CP Violation Beyond the Standard Model
(Theory of Electric Dipole Moments)

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Disclaimer

- I will mainly focus on how new sources of CP violation can be probed through electric dipole moments.
- For effects of CP violation in the Higgs sector see e.g. the lectures by Heather Logan.
- For effects of CP violation in the flavor sector see e.g. the lectures by Jure Zupan and Phoebe Hamilton.

Outline of the Lecture

1. Introduction / Motivation
2. Electric Diople Moments as Probes of New Physics
3. EDMs in the Standard Model
4. EDMs in Supersymmetric Theories
5. EDMs in Two Higgs Doublet Models

References

M. Pospelov and A. Ritz

Electric dipole moments as probes of new physics

Annals Phys. **318**, 119 (2005) [hep-ph/0504231]

J. Engel, M. J. Ramsey-Musolf and U. van Kolck

Electric Dipole Moments of Nucleons, Nuclei, and Atoms: The Standard Model and Beyond

Prog. Part. Nucl. Phys. **71**, 21 (2013) [arXiv:1303.2371 [nucl-th]]

T. Chupp, P. Fierlinger, M. Ramsey-Musolf and J. Singh

Electric dipole moments of atoms, molecules, nuclei, and particles

Rev. Mod. Phys. **91**, no.1, 015001 (2019) [arXiv:1710.02504 [physics.atom-ph]]

R. Alarcon, *et al.*

Electric dipole moments and the search for new physics

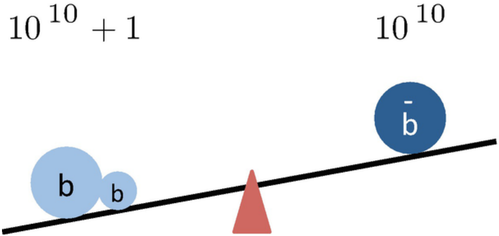
Snowmass 2021 [arXiv:2203.08103 [hep-ph]]

Introduction / Motivation

The Baryon - Antibaryon Asymmetry

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

Small (but non-zero!) asymmetry between baryon and anti-baryon number densities.



- The universe today contains almost no antimatter.
- Implies a tiny excess of baryons over antibaryons in the early universe.

The Sakharov Conditions

- To dynamically generate a baryon asymmetry, three conditions must be satisfied:

  1. Baryon number violation
  2. C and CP violation
  3. Departure from thermal equilibrium

- CP Violation is essential: without CPV, particles and antiparticles are produced and annihilate symmetrically.

- The SM contains CPV, but it is quantitatively too small
  - CKM CPV: suppressed by small Yukawas and mixing angles
  - QCD θ term: highly constrained by EDMs, $\theta \lesssim 10^{-10}$

$\Rightarrow$ Expect New Sources of CP Violation Beyond the SM

“Fishing Expeditions”

Promising Indirect Probes of New Physics

Probe more generic new physics

- Test bedrock assumptions of particle physics

  Lorentz invariance; CPT invariance; ...
  ($\Lambda \gtrsim M_{\text{Planck}} \sim 10^{19}$ GeV)

Reach to higher new physics scales

Promising Indirect Probes of New Physics

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- **Test bedrock assumptions of particle physics**

  Lorentz invariance; CPT invariance; ...
  ($\Lambda \gtrsim M_{\text{Planck}} \sim 10^{19}$ GeV)

- **Test (approximate) accidental symmetries of the SM**

  Baryon Number: e.g. proton decay
  ($\Lambda \sim \Lambda_{\text{GUT}} \sim 10^{16}$ GeV)

  Lepton Number: e.g. neutrinoless double beta decay
  ($\Lambda \sim \Lambda_{\text{see-saw}} \sim 10^{12}$ GeV)

  Flavor: e.g. flavor changing neutral currents
  ($\Lambda \sim 10^3 - 10^8$ GeV)

  CP: e.g. electric dipole moments
  ($\Lambda \sim 10^3 - 10^8$ GeV)

Reach to higher new physics scales

Promising Indirect Probes of New Physics

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  Flavor: e.g. flavor changing neutral currents
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  CP: e.g. electric dipole moments
  ($\Lambda \sim 10^3 - 10^8$ GeV)

- Test "ordinary" Standard Model processes

  Higgs precision program; Electroweak precision observables; muon anomalous magnetic moment; ...
  ($\Lambda \sim 10^3$ GeV)

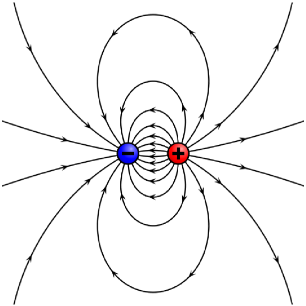
Reach to higher new physics scales

Electric Diople 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

MDMs are CP conserving
EDMs are CP violating

Relevance for 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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- Typical energy resolution in modern EDM experiments

  [e.g. JILA 2212.11841]

$$\Delta\text{Energy} \sim 10^{-19} eV$$

- Combined with strong electric fields in atoms or molecules, this translates into sensitivities of EDMs at the order of

$$\text{electric field} \sim 10\,\text{GV/cm} \quad \Rightarrow \quad d_e \lesssim \frac{\Delta\text{Energy}}{\text{electric field}} \sim 10^{-29} e\,\text{cm}$$

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- Theoretically inferred dependence of EDMs on the new physics scale

$$d_e \sim \frac{e}{16\pi^2} \times \frac{m_e}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 100\,TeV$$

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$$d_e \sim \frac{e}{16\pi^2} \times \frac{m_e}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 100\, TeV$$

EDM experiments are relevant for fundamental particle physics

CC problem

Hierarchy problem

Vacuum stability?

Strong CP problem

$$\mathcal{L}_{\rm SM} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4$$

$$+ \bar\Psi \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$+ Y H \bar\Psi \Psi$$

CKM phase

CC problem

Hierarchy problem

Vacuum stability?

