Interplay of EDMs with Higgs and Flavor Physics

Wolfgang Altmannshofer

Fermilab

Winter Workshop on Electric Dipole Moments
February 13 - 15, 2013
Fermi National Accelerator Laboratory

Some Aspects of the Interplay of EDMs with Higgs and Flavor Physics

Wolfgang Altmannshofer

Fermilab

Winter Workshop on Electric Dipole Moments
February 13 - 15, 2013
Fermi National Accelerator Laboratory

The Higgs, Flavor and CP Violation in the SM

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2 + Y_{ij} \bar{\Psi}^i_L \Psi^j_R \Phi$$

- 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 this Talk

- 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?

Outline

1. Interplay of EDMs with Flavor Physics
   - Minimal Flavor Violation
   - Generic Flavor Violation
2. Interplay of EDMs with Higgs Physics
   - Higgs CP properties at the LHC
   - Higgs CP properties and EDMs
3. Summary

Interplay of EDMs with Flavor Physics

Sources of Flavor and CP Violation beyond the SM

Many extensions of the SM contain new sources of flavor and CP violation

1. Example: MSSM

$$m_1 \tilde{B}\tilde{B} + m_2 \tilde{W}\tilde{W} + m_3 \tilde{g}\tilde{g}$$
$$+\mu \tilde{H}_u \tilde{H}_d + B\mu H_u H_d$$

$\rightarrow$ 5 phases

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

$\rightarrow$ 15 flavor mixing angles + 15 phases

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

$\rightarrow$ 18 flavor mixing angles + 27 phases

2 phases can be rotated away...

Sources of Flavor and CP Violation beyond the SM

Many extensions of the SM contain new sources of flavor and CP violation

1. Example: MSSM

$$m_1 \tilde{B}\tilde{B} + m_2 \tilde{W}\tilde{W} + m_3 \tilde{g}\tilde{g}$$
$$+\mu \tilde{H}_u \tilde{H}_d + B\mu H_u H_d$$

$\rightarrow$ 5 phases

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

$\rightarrow$ 15 flavor mixing angles + 15 phases

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

$\rightarrow$ 18 flavor mixing angles + 27 phases

2 phases can be rotated away...

2. Example: 2HDM

$$V(H_1, H_2) \supset B\mu (H_2 H_1) + \frac{\lambda_5}{2}(H_2 H_1)^2$$
$$-\lambda_6 (H_2 H_1) H_1^\dagger H_1 - \lambda_7 (H_2 H_1) H_2^\dagger H_2$$

$\rightarrow$ 4 phases

$$Y_u\, H_2 \bar{Q}_L U_R + \tilde{Y}_u\, H_1^\dagger \bar{Q}_L U_R$$
$$+Y_d\, H_1 \bar{Q}_L D_R + \tilde{Y}_d\, H_2^\dagger \bar{Q}_L D_R$$
$$+Y_\ell\, H_1 \bar{L}_L E_R + \tilde{Y}_\ell\, H_2^\dagger \bar{L}_L E_R$$

$\rightarrow$ 18 flavor mixing angles + 27 phases

2 phases can be rotated away...

- NP Flavor Problem, NP CP Problem

Minimal Flavor Violation

- largest symmetry group that commutes with the SM gauge group

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

Minimal Flavor Violation

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

- the SM Yukawa couplings are the only spurions that break G_F

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

- new sources of flavor violation are functions of the SM Yukawas

Examples

1. MSSM

- expansion of the soft terms

$$m_Q^2 = \tilde{m}_Q^2 \left(\mathbb{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger + \right.$$
$$\left. + b_3 Y_d Y_d^\dagger Y_u Y_u^\dagger + b_3^* Y_u Y_u^\dagger Y_d Y_d^\dagger + \ldots \right)$$
$$m_U^2 = \tilde{m}_U^2 \left(\mathbb{1} + b_4 Y_u^\dagger Y_u + \ldots \right)$$
$$m_D^2 = \tilde{m}_D^2 \left(\mathbb{1} + b_5 Y_d^\dagger Y_d + \ldots \right)$$
$$A_u = \tilde{A}_u \left(\mathbb{1} + b_6 Y_d Y_d^\dagger + b_7 Y_u Y_u^\dagger + \ldots \right) Y_u$$
$$A_d = \tilde{A}_d \left(\mathbb{1} + b_8 Y_u Y_u^\dagger + b_9 Y_d Y_d^\dagger + \ldots \right) Y_d$$

2. 2HDM

- expansion of the “wrong” Higgs couplings

$$\begin{aligned} \tilde{Y}_u &= \epsilon_u Y_u + \epsilon_u' Y_u Y_u^\dagger Y_u \\ &\quad + \epsilon_u'' Y_d Y_d^\dagger Y_u + \ldots \end{aligned}$$

$$\begin{aligned} \tilde{Y}_d &= \epsilon_d Y_d + \epsilon_d' Y_d Y_d^\dagger Y_d + \\ &\quad + \epsilon_d'' Y_u Y_u^\dagger Y_d + \ldots \end{aligned}$$

- Flavor Changing Neutral Currents naturally suppressed by small CKM angles and/or small Yukawa couplings

