{D}_R$$
$$+ m_L^2 \tilde{L}_L^\dagger \tilde{L}_L + m_E^2 \tilde{E}_R^\dagger \tilde{E}_R$$

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gaugino masses
$\to$ 3 phases

$$m_1 \tilde{B}\tilde{B} + m_2 \tilde{W}\tilde{W} + m_3 \tilde{g}\tilde{g}$$

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gaugino masses
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$$m_1 \tilde{B}\tilde{B} + m_2 \tilde{W}\tilde{W} + m_3 \tilde{g}\tilde{g}$$

trilinear couplings
$\rightarrow$ 27 phases

$$A_u\, H_u \tilde{Q}_L^\dagger \tilde{U}_R + A_d\, H_d \tilde{Q}_L^\dagger \tilde{D}_R + A_\ell\, H_d \tilde{L}_L^\dagger \tilde{E}_R$$

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not all phases are physical! (like in the case of the CKM matrix)

The MSSM can contain many new sources of CP violation

Higgsino and Higgs masses
$\rightarrow$ 2 phases

$$\mu \tilde{H}_u \tilde{H}_d + B\mu H_u H_d + m^2_{H_u} |H_u|^2 + m^2_{H_d} |H_d|^2$$

squark and slepton masses
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$$+ m^2_L \tilde{L}^\dagger_L \tilde{L}_L + m^2_E \tilde{E}^\dagger_R \tilde{E}_R$$

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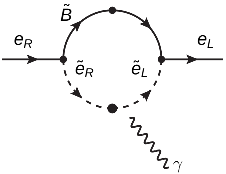
not all phases are physical! (like in the case of the CKM matrix)

2 phases can be rotated away...

Example 1:
Bino-Higgsino loop contribution
to the electron EDM

$d_e \propto$



1-Loop MSSM Contributions to EDMs

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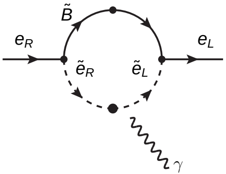

$$d_e \propto \frac{\alpha_1}{4\pi}$$

- 1-loop suppression

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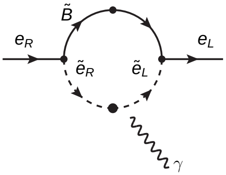

$$d_e \propto \frac{\alpha_1}{4\pi}\, m_e$$

- 1-loop suppression
- helicity suppression

1-Loop MSSM Contributions to EDMs

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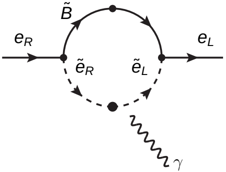

$$d_e \propto \frac{\alpha_1}{4\pi}\, m_e \tan\beta$$

- 1-loop suppression
- helicity suppression
- $\tan\beta$ enhancement

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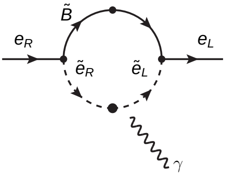
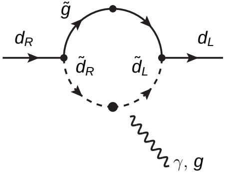


$$d_e \propto \frac{\alpha_1}{4\pi}\, m_e \tan\beta\, \frac{\mathrm{Im}(\mu m_{\tilde{B}})}{m_{\tilde{e}}^4}$$

- 1-loop suppression
- helicity suppression
- $\tan\beta$ enhancement
- sensitive to the relative phase of the bino and higgsino mass

Example 2:
gluino loop contribution
to the down quark EDM



$d_d \propto$

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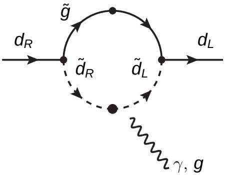
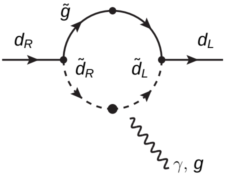
to the down quark EDM



$$d_d \propto \frac{\alpha_s}{4\pi} m_d \tan\beta \frac{\text{Im}(\mu m_{\tilde{g}})}{m_{\tilde{d}}^4}$$

