Electric Dipole Moments

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"The Allure of Ultrasensitive Experiments"
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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
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

Summary of Part I

- 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

Part II

Electric Dipole Moments, Flavor Physics, and the Higgs

The Higgs, Flavor and CP Violation in the SM

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge} + \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2 + Y_{ij} \, \bar{\Psi}_L^i \Psi_R^j \Phi$$

- Higgs mass parameter
  quadratically sensitive to the cut-off: $\Delta\mu^2 \propto \Lambda^2$
  $\rightarrow$ hierarchy problem
- quartic Higgs coupling
  λ becomes negative at large energies
  $\rightarrow$ question of vacuum (meta)stability
- Yukawa couplings
  only source of flavor violation
  only source of CP violation (apart from the QCD θ term)
  unexplained hierarchical structure
  $\rightarrow$ SM flavor puzzle

Main Questions for Today

To which extent are EDMs connected with Higgs and Flavor physics in extensions of the SM?

What can we learn about Flavor from EDMs?

What can we learn about the Higgs from EDMs?

Interplay of EDMs with Flavor Physics

Sources of Flavor and CP Violation beyond the SM

Example: Minimal Supersymmetric Standard Model

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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 + 15 angles

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

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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

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

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$\to$ 3 phases

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

trilinear couplings
$\to$ 27 phases + 18 angles

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

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2 phases can be rotated away
all flavor mixing angles are physical

Minimal Flavor Violation

- largest symmetry group that commutes with the SM gauge group

$$G_F = SU(3)_Q \otimes SU(3)_U \otimes SU(3)_D \otimes SU(3)_L \otimes SU(3)_E \otimes U(1)^5$$

- in the SM, the Yukawa couplings are the only terms that break G_F

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- promote SM Yukawas to spurions to formally restore invariance

$$y_u = 3_Q \times \bar{3}_U \ , \quad y_d = 3_Q \times \bar{3}_D \ , \quad y_\ell = 3_L \times \bar{3}_E$$

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Minimal Flavor Violation

(Chivukula, Georgi ’87; Hall, Randall ’90; D’Ambrosio et al ’02)

- Yukawas are the only flavor spurions also beyond the SM
- new sources of flavor violation are functions of the SM Yukawas

MFV Expansion of MSSM Soft Terms

soft masses
of squarks and sleptons

$$m_Q^2 = \tilde{m}_Q^2 \Big(1\!\!1 + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger +$$

$$+ b_3 Y_d Y_d^\dagger Y_u Y_u^\dagger + b_3^* Y_u Y_u^\dagger Y_d Y_d^\dagger + ... \Big)$$

$$m_U^2 = \tilde{m}_U^2 \Big(1\!\!1 + b_4 Y_u^\dagger Y_u + ... \Big)$$

$$m_D^2 = \tilde{m}_D^2 \Big(1\!\!1 + b_5 Y_d^\dagger Y_d + ... \Big)$$

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trilinear couplings

$$A_u = \tilde{A}_u \Big(1\!\!1 + b_6 Y_d Y_d^\dagger + b_7 Y_u Y_u^\dagger + ... \Big) Y_u$$
$$A_d = \tilde{A}_d \Big(1\!\!1 + b_8 Y_u Y_u^\dagger + b_9 Y_d Y_d^\dagger + ... \Big) Y_d$$

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gaugino/higgsino/higgs
masses

$$m_1, m_2, m_3, \mu, B\mu$$

- many sources of CP violation beyond the CKM are allowed in MFV

FCNCs and Minimal Flavor Violation I

example: transition from $d^{(k)} \to d^{(i)}$ described by a term of the type $(\bar{d}^{(i)} \Gamma d^{(k)})$

available building blocks: $Q_L \sim 3_Q$; $D_R \sim 3_D$; $Y_d \sim 3_Q \times \bar{3}_D$; $Y_u \sim 3_Q \times \bar{3}_U$

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going to mass eigenstates

$$Q_L \to \begin{pmatrix} V_u^L u_L \\ V_d^L d_L \end{pmatrix} \quad , \quad D_R \to V_d^R d_R , \quad U_R \to V_u^R u_R$$

$$(V_u^L)^\dagger (Y_u)(V_u^R) = y_u^{\text{diag}} \quad , \quad (V_d^L)^\dagger (Y_d)(V_d^R) = y_d^{\text{diag}} \quad , \quad (V_u^L)^\dagger (V_d^L) = V_{\text{CKM}}$$

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$$(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu Q_L) \quad \to \quad (\bar{d}_L^{(i)} V_{ti}^* V_{tk} y_t^2 \gamma^\mu d_L^{(k)}) \quad \to \quad \text{flavor change!}$$

going to mass eigenstates

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- proportional to small CKM elements (same as in the SM)

FCNCs and Minimal Flavor Violation II

try to get the transition involving right handed quarks

available building blocks: $Q_L \sim 3_Q$; $D_R \sim 3_D$; $Y_d \sim 3_Q \times \bar{3}_D$; $Y_u \sim 3_Q \times \bar{3}_U$

$$(\bar{D}_R \mathbb{1} \gamma^\mu D_R) \rightarrow (\bar{d}_R^{(i)} \gamma^\mu d_R^{(i)}) \rightarrow \text{no flavor change}$$

$$(\bar{D}_R Y_d^\dagger Y_d \gamma^\mu D_R) \rightarrow (\bar{d}_R^{(i)} (y_d^{(i)})^2 \gamma^\mu d_R^{(i)}) \rightarrow \text{no flavor change}$$

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but: no $Y_u Y_u^\dagger$ term allowed between right handed down quarks

- strong suppression of flavor changing right-handed currents (as in the SM)