Examples

1. MSSM

- expansion of the soft terms

$$m_Q^2 = \tilde{m}_Q^2 \left(\mathbb{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger + \right.$$
$$\left. + b_3 Y_d Y_d^\dagger Y_u Y_u^\dagger + b_3^* Y_u Y_u^\dagger Y_d Y_d^\dagger + \ldots \right)$$
$$m_U^2 = \tilde{m}_U^2 \left(\mathbb{1} + b_4 Y_u^\dagger Y_u + \ldots \right)$$
$$m_D^2 = \tilde{m}_D^2 \left(\mathbb{1} + b_5 Y_d^\dagger Y_d + \ldots \right)$$
$$A_u = \tilde{A}_u \left(\mathbb{1} + b_6 Y_d Y_d^\dagger + b_7 Y_u Y_u^\dagger + \ldots \right) Y_u$$
$$A_d = \tilde{A}_d \left(\mathbb{1} + b_8 Y_u Y_u^\dagger + b_9 Y_d Y_d^\dagger + \ldots \right) Y_d$$

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

2. 2HDM

- expansion of the "wrong" Higgs couplings

$$\tilde{Y}_u = \epsilon_u Y_u + \epsilon_u' Y_u Y_u^\dagger Y_u + \epsilon_u'' Y_d Y_d^\dagger Y_u + \ldots$$

$$\tilde{Y}_d = \epsilon_d Y_d + \epsilon_d' Y_d Y_d^\dagger Y_d + \epsilon_d'' Y_u Y_u^\dagger Y_d + \ldots$$

$B\mu, \lambda_5, \lambda_6, \lambda_7$

- Flavor Changing Neutral Currents naturally suppressed by small CKM angles and/or small Yukawa couplings
- many additional sources of CP violation are possible

EDMs vs FCNCs in MFV

Scales that are probed by flavor observables and EDMs in a generic MFV setup

1. neutral Kaon mixing

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

- proportional to small CKM elements
- constraint from ϵ_K (= CP violation in Kaon mixing), assuming $C \sim 1$

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

EDMs vs FCNCs in MFV

Scales that are probed by flavor observables and EDMs in a generic MFV setup

1. neutral Kaon mixing

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

- proportional to small CKM elements
- constraint from ϵ_K (= CP violation in Kaon mixing), assuming $C \sim 1$

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

2. down quark EDM

$$\frac{\tilde{C}}{\Lambda^2} H(\bar{Q}_L \, \sigma F \, Y_d D_R) \to \frac{\tilde{C}}{\Lambda^2} m_d \, (\bar{d}_L \sigma_{\mu\nu} F^{\mu\nu} d_R)$$

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

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

Example of an Exception

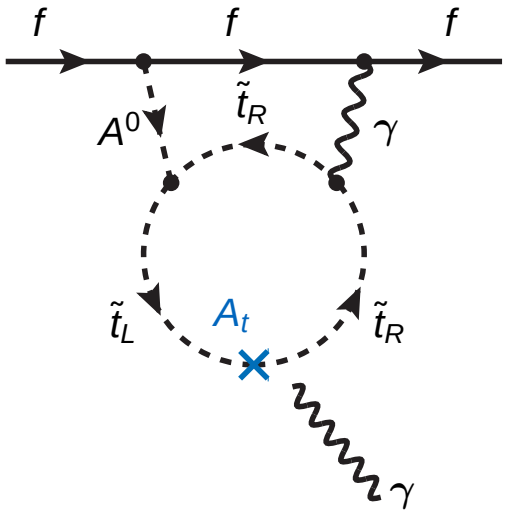
- MSSM with MFV and CP violation only from higher order terms in the trilinear couplings

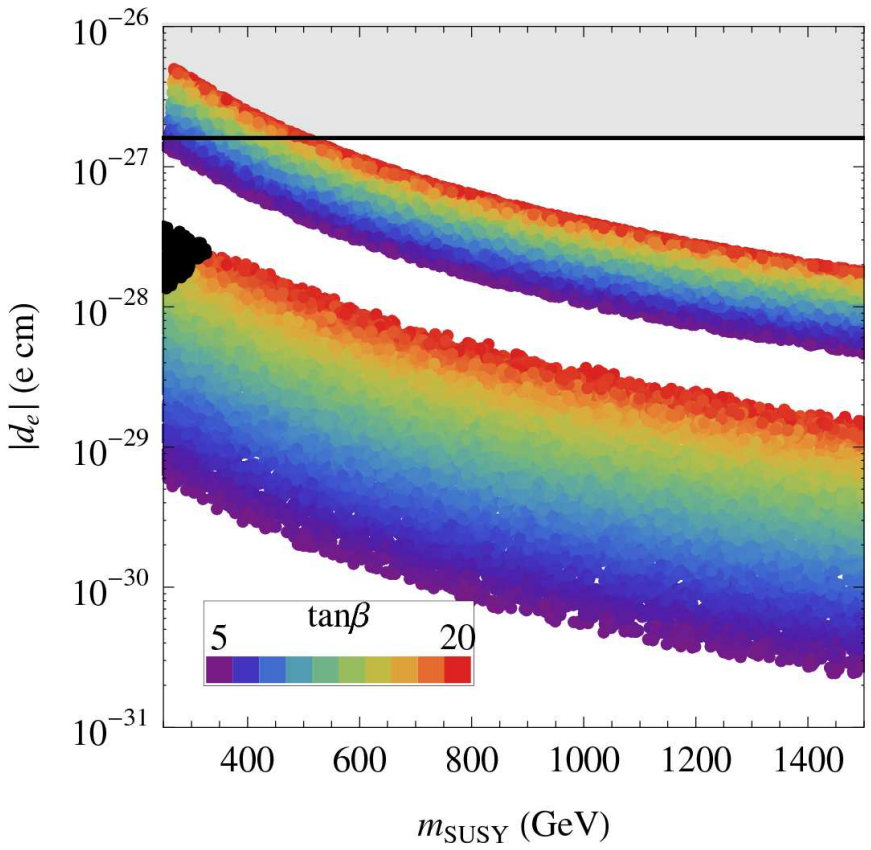
$$A_u = A(\mathbb{1} + b_6 Y_d Y_d^\dagger) Y_u$$