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$$\mathcal{L}_{\rm SM} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4$$

$$+ \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$+ Y H \bar{\Psi}\Psi + \frac{1}{\Lambda}(LH)^2 + \frac{1}{\Lambda^2}\sum_i \mathcal{O}_i^{\rm dim6}$$

CKM phase

CPV in the neutrino sector

CPV at dim 6

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \epsilon_{jk} (\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \epsilon_{jk} (\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \epsilon_{jk} (\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \epsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$

2499 baryon number conserving dim. 6 operators in total

Grzadkowski et al. 1008.4884,

Alonso et al 1312.2014

The Standard Model Effective Field Theory

$1: X^3$		$2: H^6$		$3: H^4D^2$		$5: \psi^2H^3 + \text{h.c.}$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$			Q_{HD}	$(H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$	Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$
$Q_{\widetilde W}$	$\epsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$						

$4: X^2H^2$		$6: \psi^2XH + \text{h.c.}$		$7: \psi^2H^2D$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p\tau^I\gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde H\, G^A_{\mu\nu}$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde H\, W^I_{\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde H\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$
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$Q_{H\widetilde WB}$	$H^\dagger\tau^I H\, \widetilde W^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$

$8: (\bar LL)(\bar LL)$		$8: (\bar RR)(\bar RR)$		$8: (\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
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$8: (\bar LR)(\bar RL) + \text{h.c.}$		$8: (\bar LR)(\bar LR) + \text{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$
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triple gauge boson interactions

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$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde H\, G^A_{\mu\nu}$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde H\, W^I_{\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde H\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
$Q_{H\widetilde WB}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$	$Q_{Hud} + \text{h.c.}$	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar LL)(\bar LL)$		$8: (\bar RR)(\bar RR)$		$8: (\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar LR)(\bar RL) + \text{h.c.}$		$8: (\bar LR)(\bar LR) + \text{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\epsilon_{jk}(\bar q_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\epsilon_{jk}(\bar q_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$

2499 baryon number conserving dim. 6 operators in total

Grzadkowski et al. 1008.4884,

Alonso et al 1312.2014

triple gauge boson interactions

4 fermion interactions

The Standard Model Effective Field Theory

$1: X^3$		$2: H^6$		$3: H^4D^2$		$5: \psi^2H^3 + \text{h.c.}$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$			Q_{HD}	$\left(H^\dagger D_\mu H\right)^*\left(H^\dagger D_\mu H\right)$	Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$
$Q_{\widetilde W}$	$\epsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$						

$4: X^2H^2$		$6: \psi^2XH + \text{h.c.}$		$7: \psi^2H^2D$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p\tau^I\gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde H\, G^A_{\mu\nu}$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde H\, W^I_{\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde H\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$
Q_{HWB}	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$
$Q_{H\widetilde WB}$	$H^\dagger\tau^I H\, \widetilde W^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$

$8: (\bar LL)(\bar LL)$		$8: (\bar RR)(\bar RR)$		$8: (\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$8: (\bar LR)(\bar RL) + \text{h.c.}$		$8: (\bar LR)(\bar LR) + \text{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\epsilon_{jk}(\bar q_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\epsilon_{jk}(\bar q_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\epsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$

2499 baryon number conserving dim. 6 operators in total

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The Standard Model Effective Field Theory

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde H\, G^A_{\mu\nu}$
Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde H\, W^I_{\mu\nu}$
Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde H\, B_{\mu\nu}$
Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar L L)(\bar L L)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$

$8: (\bar R R)(\bar R R)$	
Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$
Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$
Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$
Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$
Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar L L)(\bar R R)$	
Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar L R)(\bar R L) + \text{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_{tj})$

$8: (\bar L R)(\bar L R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\epsilon_{jk}(\bar q_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\epsilon_{jk}(\bar q_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$

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Higgs-gauge interactions

The Standard Model Effective Field Theory

$1: X^3$		$2: H^6$		$3: H^4D^2$		$5: \psi^2H^3 + \text{h.c.}$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$			Q_{HD}	$(H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$	Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$						

$4: X^2H^2$		$6: \psi^2 XH + \text{h.c.}$		$7: \psi^2H^2D$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde H\, G^A_{\mu\nu}$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde H\, W^I_{\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde H\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
$Q_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar LL)(\bar LL)$		$8: (\bar RR)(\bar RR)$		$8: (\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar LR)(\bar RL) + \text{h.c.}$		$8: (\bar LR)(\bar LR) + \text{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\epsilon_{jk}(\bar q_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\epsilon_{jk}(\bar q_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$

2499 baryon number conserving dim. 6 operators in total

Grzadkowski et al. 1008.4884,

Alonso et al 1312.2014

triple gauge boson interactions

4 fermion interactions

Higgs penguins

Higgs-gauge interactions

Z-penguins

The Standard Model Effective Field Theory

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde H\, G^A_{\mu\nu}$
Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde H\, W^I_{\mu\nu}$
Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde H\, B_{\mu\nu}$
Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar L L)(\bar L L)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$

$8: (\bar R R)(\bar R R)$	
Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$
Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$
Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$
Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$
Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$
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Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
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Counting CP Phases in SMEFT

Counting sources of CP violation is non-trivial,
because one has freedom to re-phase fields.

"number of complex parameters" $\neq$ "number of CP violating sources"

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- It is often useful to phrase everything in terms of flavor invariants that are independent of a unitary relabeling of fields. In the SM

$$\text{"CKM phase"} \sim \text{Im}\,\text{Det}\Big[Y_u Y_u^\dagger, Y_d Y_d^\dagger\Big] \quad \text{(Jarlskog invariant)}$$

$$\text{"strong CP phase"} \;\; \bar{\theta} \sim \theta_{\text{QCD}} - \text{Arg}\,\text{Det}\big(Y_u Y_d\big)$$

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- In the SMEFT one finds additional 699 fermionic + 6 purely bosonic sources of CP violation that are observable at the $1/\Lambda^2$ level.