EDMs and Minimal Flavor Violation

EDM operators connect left with right handed fermions
$\rightarrow$ not invariant under the flavor group

$$H(\bar{Q}_L\,\sigma_{\mu\nu}\quad D_R)F^{\mu\nu}$$

$$H(\bar{Q}_L\,\sigma_{\mu\nu}\quad U_R)F^{\mu\nu}$$

$$H(\bar{L}_L\,\sigma_{\mu\nu}\quad E_R)F^{\mu\nu}$$

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$$H(\bar{Q}_L \, \sigma_{\mu\nu} \, Y_d \, D_R) F^{\mu\nu}$$

$$H(\bar{Q}_L \, \sigma_{\mu\nu} \, Y_u \, U_R) F^{\mu\nu}$$

$$H(\bar{L}_L \, \sigma_{\mu\nu} \, Y_\ell \, E_R) F^{\mu\nu}$$

- need insertion of the corresponding Yukawa couplings to restore invariance under G_F

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$$H(\bar{Q}_L \, \sigma_{\mu\nu} \, Y_d \, D_R)F^{\mu\nu} \quad \rightarrow \quad m_d \, (\bar{d}_L \sigma_{\mu\nu} d_R)F^{\mu\nu}$$

$$H(\bar{Q}_L \, \sigma_{\mu\nu} \, Y_u \, U_R)F^{\mu\nu} \quad \rightarrow \quad m_u \, (\bar{u}_L \sigma_{\mu\nu} u_R)F^{\mu\nu}$$

$$H(\bar{L}_L \, \sigma_{\mu\nu} \, Y_\ell \, E_R)F^{\mu\nu} \quad \rightarrow \quad m_e \, (\bar{e}_L \sigma_{\mu\nu} e_R)F^{\mu\nu}$$

- need insertion of the corresponding Yukawa couplings to restore invariance under G_F
- proportionality to the fermion masses

Sensitivity to High Scales: FCNCs vs. EDMs

1. neutral Kaon mixing (d anti-s $\leftrightarrow$ anti-d s)

$$(\bar{d}_L \gamma_\mu s_L)(\bar{d}_L \gamma^\mu s_L)$$

Sensitivity to High Scales: FCNCs vs. EDMs

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$$y_t^4 \; (V_{ts} V_{td}^*)^2 \; (\bar{d}_L \gamma_\mu s_L)(\bar{d}_L \gamma^\mu s_L)$$

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$$\frac{C}{\Lambda^2} y_t^4 \, (V_{ts} V_{td}^*)^2 \, (\bar{d}_L \gamma_\mu s_L)(\bar{d}_L \gamma^\mu s_L)$$

- constraint from ϵ_K (= CP violation in Kaon mixing), assuming $C \sim 1$

$$\Lambda \gtrsim \; 5\text{TeV}$$

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2. down quark EDM

$$\frac{\tilde{C}}{\Lambda^2} m_d \, (\bar{d}_L \sigma_{\mu\nu} d_R) F^{\mu\nu}$$

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$$\Lambda \gtrsim 0.5\text{TeV}$$

2. down quark EDM

$$\frac{\tilde{C}}{\Lambda^2} m_d \, (\bar{d}_L \sigma_{\mu\nu} d_R) F^{\mu\nu}$$

- constraint from neutron EDM, assuming $\tilde{C} \sim 1$ with O(1) phase

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

Sensitivity to High Scales: FCNCs vs. EDMs

1. neutral Kaon mixing (d anti-s $\leftrightarrow$ anti-d s)

$$\frac{C}{\Lambda^2} y_t^4 \, (V_{ts} V_{td}^*)^2 \, (\bar{d}_L \gamma_\mu s_L)(\bar{d}_L \gamma^\mu s_L)$$

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$$\Lambda \gtrsim \; 0.5\text{TeV}$$

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$$\frac{\tilde{C}}{\Lambda^2} m_d \, (\bar{d}_L \sigma_{\mu\nu} d_R) F^{\mu\nu}$$

- constraint from neutron EDM, assuming $\tilde{C} \sim 1/16\pi^2$ with O(1) phase

$$\Lambda \gtrsim 5 \text{ TeV}$$

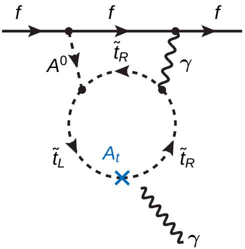
Example of a Concrete Model

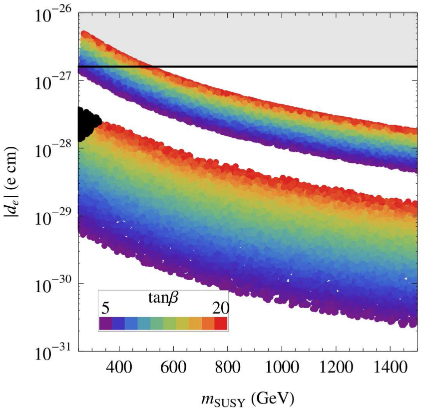
- MSSM with MFV and CP violation only from higher order terms in the trilinear couplings

$$A_u = A(\mathbb{1} + b_6 Y_d Y_d^\dagger + b_7 Y_u Y_u^\dagger) Y_u$$

$\rightarrow$ only 3rd generation feels CPV

$\rightarrow$ FCNCs at 1loop but EDMs at 2loop



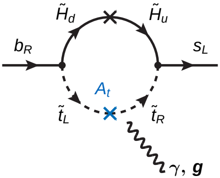


$\rightarrow$ EDMs can be under control for TeV spectrum and O(1) phase

WA, Buras, Paradisi '08; Paradisi, Straub '09

Correlations with Flavor Observables

- CPV 1loop contributions to $b \to s\gamma$

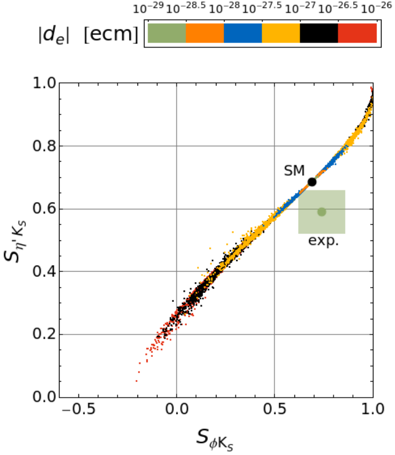


- expect CPV effects in B physics

$\to$ direct CP asymmetry in $B \to X_s\gamma$

$\to$ time dependent CP asymmetries in $B \to \phi K_S$, $B \to \eta' K_S$

$\to$ CP asymmetries in $B \to K^*\mu^+\mu^-$



WA, Buras, Paradisi '08;