$$\text{or} \quad A_u = A(\mathbb{1} + b_7 Y_u Y_u^\dagger) Y_u$$

→ only 3rd generation feels CPV

→ FCNCs at 1loop but EDMs at 2loop



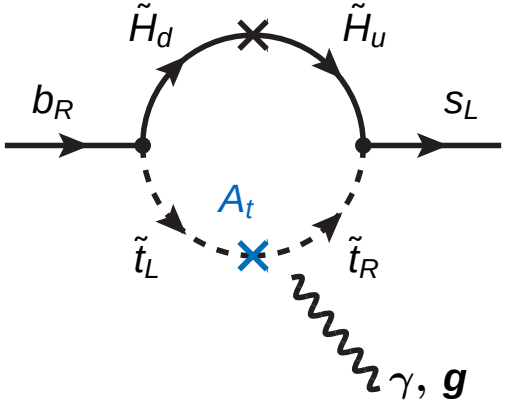


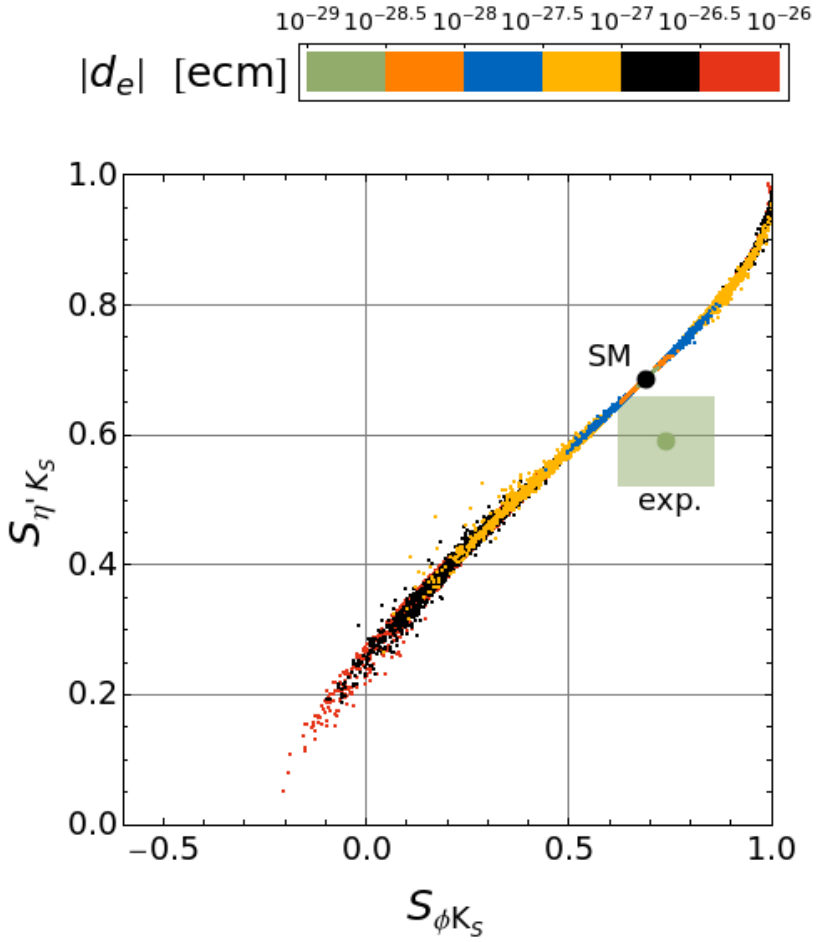
→ EDMs are under control for TeV spectrum and O(1) phase

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

Correlations with Flavor Observables

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





- sizable CP effects can be expected in B physics

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

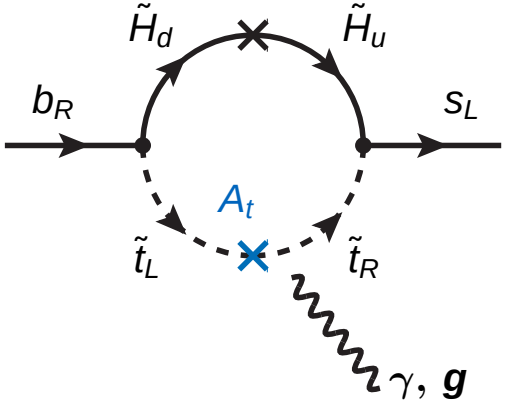
$\to$ time dependent CP asymmetries in $B \to \phi K_S$, $B \to \eta' K_S$