  Bonnefoy, Gendy, Grojean, Ruderman 2112.03889

Experimentally Accessible EDMs

- neutron EDM (ultra cold neutrons in an external E field)
- EDMs of paramagnetic atoms/molecules (un-paired electron)
- EDMs of diamagnetic atoms/molecules (closed electron shell)
- EDMs of proton, muon (storage rings)

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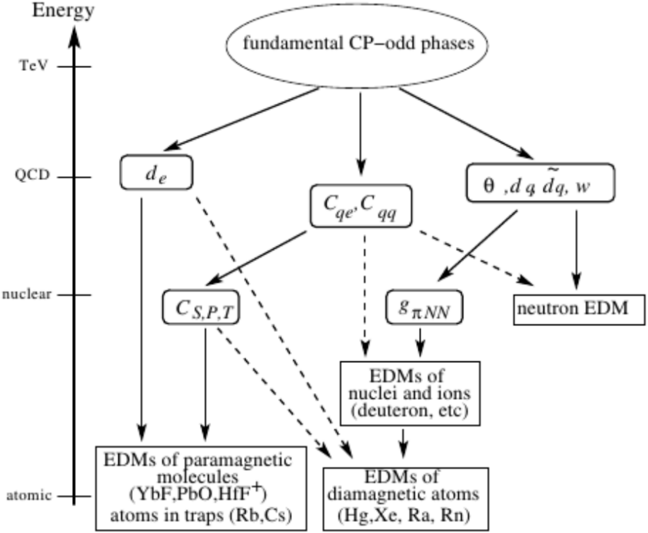
in most cases one needs to predict the EDMs of composite systems
in terms of fundamental CP violating sources

Experimentally Accessible EDMs



Pospelov, Ritz hep-ph/0504231

CP Violating Interactions

CP-odd Lagrangian at the GeV scale

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

QCD theta term

terms at dimension 4

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

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

terms at dimension 4 , dimension 5

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, ...

Expressions for Observable EDMs

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

- contain an unpaired electron
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  $\rightarrow$ mainly sensitive to the electron EDM that sees an enhanced effective electric field inside the atom/molecule
- In addition such systems have sensitivity to CP violating electron nucleon interactions.

$$\text{e.g.} \quad d_{\text{Tl}} \simeq -585 d_e - 43 e \times C_S \times \text{GeV}$$

- The numerical coefficients depend on the system

  $\Rightarrow$ Measurement of multiple systems allows one to disentangle between d_e and C_S

Expressions for Observable EDMs

proton and neutron EDMs

- Mainly sensitivity to the QCD theta term
  (e.g. Akan et al. 1406.2882)

$$d_n \simeq (2.7 \pm 1.2) \times \bar{\theta} \times 10^{-16} e\,\text{cm}$$
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- Most popular solution is the axion, that dynamically sets $\bar{\theta} = 0$.

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- Additional contributions from CP-odd pion nucleon couplings. (mainly induced by chromo-EDMs)
- Also the Weinberg 3 gluon operator can contribute.

$$d_n \simeq 0.73 d_d - 0.18 d_u + e(0.2\tilde{d}_d + 0.1\tilde{d}_u) + e \times 23\,\text{MeV} \times w$$

$$d_p \simeq 0.73 d_u - 0.18 d_d - e(0.4\tilde{d}_u + 0.05\tilde{d}_d) - e \times 33\,\text{MeV} \times w$$

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- Additional contributions from strange EDM and chromo-EDM could by sizable as well (Vecchi 2506.23402). However, lattice says that they are small (Park et al. 2503.07100).

Current Experimental Bounds: Electron

- "Electron EDM" from HfF^+ molecular ions JILA 2212.11841
  or ThO molecules ACME, Nature 562 (2018)

$$d_e^{HfF^+} < 4.1 \times 10^{-30}\ e\,\text{cm} \quad @\ 90\%\ \text{C.L.}$$

$$d_e^{ThO} < 1.1 \times 10^{-29}\ e\,\text{cm} \quad @\ 90\%\ \text{C.L.}$$

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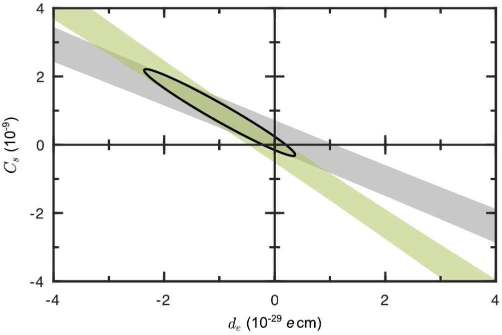
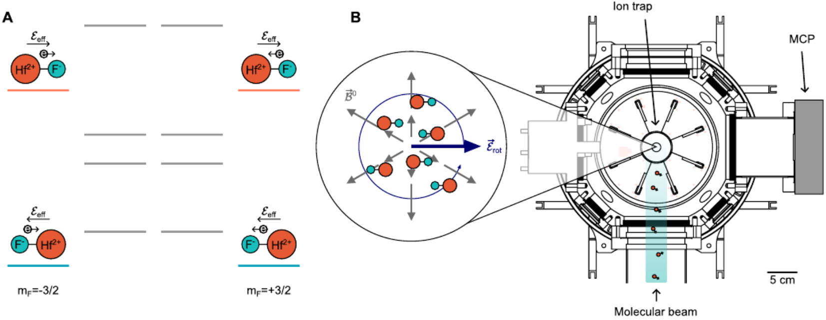


- compbining the two results allows one to disentangle the EDM of the elecron and the CP-violating electron-nucleon coupling
- might be possible to push sensitivity by another order of magnitude.

The EDM Search at JILA

JILA = Joint Institute for Laboratory Astrophysics in Boulder, CO

Roussy et. al 2212.11841



- HfF^+ ions are kept in a trap using rotating E and B fields
- The unpaired electron in HfF^+ feels a strong effective electric field
- The electron EDM (or CP violating electron nucleon interactions) would give a tiny shift in the energy levels

Current Experimental Bounds: Neutron

- Neutron EDM (Abel et. al 2001.11966)

$$d_n < 1.8 \times 10^{-26}\ e\,\text{cm} \quad \text{@ } 90\%\ \text{C.L.}$$

- Planned neutron EDM experiments have sensitivity goals at the $10^{-27} e\,\text{cm}$ to $10^{-28} e\,\text{cm}$ level.