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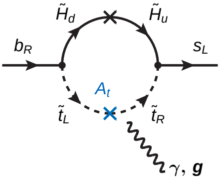

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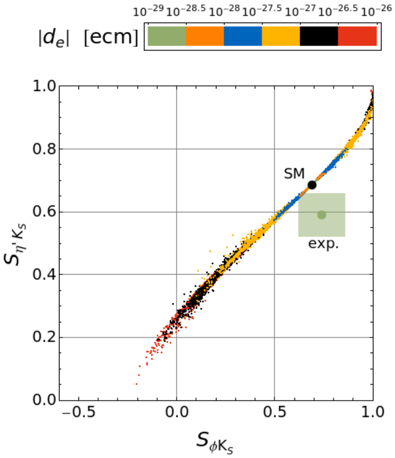
- but: latest EDM results give very strong bounds!



WA, Buras, Paradisi '08;
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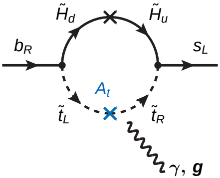

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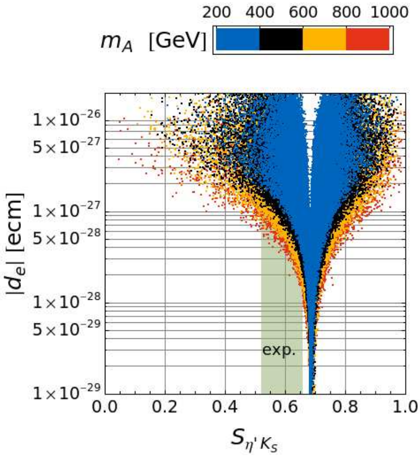

WA, Buras, Paradisi '08;
Barbieri, Lodone, Straub '11

FCNCs with Generic Flavor Violation

Assume presence of additional flavor spurions:

e.g. $X_q^L = 8_Q$, $X_u^R = 8_U$, $X_d^L = 8_D$, $X_\ell^L = 8_L$, $X_e^R = 8_E$

$$(\bar{Q}_L \quad \gamma^\mu Q_L)$$

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$$(\bar{Q}_L X_q^L \gamma^\mu Q_L) \quad \to \quad (\bar{d}_L^{(i)} (X_q^L)_{ik} \gamma^\mu d_L^{(k)})$$

- contributions to FCNCs are not suppressed by small CKM elements

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$$(\bar{D}_R X_d^R \gamma^\mu D_R) \quad \rightarrow \quad (\bar{d}_R^{(i)} (X_d^R)_{ik} \gamma^\mu d_R^{(k)})$$

- contributions to FCNCs are not suppressed by small CKM elements
- also flavor changing right-handed currents can be induced

Assume presence of additional flavor spurions:

e.g. $X_q^L = 8_Q, X_u^R = 8_U, X_d^L = 8_D, X_\ell^L = 8_L, X_e^R = 8_E$

$H(\bar{Q}_L \ \sigma_{\mu\nu} \qquad D_R)F^{\mu\nu}$

$H(\bar{Q}_L \ \sigma_{\mu\nu} \qquad U_R)F^{\mu\nu}$

$H(\bar{L}_L \ \sigma_{\mu\nu} \qquad E_R)F^{\mu\nu}$

EDMs with Generic Flavor Violation

Assume presence of additional flavor spurions:

e.g. $X_q^L = 8_Q,\, X_u^R = 8_U,\, X_d^L = 8_D,\, X_\ell^L = 8_L,\, X_e^R = 8_E$

$$H(\bar{Q}_L\ \sigma_{\mu\nu}\ X_q^L Y_d X_d^R\ D_R)F^{\mu\nu}$$

$$H(\bar{Q}_L\ \sigma_{\mu\nu}\ X_q^L Y_u X_u^R\ U_R)F^{\mu\nu}$$

$$H(\bar{L}_L\ \sigma_{\mu\nu}\ X_\ell^L Y_\ell X_e^R\ E_R)F^{\mu\nu}$$

EDMs with Generic Flavor Violation

Assume presence of additional flavor spurions:

e.g. $X_q^L = 8_Q$, $X_u^R = 8_U$, $X_d^L = 8_D$, $X_\ell^L = 8_L$, $X_e^R = 8_E$

$$H(\bar{Q}_L \, \sigma_{\mu\nu} \, X_q^L Y_d X_d^R \, D_R) F^{\mu\nu} \quad \rightarrow \quad m_b (X_q^L)_{db} (X_d^R)_{bd} \; (\bar{d}_L \sigma_{\mu\nu} d_R) F^{\mu\nu}$$

$$H(\bar{Q}_L \, \sigma_{\mu\nu} \, X_q^L Y_u X_u^R \, U_R) F^{\mu\nu} \quad \rightarrow \quad m_t (X_q^L)_{ut} (X_u^R)_{tu} \; (\bar{u}_L \sigma_{\mu\nu} u_R) F^{\mu\nu}$$

$$H(\bar{L}_L \, \sigma_{\mu\nu} \, X_\ell^L Y_\ell X_e^R \, E_R) F^{\mu\nu} \quad \rightarrow \quad m_\tau (X_\ell^L)_{e\tau} (X_e^R)_{\tau e} \; (\bar{e}_L \sigma_{\mu\nu} e_R) F^{\mu\nu}$$