- 1-loop suppression
- helicity suppression
- $\tan\beta$ enhancement
- sensitive to the relative phase of the gluino and higgsino mass

Example 2:
gluino loop contribution
to the down quark EDM



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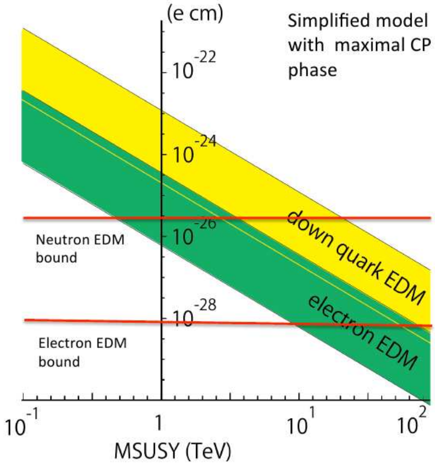
sensitivity to squarks and sleptons at the level of several TeV to several 10's of TeV (depending on $\tan\beta$)



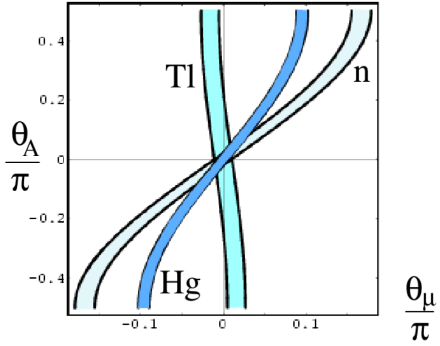
(Hisano @ Moriond EW 2014)

EDM bounds push SUSY particles far above the TeV scale

assumptions:

no cancellations between various contributions

order 1 CP violating phases



(Pospelov, Ritz 2005)

possible cancellations can be constrained by looking at several EDM constraints simultaneously

in the plot:

$m_{\text{SUSY}} = 500GeV$, $\tan\beta = 3$

consider phase of the Higgsino mass θ_μ; and universal phase of all trilinear couplings θ_A

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+ many other clever constructions that try to suppress CP phases

2-Loop MSSM Contributions to EDMs

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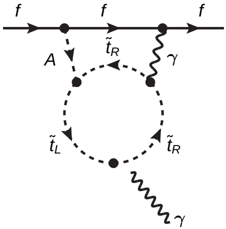

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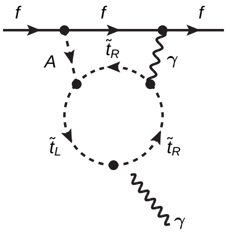

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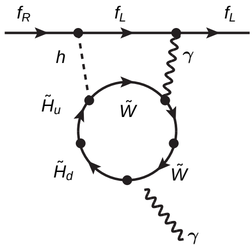

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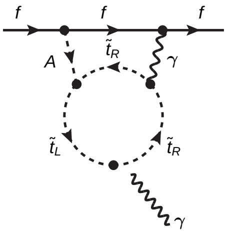

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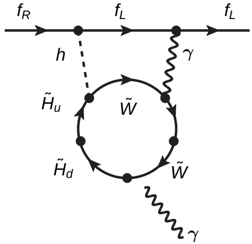

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current bounds on EDMs start to probe the 2 loop contributions if the involved particles are at the TeV scale

Summary

- Electric Dipole Moments are sensitive to CP violation beyond the Standard Model at the TeV scale and beyond
- Standard Model "background" is negligible for the foreseeable future
- EDMs of atoms, molecules, nucleons, etc are sensitive to different combinations of CP violating interactions

  $\rightarrow$ possibility to disentangle the source by measuring many different EDMs