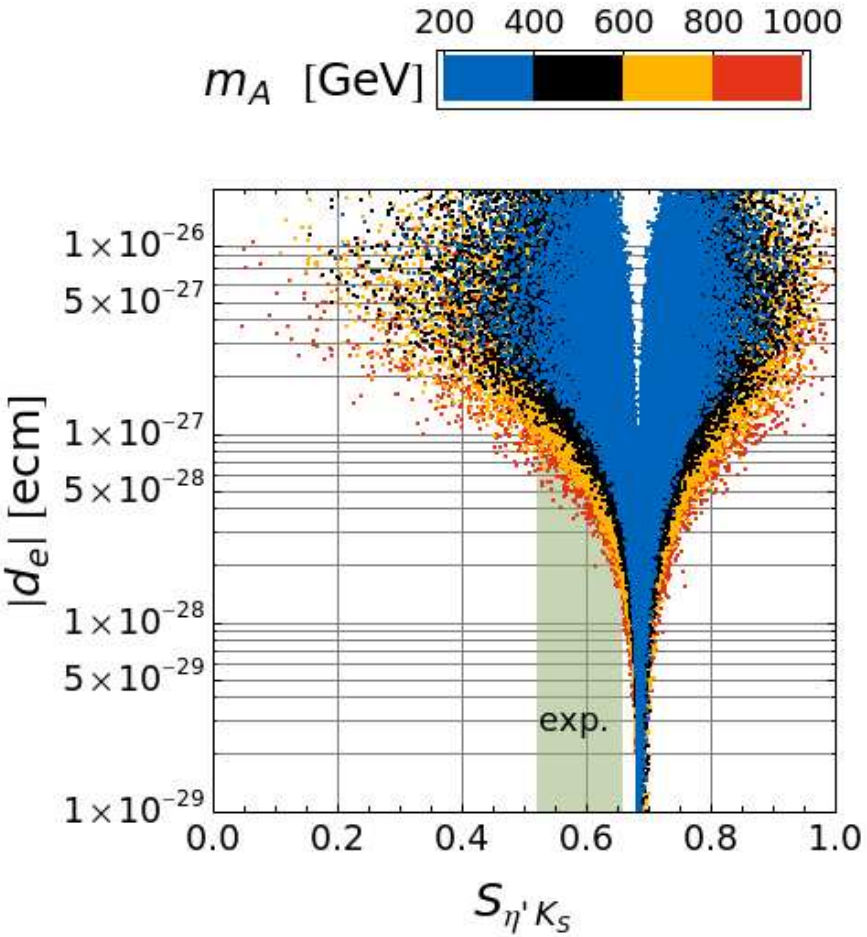
$\to$ CP asymmetries in $B \to K^* \mu^+ \mu^-$

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

Correlations with Flavor Observables

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





- sizable CP effects can be expected in B physics

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

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

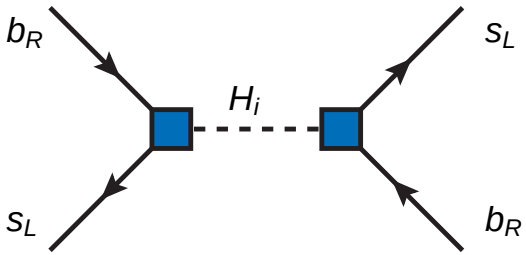
$\to$ CP asymmetries in $B \to K^*\mu^+\mu^-$