- proportional to 3rd generation masses
  due to flavor effects ("flavored EDMs")

Sensitivity to High Scales: FCNCs vs. EDMs

1. neutral Kaon mixing

$$\frac{C}{\Lambda^2}\,(X_d^L)_{ds}(X_d^R)_{ds}\,(\bar{d}_L\gamma_\mu s_L)(\bar{d}_R\gamma^\mu s_R)$$

- no suppression by small CKM elements
- constraint from ϵ_K, assuming $C(X_q^L)_{ds}(X_d^R)_{ds} \sim 1$ with O(1) phase

$$\Lambda \gtrsim 3 \times 10^5 \text{ TeV}$$

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2. up quark EDM

$$\frac{\tilde{C}}{\Lambda^2}m_t\,(X_u^L)_{ut}(X_u^R)_{tu}\,(\bar{u}_L\sigma_{\mu\nu}F^{\mu\nu}u_R)$$

- proportional to the top quark mass due to flavor effects
- constraint from d_n, assuming $\tilde{C}(X_q^L)_{ut}(X_u^R)_{tu} \sim 1$ with O(1) phase

$$\Lambda \gtrsim 5\times 10^3~\text{TeV}$$

Sensitivity to High Scales: FCNCs vs. EDMs

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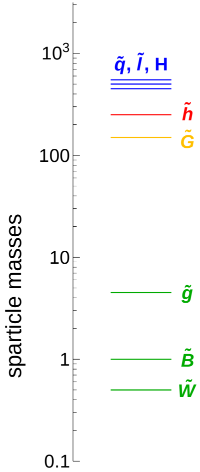
$$\Lambda \gtrsim 5 \times 10^2 \text{ TeV}$$

Concrete Example: Mini-Split SUSY



- 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

Hall, Nomura ; Arvanitaki et al. ;
Kane et al. ; Yanagida et al. ; Wells ;
Arkani-Hamed et al. ; ...

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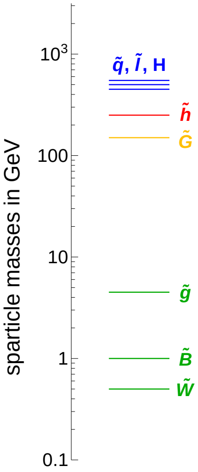

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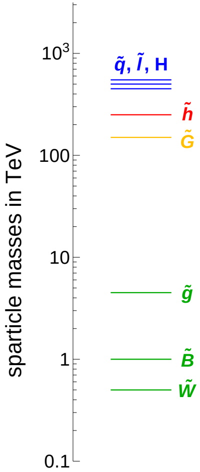

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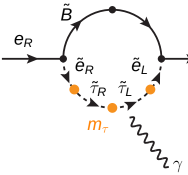
- scalar masses from gravity mediation
- gaugino masses from anomaly mediation, 1-loop factor lighter
- Higgsino mass model dependent: could be order gravitino mass or additionally suppressed
- natural version of this spectrum has been long ruled out
- for 100-1000 TeV squarks, a 125 GeV Higgs is "effortless"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

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

EDMs in Mini-Split SUSY

flavor effects can strongly enhance EDMs in mini-split SUSY

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



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

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

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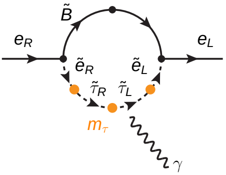

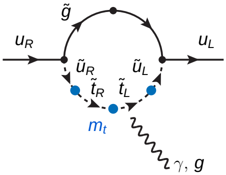

$$d_e \quad \propto \quad \frac{\alpha_1}{4\pi} \frac{m_\tau}{m_{\tilde{\ell}}^2} \frac{\mu m_{\tilde{B}}}{m_{\tilde{\ell}}^2} \tan\beta \, (\delta^R_{e\tau} \delta^L_{\tau e})$$

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

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

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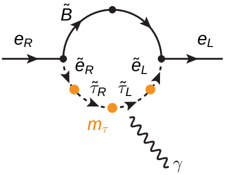

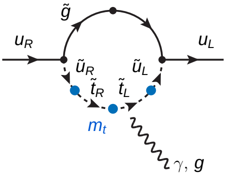

$$d_e \propto \frac{\alpha_1}{4\pi} \frac{m_\tau}{m_{\tilde{\ell}}^2} \frac{\mu m_{\tilde{B}}}{m_{\tilde{\ell}}^2} \tan\beta \, (\delta^R_{e\tau} \delta^L_{\tau e})$$

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

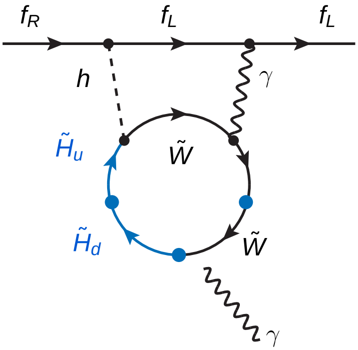
sensitivity to squarks and sleptons at the level of 100 TeV
if Higgsinos are heavy

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

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



Sensitivity of EDMs in Mini-Split SUSY

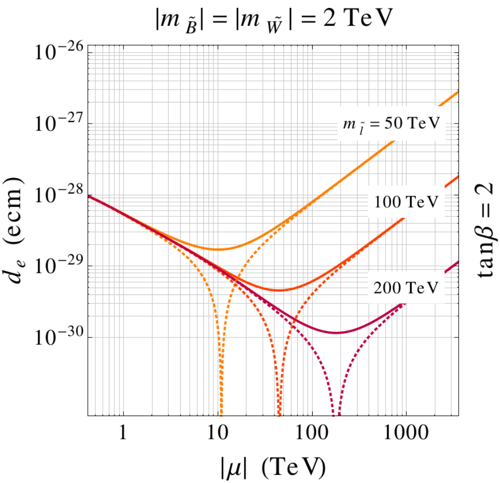
combining 1loop and 2loop contributions, EDMs probe complementary regions of parameter space

current bounds

electron EDM:
$d_e \lesssim 8.7 \times 10^{-29}$ecm

EDM bounds can be still improved by several orders of magnitude!