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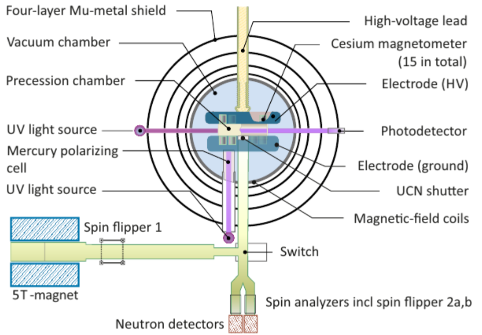
- Proposed proton EDM experiments could reach the $10^{-29}\,e\,\text{cm}$ level.

PSI = Paul Scherrer Institute
(Villigen, Switzerland)

Abel et. al 2001.11966



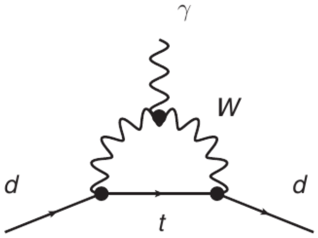
- Ultra-cold neutrons are put in a B field and precess with the Larmor frequency $\omega_0 = 2\mu_n B$
- Switch on an additional electric field. If the neutron has an EDM the Larmor frequency will slightly increase or decrease depending on whether the E and B field are parallel or anti-parallel

$$\omega = \omega_0 \pm 2 d_n E$$

EDMs in the SM

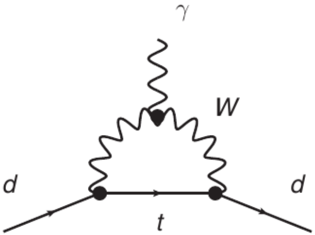
Quark EDMs from the CKM Matrix

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



$d_d \propto$

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



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

- loop suppressed

Quark EDMs from the CKM Matrix

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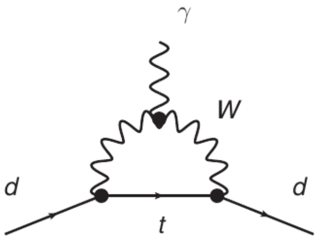
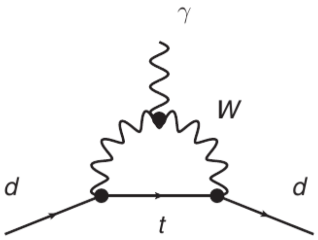


$$d_d \propto \frac{e}{16\pi^2} G_F$$

- loop suppressed
- first order in the weak interactions

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



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

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- first order in the weak interactions
- helicity suppressed

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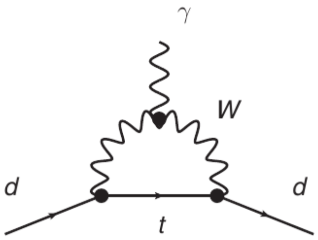
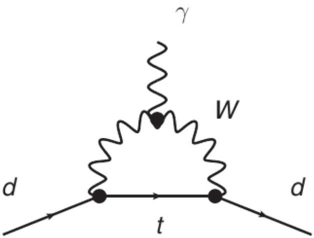


$$d_d \propto \frac{e}{16\pi^2} G_F m_d \mathrm{Im}(V_{td} \quad)$$

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

Quark EDMs from the CKM Matrix

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



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

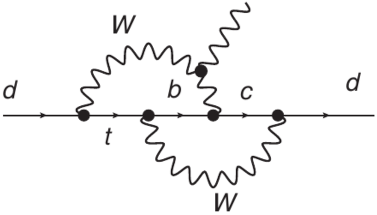
- loop suppressed
- first order in the weak interactions
- helicity suppressed
- try to pick up a CKM element that contains a CP violating phase
- 1 loop is not sufficient...

Quark EDMs from the CKM Matrix

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

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

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



Quark EDMs from the CKM Matrix

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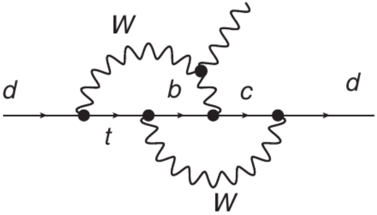
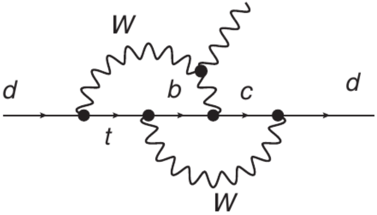


$$d_d \propto \frac{e}{(16\pi^2)^2} G_F^2 m_c^2 m_d$$

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

- 2 loop suppressed

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

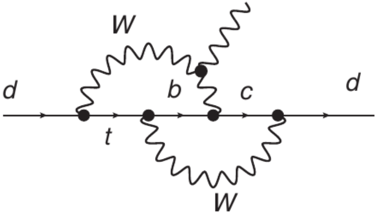


$$d_d \propto \frac{e}{(16\pi^2)^2} G_F^2 m_c^2 m_d$$
$$\times \mathrm{Im}(V_{td} V_{tb}^* V_{cb} V_{cd}^*)$$

- 2 loop suppressed
- second order in the weak interactions

Quark EDMs from the CKM Matrix

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



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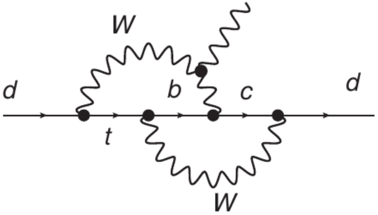
$$\times \text{Im}(V_{td} V_{tb}^* V_{cb} V_{cd}^*)$$

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

Quark EDMs from the CKM Matrix

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



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

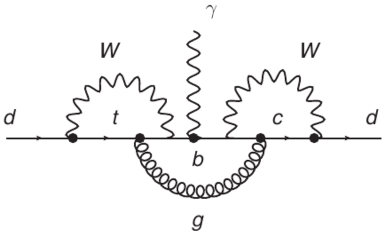
$$\times \text{Im}(V_{td} V_{tb}^* V_{cb} V_{cd}^*)$$

- 2 loop suppressed
- second order in the weak interactions
- try to 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