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

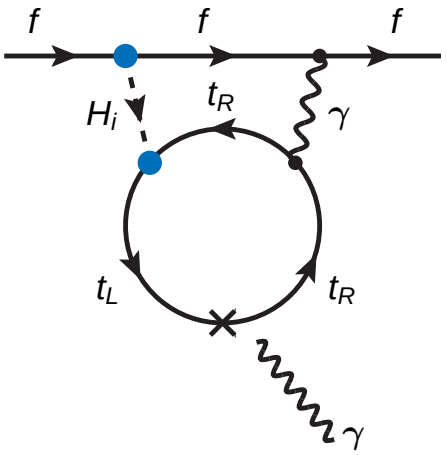
Another Example

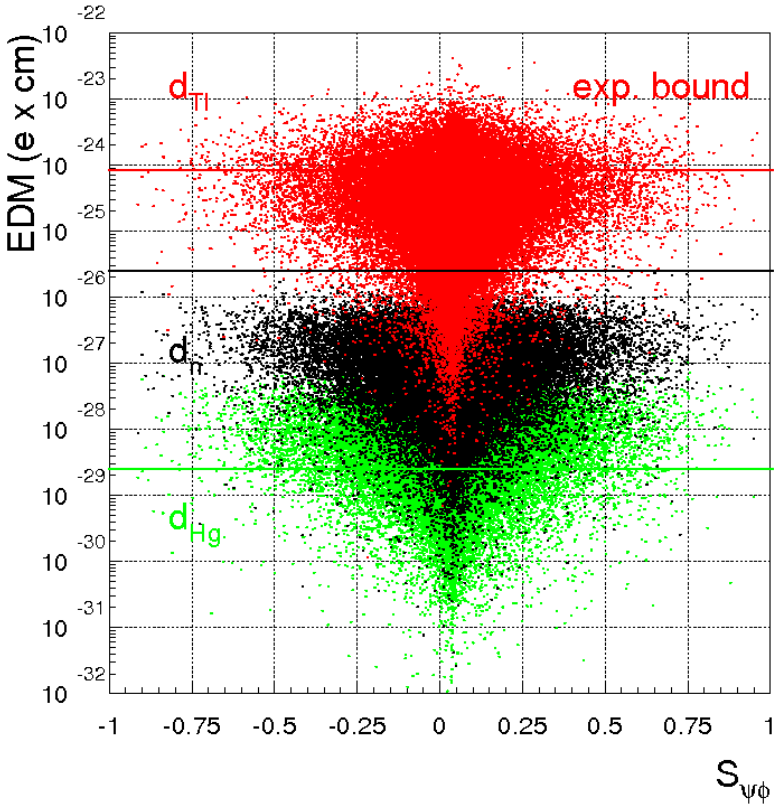
2HDM with MFV and generic phases

→ B mixing at tree level



→ EDMs at 2loop





Buras, Isidori, Paradisi '10

EDMs vs FCNCs with Generic Flavor Violation

Assume additional flavor spurions: e.g. $X_q^L = 8_Q, X_u^R = 8_U, X_d^L = 8_D$

1. neutral Kaon mixing

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

- 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

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

EDMs vs FCNCs with Generic Flavor Violation

Assume additional flavor spurions: e.g. $X_q^L = 8_Q, X_u^R = 8_U, X_d^L = 8_D$

1. neutral Kaon mixing

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

- 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

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

2. up quark EDM

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

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

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

Concrete Example: SUSY Alignment Models (I)

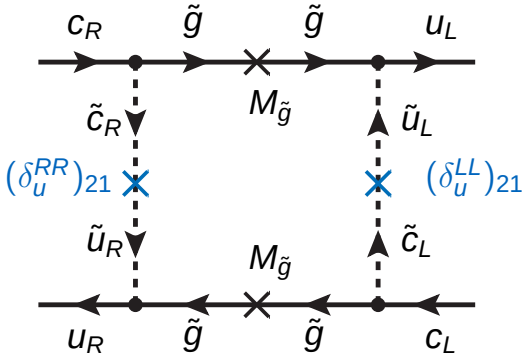
$$m_Q^2 = \tilde{m}_Q^2(\mathbb{1} + \delta_q^{LL})$$
$$m_U^2 = \tilde{m}_U^2(\mathbb{1} + \delta_u^{RR})$$
$$m_D^2 = \tilde{m}_D^2(\mathbb{1} + \delta_d^{RR})$$

- use flavor symmetries to align new sources of flavor violation (δ's) with the SM Yukawas
- abelian alignment models predict lower and upper bounds for squark flavor mixing angles (Nir, Raz '02), e.g.

$$(\delta_u^{RR})_{12} \sim \lambda^2 - \lambda^4$$

- masses of the left handed squarks can be aligned either in the up or in the down sector

$$(\delta_u^{LL})_{12} \simeq (\delta_d^{LL})_{12} + \lambda \frac{\Delta \tilde{m}_{12}^2}{\tilde{m}_Q^2}$$



- models are constructed such that $(\delta_d^{LL})_{12} \simeq 0$, to avoid constraints from $K - \bar{K}$ mixing

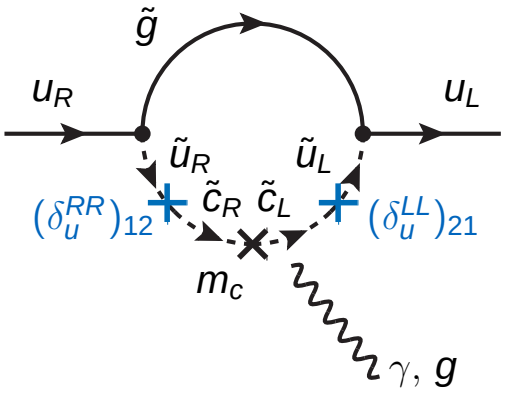
$$\Rightarrow \quad (\delta_u^{LL})_{12} \sim \lambda$$

- immediate consequence: Large NP effects in $D^0 - \bar{D}^0$ mixing (Nir, Seiberg '93)

$$\mathrm{Im}\, M_{12}^D \propto \mathrm{Im}\left[(\delta_u^{LL})_{21}(\delta_u^{RR})_{21}\right]$$

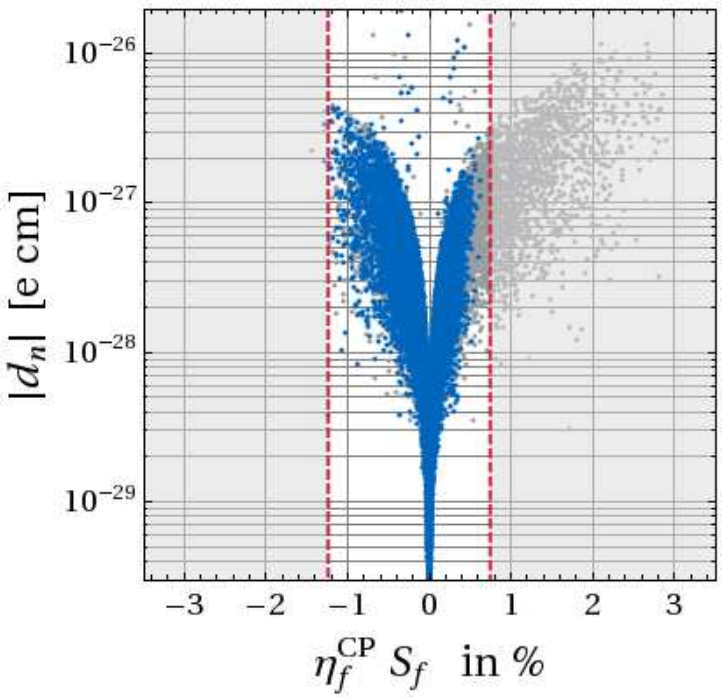
Concrete Example: SUSY Alignment Models (II)

- same flavor structures also lead to a "flavored" up quark (C)EDM



$$d_u^{(c)} \propto m_c \, \mathrm{Im}\left[(\delta_u^{LL})_{21}(\delta_u^{RR})_{21}\right]$$