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



WA, Harnik, Zupan '13

Sensitivity of EDMs in Mini-Split SUSY

combining 1loop and
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EDMs probe complementary
regions of parameter space

current bounds

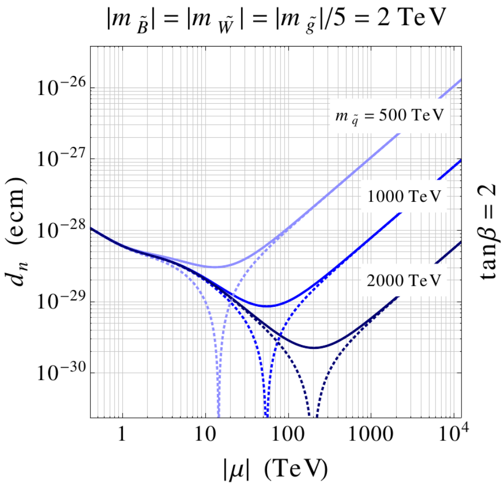
electron EDM:
$d_e \lesssim 8.7 \times 10^{-29}$ecm

neutron EDM:
$d_n \lesssim 2.9 \times 10^{-26}$ecm

EDM bounds can be still
improved by several
orders of magnitude!

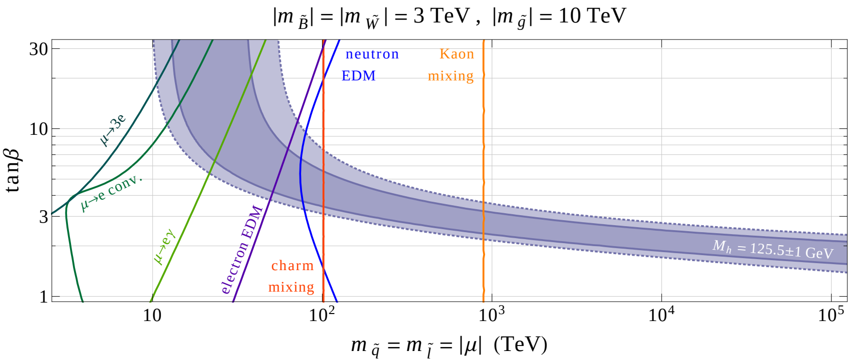
$d_e \lesssim 10^{-30}$ecm

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



WA, Harnik, Zupan ’13

Current Sensitivities in a Slice of Parameter Space

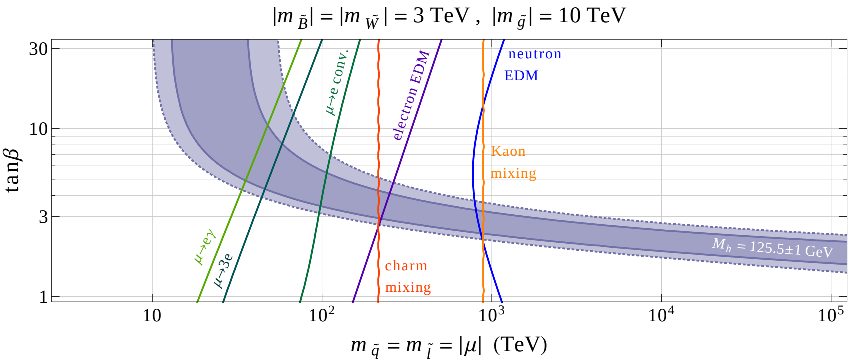


- PeV squarks already probed by CP violation in Kaon mixing
- CP violation in charm mixing and the neutron EDM reach up to O(100 TeV)

assumptions for the plot:

- all relevant mass insertions $|\delta_{ij}| = 0.3$
- all relevant phases $\sin\phi_i = 1$
- no large cancellations between the various contributions

Future Sensitivities in a Slice of Parameter Space



- neutron EDM (in gen. EDMs of hadronic systems) probe squarks at O(PeV)
- electron EDM and $\mu \to e$ conversion probe sleptons above 100 TeV
- SUSY flavor structure is unknown
  $\to$ important to reach the PeV scale with as many observables as possible

expected improvements

- CPV in D mixing : factor 10
- d_n : factor 300
- d_e : factor 90
- $\mu \to e$ conv. : factor 10^4

Summary of Flavor and EDM Connection

- EDMs and FCNCs are sensitive probes of new CP and flavor violating sources at high scales
- in MFV frameworks, EDMs are generically more sensitive to new phases than flavor observables
- in presence of flavor structures beyond MFV, “flavored” EDMs are sensitive to very high scales (thousands of TeV!)
  but Kaon mixing reaches even higher
- in many concrete models, flavor observables and EDMs can be correlated, details are model dependent
  $\rightarrow$ info from flavor and EDM experiments is complementary
  $\rightarrow$ possibility to distinguish models

Interplay of EDMs with Higgs Physics

Higgs Couplings to SM Particles

couplings of a electrically neutral spin 0 particle to SM particles; e.g.

$$
\begin{aligned}
S\bar{f}f &+ iA\bar{f}\gamma_5 f \\
vSW_\mu W^\mu &+ \frac{1}{\Lambda}AW_{\mu\nu}\tilde{W}^{\mu\nu} \\
vSZ_\mu Z^\mu &+ \frac{1}{\Lambda}AZ_{\mu\nu}\tilde{Z}^{\mu\nu} \\
\frac{1}{\Lambda}SF_{\mu\nu}F^{\mu\nu} &+ \frac{1}{\Lambda}AF_{\mu\nu}\tilde{F}^{\mu\nu} \\
\frac{1}{\Lambda}SG_{\mu\nu}G^{\mu\nu} &+ \frac{1}{\Lambda}AG_{\mu\nu}\tilde{G}^{\mu\nu}
\end{aligned}
$$