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

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

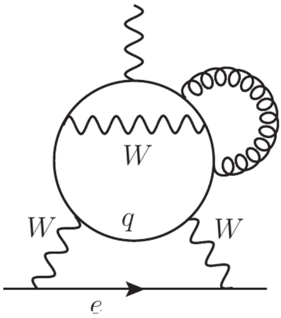
- two electro-weak loops
- one additional gluon loop

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

(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)



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

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

- three electro-weak loops
- one additional gluon loop

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

(Pospelov, Ritz 2013)

Atomic/Molecular EDMs from the CKM Matrix

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

e.g. for ThO $\quad d_e + C_S \times 1.5 \times 10^{-20} e\,\text{cm} \qquad$ with $\quad \mathcal{L} \supset C_S \frac{G_F}{\sqrt{2}} (\bar{e} i \gamma_5 e)(\bar{p}p + \bar{n}n)$

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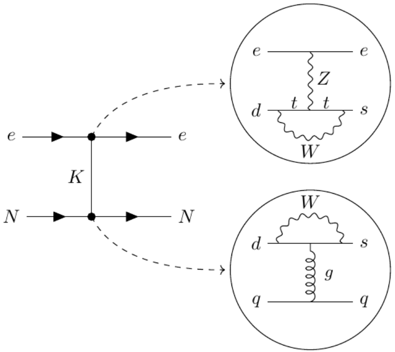
largest SM contribution comes from the
CP violating electron nucleon coupling



"equivalent electron EDM benchmark"

$d_e^{\rm equiv} \sim 10^{-35}\ ecm$

(Ema, Gao, Pospelov 2202.10524)

The Neutron/Proton 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

$$d_n \simeq 0.73 d_d - 0.18 d_u + e(0.2\tilde{d}_d + 0.1\tilde{d}_u) + \text{strange contribution ?}$$

$+$contributions from the Weinberg operator

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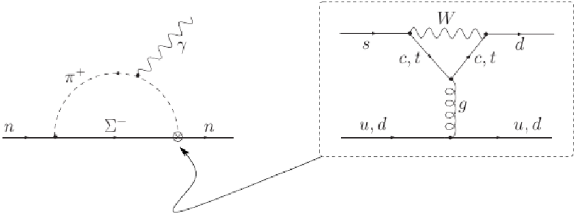
$+$contributions from the Weinberg operator

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)
(Seng, 2014)

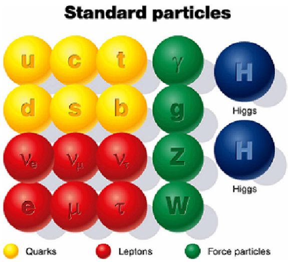
Standard Model Benchmarks for EDMs are
Many Orders of Magnitude Below
the Current Experimental Sensitivities

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

EDMs and SUSY

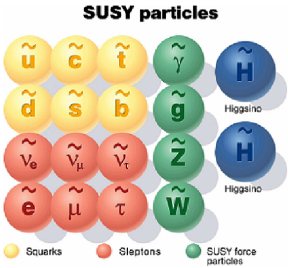
The Minimal Supersymmetric Standard Model

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

CP Violation in the MSSM

The MSSM can contain many new sources of CP violation

Higgsino and Higgs masses
$\rightarrow$ 2 phases

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

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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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$$m^2_Q \tilde{Q}^\dagger_L \tilde{Q}_L + m^2_U \tilde{U}^\dagger_R \tilde{U}_R + m^2_D \tilde{D}^\dagger_R \tilde{D}_R$$
$$+ m^2_L \tilde{L}^\dagger_L \tilde{L}_L + m^2_E \tilde{E}^\dagger_R \tilde{E}_R$$

gaugino masses
$\rightarrow$ 3 phases

$$m_{\tilde{B}} \tilde{B}\tilde{B} + m_{\tilde{W}} \tilde{W}\tilde{W} + m_{\tilde{g}} \tilde{g}\tilde{g}$$

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

gaugino masses
→ 3 phases

$$m_{\tilde{B}} \tilde{B}\tilde{B} + m_{\tilde{W}} \tilde{W}\tilde{W} + m_{\tilde{g}} \tilde{g}\tilde{g}$$

trilinear couplings
→ 27 phases

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

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$\to$ 2 phases

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$+ m_L^2 \tilde{L}_L^\dagger \tilde{L}_L + m_E^2 \tilde{E}_R^\dagger \tilde{E}_R$

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

CP Violation in the MSSM

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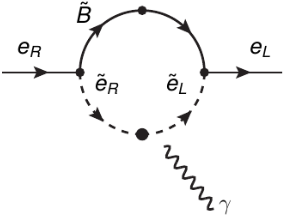
not all phases are physical! (like in the case of the CKM matrix)

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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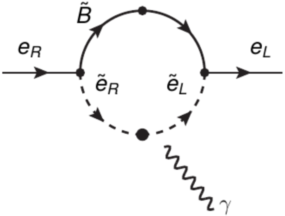

$$d_e \propto \frac{\alpha_1}{4\pi}$$

- 1-loop suppression

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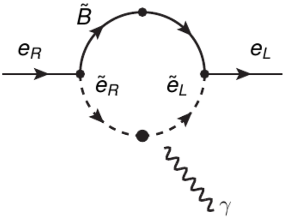

$$d_e \propto \frac{\alpha_1}{4\pi}\, m_e$$

- 1-loop suppression
- helicity suppression

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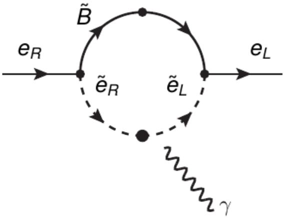

$$d_e \propto \frac{\alpha_1}{4\pi}\, m_e \tan\beta$$

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

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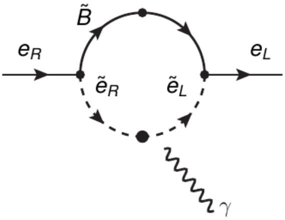
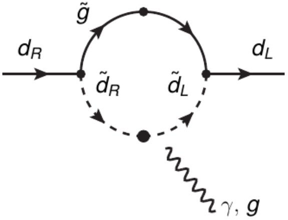


$$d_e \propto \frac{\alpha_1}{4\pi}\, m_e \tan\beta\, \frac{\text{Im}(\mu m_{\tilde{B}})}{m_{\tilde{e}}^4}$$