- chiral enhancement by m_c/m_u
- the up quark (C)EDM leads in turn to EDMs e.g. of the neutron and of mercury



- large CP violation in $D^0 - \bar{D}^0$ mixing in abelian flavor models implies lower bounds on hadronic EDMs

(WA, Buras, Paradisi '10)

$$d_n \gtrsim 10^{-(28-29)} e\,\mathrm{cm}$$

$$d_{\mathrm{Hg}} \gtrsim 10^{-(30-31)} e\,\mathrm{cm}$$

Summary (I)

- 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 highly 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

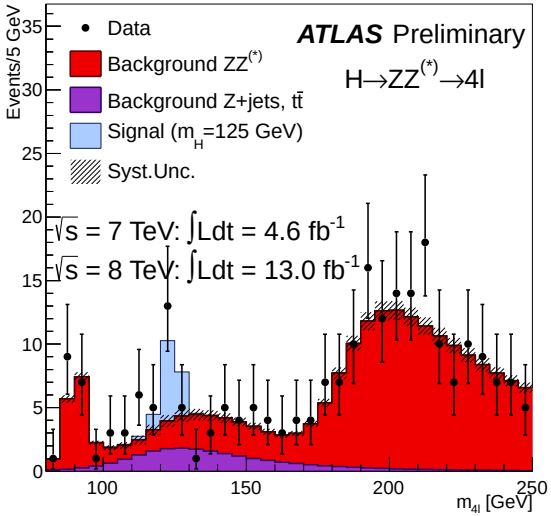
$$
\begin{aligned}
S\bar{f}f &+ iA\bar{f}\gamma_5 f \\
vSW_\mu W^\mu &+ \frac{1}{\Lambda}AW_{\mu\nu}\tilde{W}^{\mu\nu} \\
vSZ_\mu Z^\mu &+ \frac{1}{\Lambda}AZ_{\mu\nu}\tilde{Z}^{\mu\nu} \\
\frac{1}{\Lambda}SF_{\mu\nu}Z^{\mu\nu} &+ \frac{1}{\Lambda}AF_{\mu\nu}\tilde{Z}^{\mu\nu} \\
\frac{1}{\Lambda}SF_{\mu\nu}F^{\mu\nu}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

- pure scalar S, ($J^{PC} = 0^{++}$)
- pure pseudoscalar A, ($J^{PC} = 0^{-+}$)
- the Higgs might be a mixture of scalar and pseudoscalar

$$h = \cos\alpha\, S + \sin\alpha\, A$$

$h \to ZZ$

ATLAS-CONF-2012-169



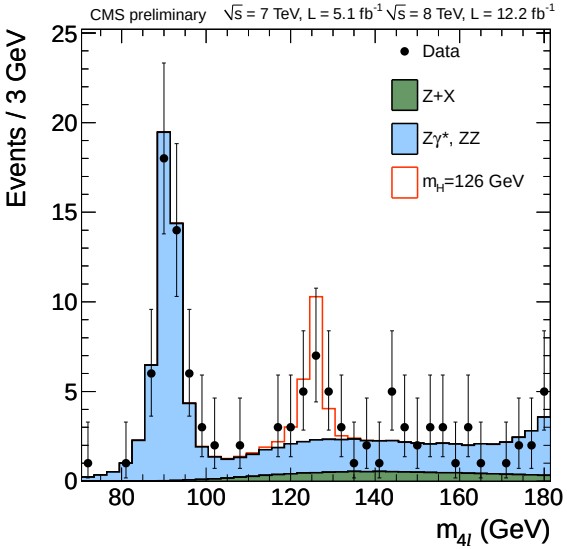
- the Higgs apparently couples to Z bosons

$$\mu = 1.3^{+0.5}_{-0.4} \quad \text{(ATLAS)}$$

$$\mu = 0.80^{+0.35}_{-0.28} \quad \text{(CMS)}$$

- ZZ rate cannot distinguish between the operators

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



CMS-PAS-HIG-12-041

$h \to \gamma\gamma$

- the Higgs apparently couples to photons

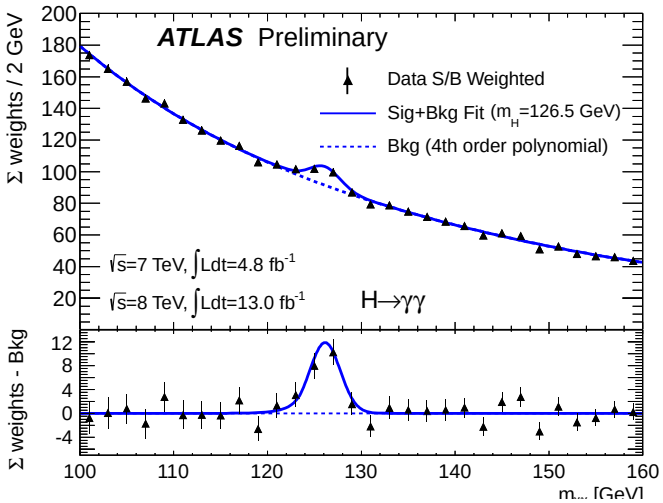
$$\mu = 1.80^{+0.42}_{-0.36} \quad \text{(ATLAS)}$$