- pure scalar S, ($J^{\mathrm{PC}} = 0^{++}$)
- pure pseudoscalar A, ($J^{\mathrm{PC}} = 0^{-+}$)
- in each case, the couplings of the discovered Higgs could be arbitrary linear combinations of the scalar and pseudoscalar case

$h \to ZZ$

- the Higgs couples to Z bosons

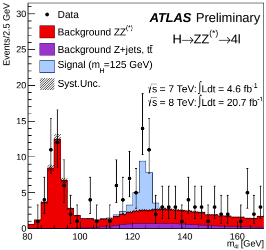
$$\mu = 1.44^{+0.40}_{-0.35} \quad \text{(ATLAS)}$$

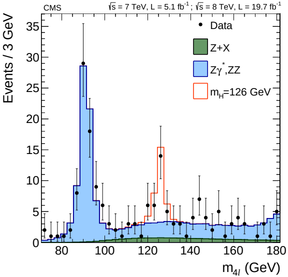
$$\mu = 0.93^{+0.26}_{-0.23}{}^{+0.13}_{-0.09} \quad \text{(CMS)}$$

- ZZ rate cannot distinguish between the operators

$$hZ_\mu Z^\mu \quad , \quad hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$$

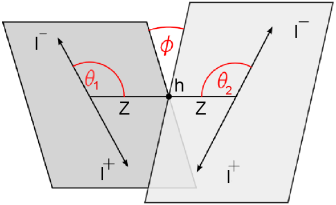
ATLAS-CONF-2013-013





CMS-PAS-HIG-13-002

CP Properties from $h \to ZZ$

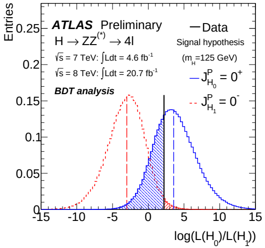


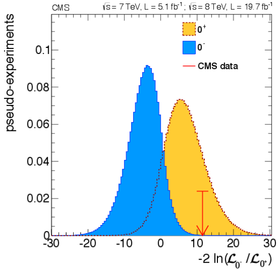
- use angular distributions of the leptons to distinguish between scalar and pseudoscalar

$$hZ_\mu Z^\mu \quad \leftrightarrow \quad hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$$

- pure pseudoscalar coupling to Z bosons is excluded at 99.6% (Atlas) / 99.8% (CMS)

ATLAS-CONF-2013-013





CMS-PAS-HIG-13-002

$h \to \gamma\gamma$

- the Higgs couples to photons

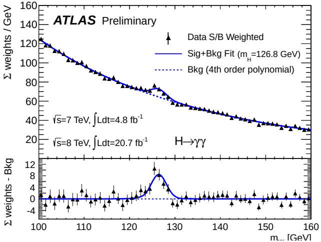
$$\mu = 1.65 \pm 0.24^{+0.25}_{-0.18} \quad \text{(ATLAS)}$$

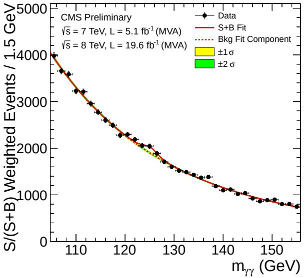
$$\mu = 0.78^{+0.28}_{-0.26} \quad \text{(CMS)}$$

- in the SM: W and top loops
- $\gamma\gamma$ rate cannot distinguish between the operators

$$hF_{\mu\nu}F^{\mu\nu} \quad , \quad hF_{\mu\nu}\tilde{F}^{\mu\nu}$$

ATLAS-CONF-2013-012





CMS-PAS-HIG-13-001

- hFF and $hF\tilde{F}$ contributions interfere in the angular distribution over the angle between the photon polarizations

$$A(h \to \gamma\gamma) \sim (A_{\rm SM} + A_{hFF}) \cos\phi + A_{hF\tilde{F}} \sin\phi$$

$$\frac{\Gamma(h \to \gamma\gamma)}{d\phi} \propto \cos^2(\phi - \xi) \quad , \qquad \tan\xi = \frac{A_{hF\tilde{F}}}{A_{\rm SM} + A_{hFF}}$$

CP Properties from $h \to \gamma\gamma$

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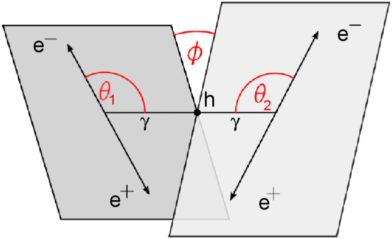
- if the photons convert into electrons, the angle between the decay planes of the electrons “remembers” the angle between the photon polarizations



Voloshin ’12 Bishara et al. ’13

$h \to \tau\tau$

- the Higgs (most likely) couples to taus

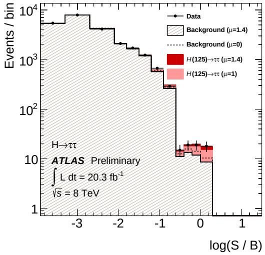
$$\mu = 1.4^{+0.5}_{-0.4} \quad \text{(ATLAS)}$$

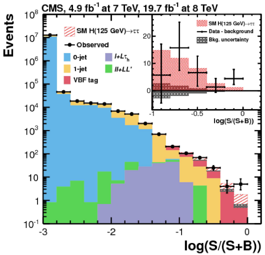
$$\mu = 0.78 \pm 0.27 \quad \text{(CMS)}$$