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

1-Loop MSSM Contributions to EDMs

Example 2:
gluino loop contribution
to the down quark EDM



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1-Loop MSSM Contributions to EDMs

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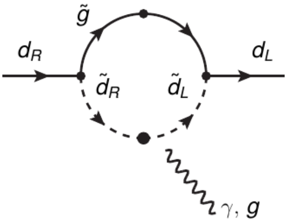

$$d_d \propto \frac{\alpha_s}{4\pi} m_d \tan\beta \frac{\text{Im}(\mu m_{\tilde{g}})}{m_{\tilde{d}}^4}$$

- 1-loop suppression
- helicity suppression
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1-Loop MSSM Contributions to EDMs

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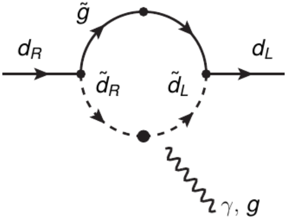

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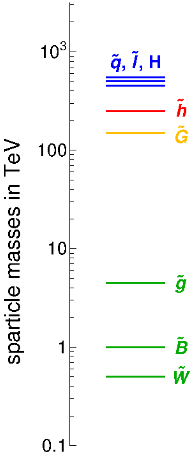
- 1-loop suppression
- helicity suppression
- $\tan\beta$ enhancement
- sensitive to the relative phase of the gluino and higgsino mass

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

$\Rightarrow$ *SUSY CP Problem*

[see e.g. Kaneta et al. 2303.02822 for a recent state of the art analysis]

Concrete Example: Mini-Split SUSY



Hall, Nomura 1111.4519;

Ibe et al. 1202.2253;

Arvanitaki et al. 1210.0555;

Arkani-Hamed et al. 1212.6971; ...

- scalar masses from gravity mediation
- gaugino masses from anomaly mediation, 1-loop factor lighter
- Higgsino mass model dependent: could be order gravitino mass or additionally suppressed

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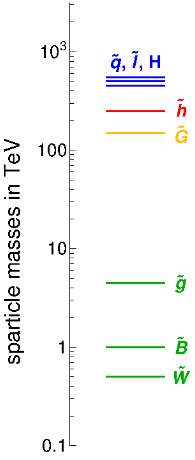

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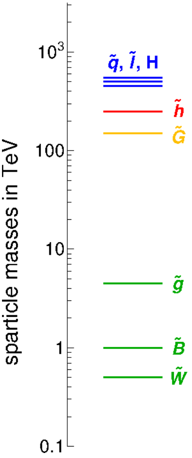

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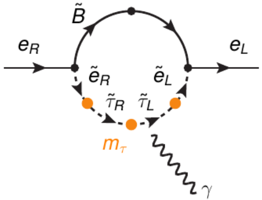
- scalar masses from gravity mediation
- gaugino masses from anomaly mediation, 1-loop factor lighter
- Higgsino mass model dependent: could be order gravitino mass or additionally suppressed
- natural version of this spectrum has been long ruled out
- for 100-1000 TeV squarks, a 125 GeV Higgs is "effortless"
- gauge coupling unification still works
- allow for generic flavor violation

$$\hat{m}^2_{\tilde{q}} = m^2_{\tilde{q}}(\mathbb{1} + \delta_q) \quad , \quad \hat{m}^2_{\tilde{\ell}} = m^2_{\tilde{\ell}}(\mathbb{1} + \delta_\ell)$$

flavor effects can strongly enhance EDMs in mini-split SUSY

(McKeen, Pospelov, Ritz '13; WA, Harnik, Zupan '13)



$$d_e \propto \frac{\alpha_1}{4\pi} \frac{m_\tau}{m_{\tilde{\ell}}^2} \frac{\mu m_{\tilde{B}}}{m_{\tilde{\ell}}^2} \tan\beta \, (\delta^R_{e\tau} \delta^L_{\tau e})$$

in the presence of sizable sfermion mixing,
1st generation EDMs are proportional to 3rd generation masses

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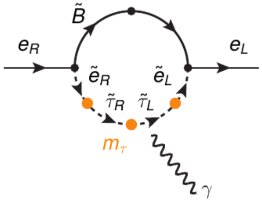
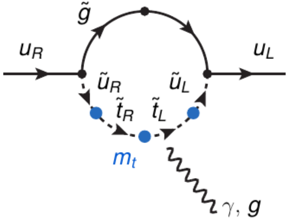
(McKeen, Pospelov, Ritz '13; WA, Harnik, Zupan '13)





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$$d_u \propto \frac{\alpha_s}{4\pi} \frac{m_t}{m_{\tilde{q}}^2} \frac{\mu m_{\tilde{g}}}{m_{\tilde{q}}^2} \frac{1}{\tan\beta} (\delta^R_{ut} \delta^L_{tu})$$

$$\tilde{d}_u \propto \frac{\alpha_s}{4\pi} \frac{m_t}{m_{\tilde{q}}^2} \frac{\mu m_{\tilde{g}}}{m_{\tilde{q}}^2} \frac{1}{\tan\beta} (\delta^R_{ut} \delta^L_{tu}) \log\left(\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}\right)$$

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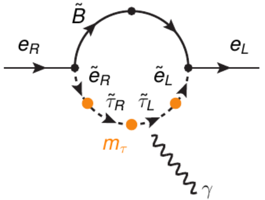

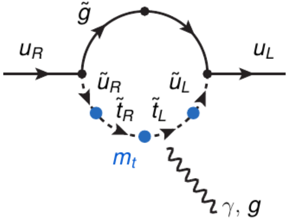

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in the presence of sizable sfermion mixing,
1st generation EDMs are proportional to 3rd generation masses