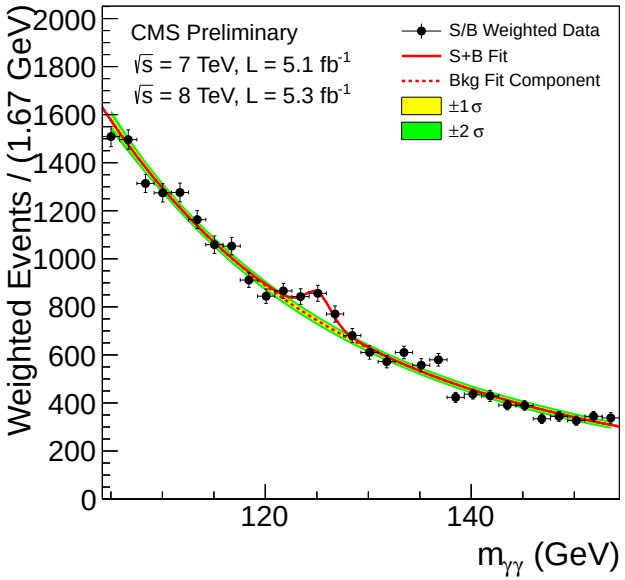
$$\mu = 1.56 \pm 0.43 \quad \text{(CMS)}$$

- 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-2012-168





CMS-PAS-HIG-12-015

CP Properties from Higgs Rates

- couplings of a pure pseudoscalar

$$\frac{a}{\Lambda}\, h \left(B_{\mu\nu}\tilde{B}^{\mu\nu} + b W_{\mu\nu}\tilde{W}^{\mu\nu} \right)$$

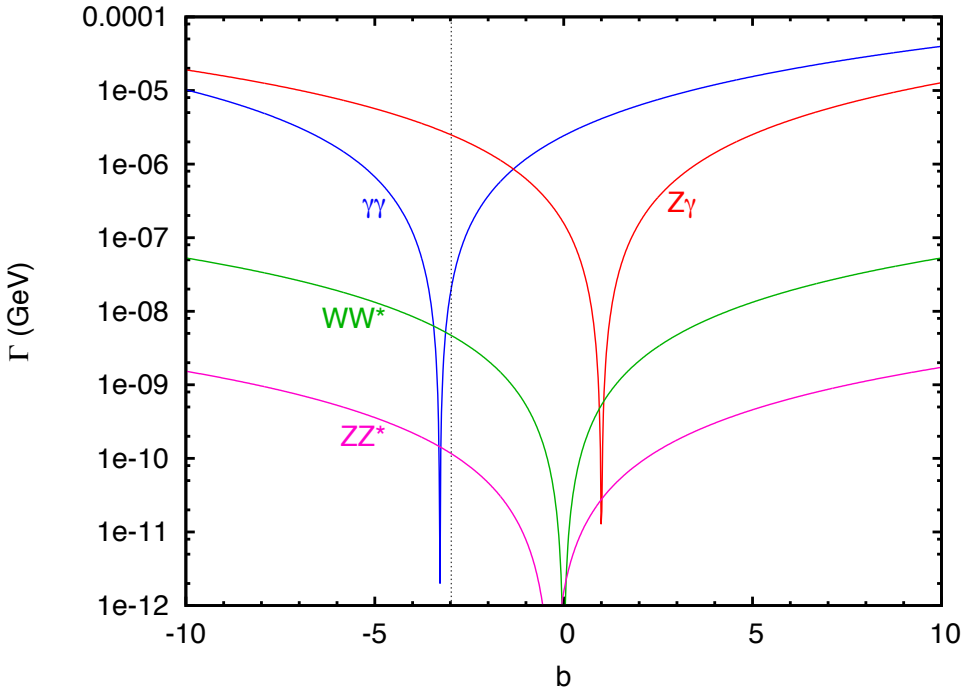
- relative size of

$$h \to ZZ$$
$$h \to WW$$
$$h \to \gamma\gamma$$
$$h \to Z\gamma$$

depend on one parameter b

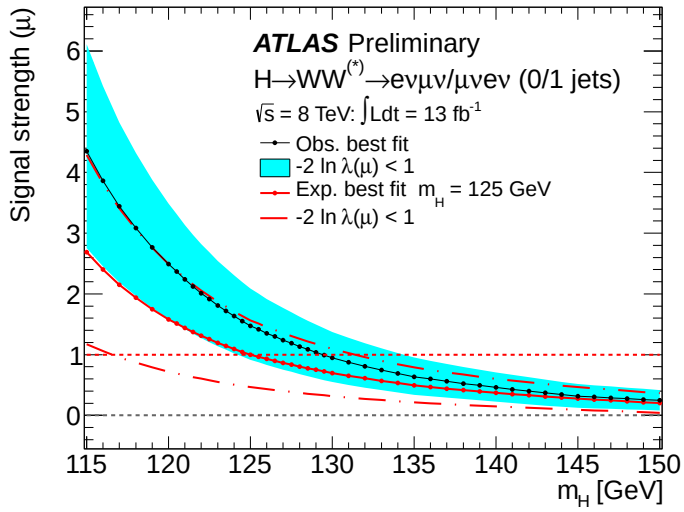
- using measured $h \to ZZ$ and $h \to \gamma\gamma$ rates as input leads to predictions