- $\tau\tau$ rate cannot distinguish between the operators

$$h\bar{\tau}\tau \quad , \quad h\bar{\tau}i\gamma_5\tau$$

ATLAS-CONF-2013-108





CMS arXiv:1401.5041

CP Properties from $h \to \tau\tau$

the spin directions of the taus contain information on the CP properties of the $h\tau\tau$ coupling

$$\cos\Delta \; h\bar{\tau}\tau + \sin\Delta \; h\bar{\tau}i\gamma_5\tau$$

tau decay products retain non-trivial information about the tau spin

$$h \to \tau^+\tau^- \quad , \quad \tau^\pm \to (\rho^\pm \to \pi^\pm\pi^0)\nu_\tau$$

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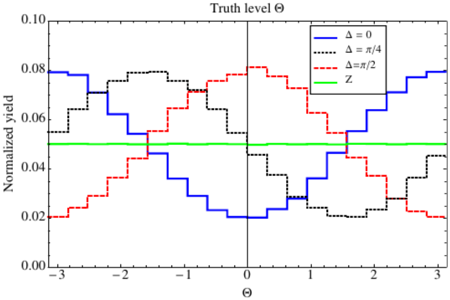
sensitivities to
CP-odd admixtures
to the $h\tau\tau$ coupling:

$\delta\Delta \sim 4.4^\circ$ @ ILC (250 GeV)

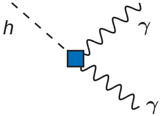
$\delta\Delta \sim 10^\circ$ @ LHC (3000/fb)



(Harnik, Martin, Okui, Primulando, Yu '13)

- CPV in $h \to \gamma\gamma$
  strongly related to EDMs

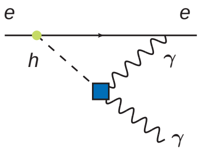
$$\frac{\tilde{C}v}{\Lambda^2}\, h\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$



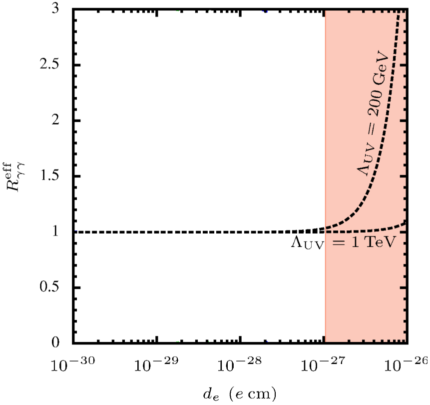
$h \to \gamma\gamma$ and EDMs (I)

- CPV in $h \to \gamma\gamma$
  strongly related to EDMs

$$\frac{\tilde{C} v}{\Lambda^2}\, h\, F_{\mu\nu}\tilde{F}^{\mu\nu} \quad + \quad y_e\, h\bar{e}e$$



$$\to \quad \frac{d_e}{e} = \frac{\tilde{C}}{4\pi^2}\, m_e\, \frac{1}{\Lambda^2} \log\left(\frac{\Lambda_{\rm UV}^2}{m_h^2}\right)$$



(adapted from McKeen, Pospelov, Ritz ’12)

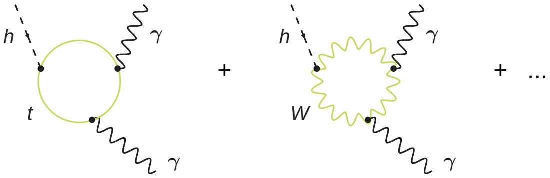
$\Rightarrow$ possible effects of the $hF\tilde{F}$ operator in $h \to \gamma\gamma$ are highly constrained by EDMs

$h \to \gamma\gamma$ and EDMs (II)

- assume that SM-like W boson and top loops are responsible for $h \to \gamma\gamma$

$\Rightarrow$ EDMs give information about the couplings of the Higgs to light fermions

SM W and top loops in $h \to \gamma\gamma$



$h \to \gamma\gamma$ and EDMs (II)

- assume that SM-like W boson and top loops are responsible for $h \to \gamma\gamma$

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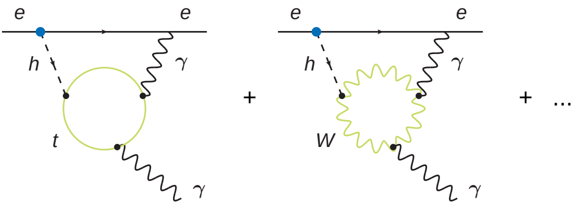
SM W and top loops in $h \to \gamma\gamma \quad + \quad i y'_e \, h \, \bar{e}\gamma_5 e$



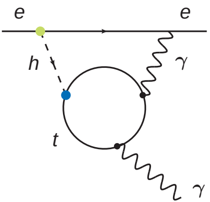
$$\to \quad \frac{d_e}{e} = \frac{3\alpha}{8\pi^2} \frac{y'_e}{v} \left[\frac{1}{2} f\left(\frac{m_W^2}{m_h^2}\right) - \frac{4}{9} f\left(\frac{m_t^2}{m_h^2}\right) \right]$$

$\Rightarrow \quad y'_e \lesssim 2 \times 10^{-8} \quad ,$ (compare to SM Yukawa coupling $y_e^{\rm SM} \simeq 3 \times 10^{-6}$)

- assume that the coupling to electrons is SM-like but allow for CP violation in the top Yukawa

$\Rightarrow$ EDMs give information about the couplings of the Higgs to the top

SM W loop $+$ CPV top loop in $h \to \gamma\gamma$ $+$ $y_e\, h\, \bar{e}e$



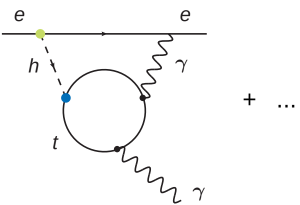
+ ...