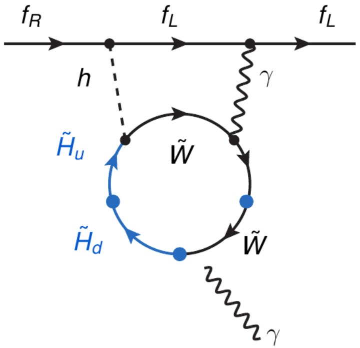
sensitivity to squarks and sleptons at the level of 100 TeV
if Higgsinos are heavy

Additional 2-loop Contributions

2-loop Barr-Zee diagrams can give sizable contributions to EDMs if both
Winos and Higgsinos are light

Giudice, Romanino '05

$$d_f^{2\text{loop}} \propto \frac{e^4}{(16\pi^2)^2} \frac{m_f}{m_{\tilde{W}} \mu}$$



Sensitivity of EDMs in Mini-Split SUSY

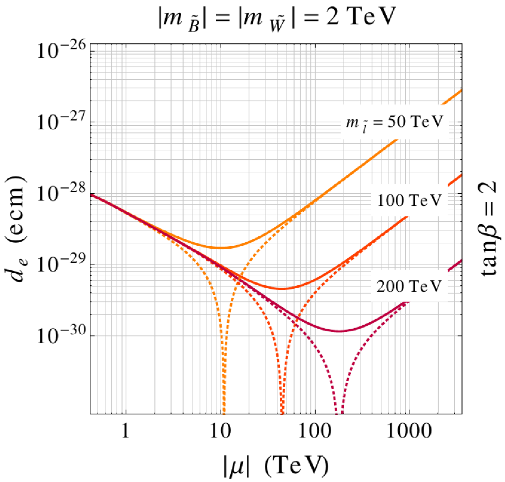
combining 1loop and 2loop contributions, EDMs probe complementary regions of parameter space

current bounds

electron EDM:
$d_e \lesssim 4.1 \times 10^{-30} e\text{cm}$

EDM sensitivity can be further improved with planned experiments

$d_e \lesssim 10^{-30} e\text{cm}$



WA, Harnik, Zupan '13

Sensitivity of EDMs in Mini-Split SUSY

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electron EDM:
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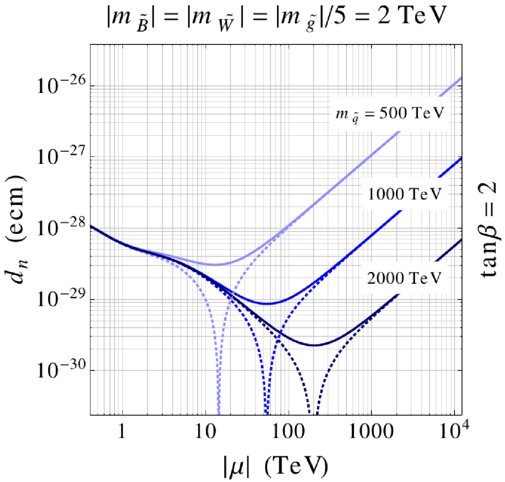
neutron EDM:
$d_n \lesssim 1.8 \times 10^{-26} ecm$

EDM sensitivity can be
further improved with
planned experiments

$d_e \lesssim 10^{-30} ecm$

$d_n \lesssim 10^{-28} ecm$



WA, Harnik, Zupan '13

EDMs in 2HDMs

[from Heather Logan's lectures earlier this week]

Two of the parameters of the softly-broken-Z_2-symmetric scalar potential can be complex (only their relative phase is physical):

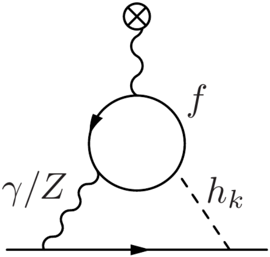
$$\begin{aligned} V &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] \\ &+ \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left|\Phi_1^\dagger \Phi_2\right|^2 \\ &+ \left\{ \frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.} \right\}. \end{aligned}$$

Most important effect is to induce mixing between h^0, H^0 and A^0: three neutral mass eigenstates, none of them CP eigenstates!

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \phi_v^{0,r} \\ \phi_0^{0,r} \\ \phi_0^{0,i} \end{pmatrix} = R \begin{pmatrix} c_\beta \phi_1^{0,r} + s_\beta \phi_2^{0,r} \\ -s_\beta \phi_1^{0,r} + c_\beta \phi_2^{0,r} \\ -s_\beta \phi_1^{0,i} + c_\beta \phi_2^{0,i} \end{pmatrix}$$

EDMs in the Softly-Broken Z_2-Symmetric 2HDM

- 1-loop contributions to EDMs of the electron, up quark, and down quark are suppressed by two powers of small first generation Yukawa couplings $\rightarrow$ typically negligible.
- Most important effect arises at the 2-loop level, where the Higgs boson can couple to the heaviest SM particles: top quark and weak gauge bosons.



- Most famous class of contributions:

  "Barr-Zee diagrams"

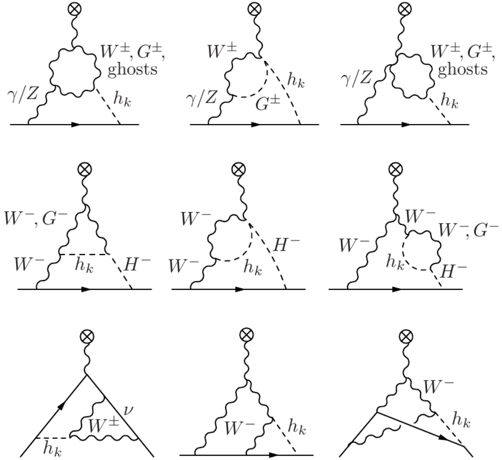
EDMs in the Softly-Broken Z_2-Symmetric 2HDM

- Barr-Zee diagrams with gauge boson loops are not gauge invariant by themselves.