$h \to \gamma\gamma$ and EDMs (III)

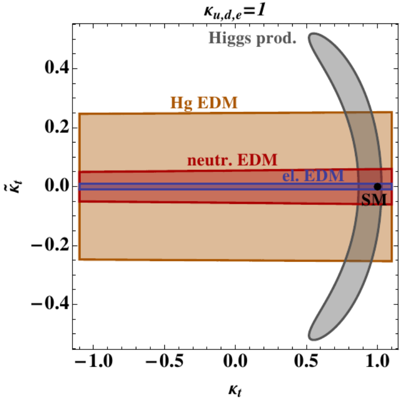
- assume that the coupling to electrons is SM-like but allow for CP violation in the top Yukawa

$\Rightarrow$ EDMs give information about the couplings of the Higgs to the top

SM W loop + CPV top loop in $h \to \gamma\gamma$ + $y_e\, h\, \bar{e}e$



Brod, Haisch, Zupan ’13



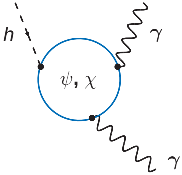
Enhanced $h \to \gamma\gamma$ and EDMs

- simple extensions of the SM that can accommodate an enhanced $h \to \gamma\gamma$ rate:
  $\to$ one generation of vector-like "leptons"
  ψ, ψ^c, χ, χ^c

$$M = \begin{pmatrix} m_L & yv \\ \tilde{y}v & m_E \end{pmatrix}$$

irreducible CP phase
$\phi = \mathrm{Arg}(m_L^* m_E^* y \tilde{y})$

- can consider various $SU(2)_L$ and $U(1)$ quantum numbers



- simple extensions of the SM that can accommodate an enhanced $h \to \gamma\gamma$ rate:
  $\to$ one generation of vector-like "leptons"
  $\psi, \psi^c, \chi, \chi^c$

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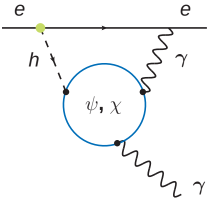
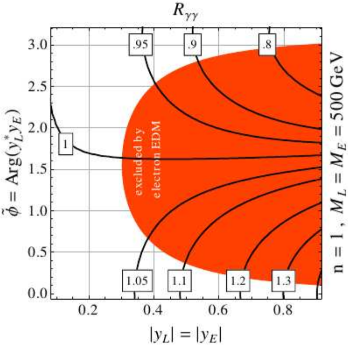
irreducible CP phase
$\phi = \text{Arg}(m_L^* m_E^* y \tilde{y})$

- can consider various $SU(2)_L$ and $U(1)$ quantum numbers
- EDMs set strong constraints on ϕ



see also McKeen, Pospelov, Ritz '12; Fan, Reece '13

WA, Bauer, Carena, '13

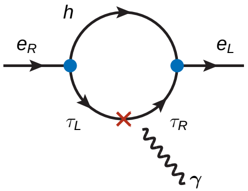


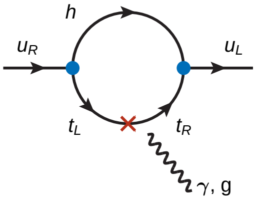
$$R_{\gamma\gamma} \propto \frac{\partial}{\partial v} \log(\det M^\dagger M)$$

$$d_e \propto \frac{\partial}{\partial v} \arg(\det M)$$

Flavor Violating Higgs Couplings and EDMs

- Consider flavor changing Higgs couplings: $Y_{ff'}\, h\, \bar{f}_L f'_R \;+\; Y_{f'f}\, h\, \bar{f}'_L f_R$





$$\left(\frac{d_e}{e}\right) \simeq \frac{1}{16\pi^2} \mathrm{Im}(Y_{e\tau} Y_{\tau e}) \frac{m_\tau}{m_h^2}\, f\left(\frac{m_\tau^2}{m_h^2}\right) \qquad \left(\frac{d_u}{e}\right) \simeq \frac{1}{16\pi^2} \mathrm{Im}(Y_{ut} Y_{tu}) \frac{m_t}{m_h^2}\, f\left(\frac{m_t^2}{m_h^2}\right)$$

- EDMs give bounds on imaginary parts of flavor changing Higgs couplings

$$|\mathrm{Im}(Y_{e\tau} Y_{\tau e})| \lesssim 1 \times 10^{-9} \qquad \text{compare to } \; Y_e^{\rm SM} Y_\tau^{\rm SM} \simeq 3 \times 10^{-8}$$

$$|\mathrm{Im}(Y_{ut} Y_{tu})| < 4.4 \times 10^{-8} \qquad \text{compare to } \; Y_u^{\rm SM} Y_t^{\rm SM} \simeq 8 \times 10^{-6}$$

Blankenburg, Ellis, Isidori ’12; Harnik, Kopp, Zupan ’12

Summary of Higgs and EDM Connection

- EDMs give strong constraints on CP violation in $h \to \gamma\gamma$ (assuming SM like couplings of the Higgs to light fermions)
- EDMs give strong constraints on CP violating couplings of the Higgs to light fermions and the top
- models that can enhance the $h \to \gamma\gamma$ rate are often strongly constrained by EDMs
- also CP violation in flavor violating Higgs couplings can be constrained by EDMs

Summa Summarum

- EDMs are background free probes of CP violation
beyond the Standard Model at the TeV scale and beyond

- EDM $\leftrightarrow$ Flavor Interplay:

  $\rightarrow$ flavor effects can boost the NP reach of EDMs
  ("flavored EDMs")

  $\rightarrow$ EDMs and flavor observables can give complementary
  information on CP violation in NP models

- EDM $\leftrightarrow$ Higgs Interplay:

  $\rightarrow$ EDMs are highly sensitive to CP violation in the Higgs sector

  $\rightarrow$ opportunity to get indirect info on the Higgs couplings to light fermions