  (e.g. Abe et al. 1311.4704)

- For a consistent result need also “kite” diagrams

  (WA, Gori, Hamer, Patel 2009.01258)



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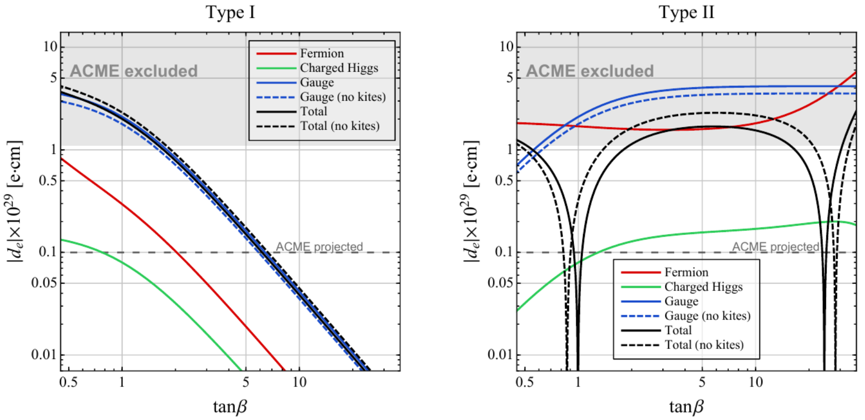

- Kite diagrams are not completely negligible. Can have significant impact on cancellation regions.

Electron EDM in the Fully Generic 2HDM

- Abandon the Z_2 symmetry and allow for flavor and CP violation in the Yukawa sector as well.
- Results for the electron EDM are available; quark EDMs, chromo EDMs, and the Weinberg operator are still work in progress.

  WA, Assi, Brod, Hamer, Julio, Uttayarat, Volkov 2410.17313 + work in progress
- Results are available as a public python code at the git repository

  https://gitlab.com/jbrod/general-2hdm-pheno

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

Tight Lines!

Back Up

Yukawa Couplings of the SM Fermions

the flavor and CP violation is introduced in the SM through the Yukawa couplings

$$Y\ H\bar{\Psi}\Psi = \sum_{i,j}(\hat{Y}_u)_{ij} H^c \bar{Q}_i u_j + \sum_{i,j}(\hat{Y}_d)_{ij} H \bar{Q}_i d_j + \sum_{i,j}(\hat{Y}_\ell)_{ij} H \bar{L}_i e_j \ + \ \text{h.c.}$$

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after electro-weak symmetry breaking we get fermion masses

$$\rightarrow \sum_{i,j}(\hat{m}_u)_{ij} \bar{u}_i^L u_j^R + \sum_{i,j}(\hat{m}_d)_{ij} \bar{d}_i^L d_j^R + \sum_{i,j}(\hat{m}_\ell)_{ij} \bar{e}_i^L e_j^R \ + \ \text{h.c.}$$

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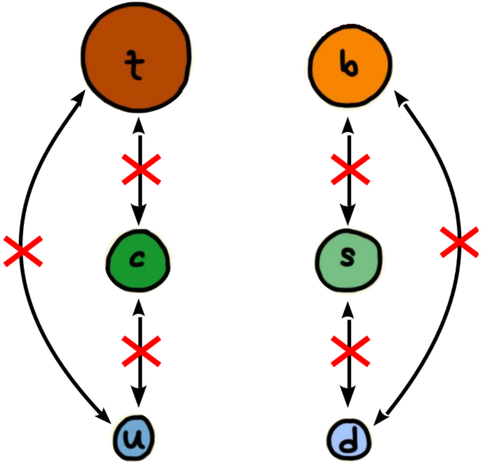
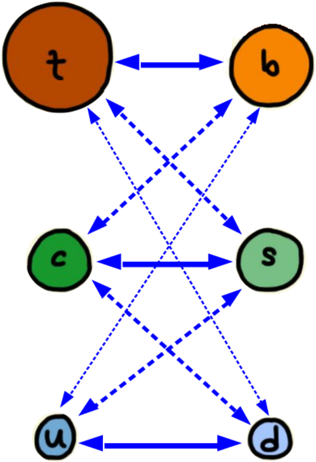
Remnant after going to mass eigenstates:CKM quark mixing matrix no FCNCs at tree level

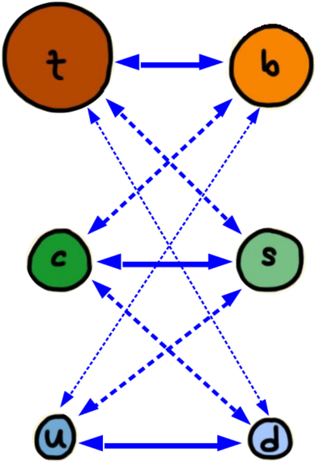




no FCNCs at tree level

transitions among the generations are mediated by the $W^\pm$ bosons and their relative strength is parametrized by the CKM matrix

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



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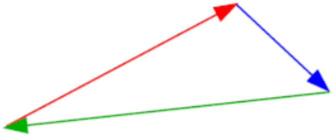
CKM matrix is unitary and determined by 4 independent parameters: 3 mixing angles and 1 CPV phase

The CKM matrix is unitary $\rightarrow$ relations between CKM elements

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

three complex numbers adding up to 0



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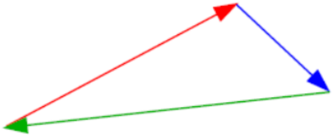

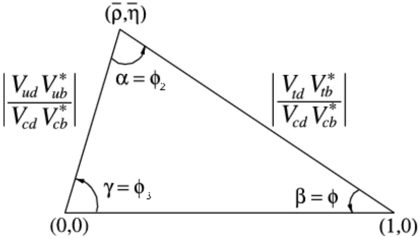

It is convenient to normalize one side to 1

$$\bar\rho + i\bar\eta = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

CPV corresponds to $\bar\eta \neq 0$

Experimental Status of the CKM Matrix

global fits
of all data give
overall consistent
picture within
$O(10\%)$ uncertainties

$$\lambda = 0.22498^{+0.00023}_{-0.00021}$$

$$A = 0.8215^{+0.0047}_{-0.0082}$$

$$\bar\rho = 0.1562^{+0.0112}_{-0.0040}$$

$$\bar\eta = 0.3551^{+0.0051}_{-0.0057}$$

http://ckmfitter.in2p3.fr/
http://www.utfit.org/