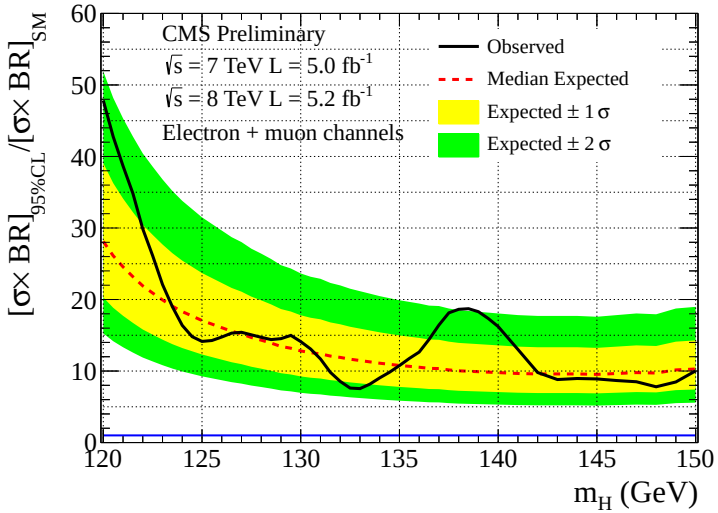
$$\mu(h \to WW) \sim 0$$
$$\mu(h \to Z\gamma) \sim 170$$

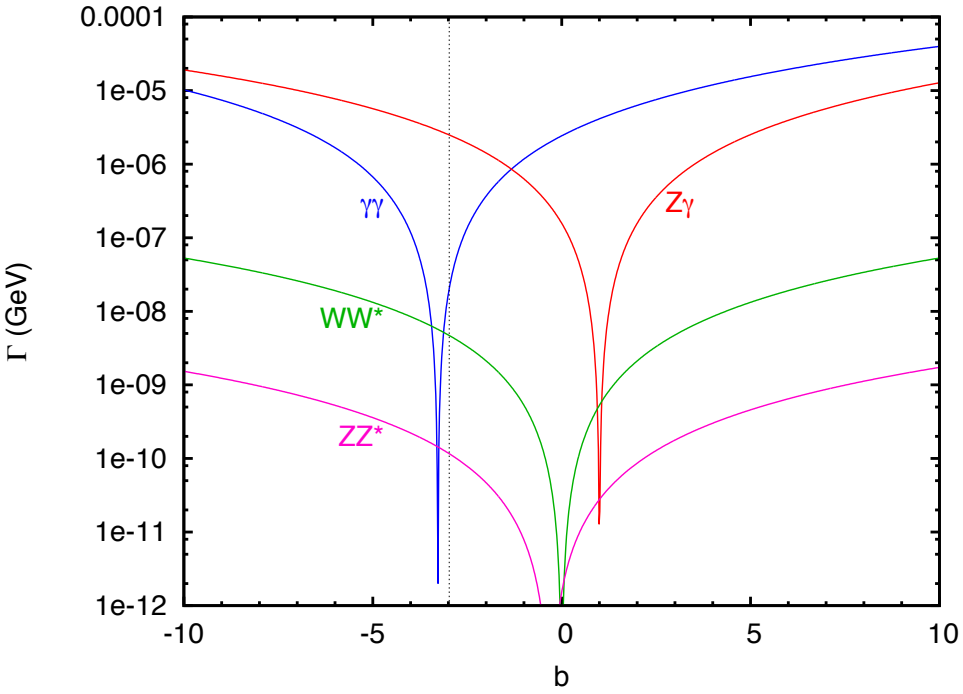


Coleppa, Kumar, Logan '12;
Freitas, Schwaller '12

CP Properties from Higgs Rates





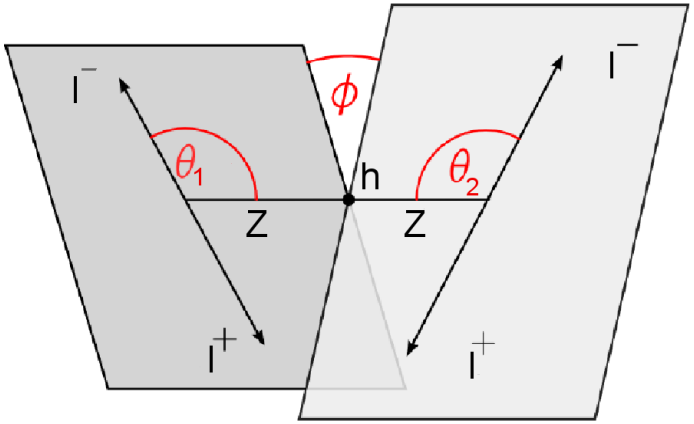


- pure pseudoscalar scenario is clearly excluded by the data

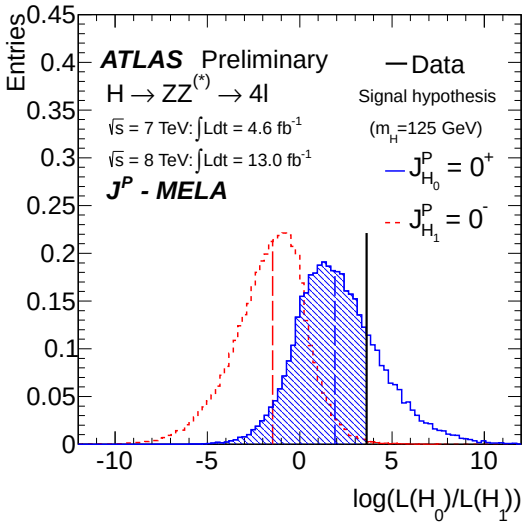
Coleppa, Kumar, Logan '12;

Freitas, Schwaller '12

CP Properties from $h \to ZZ$



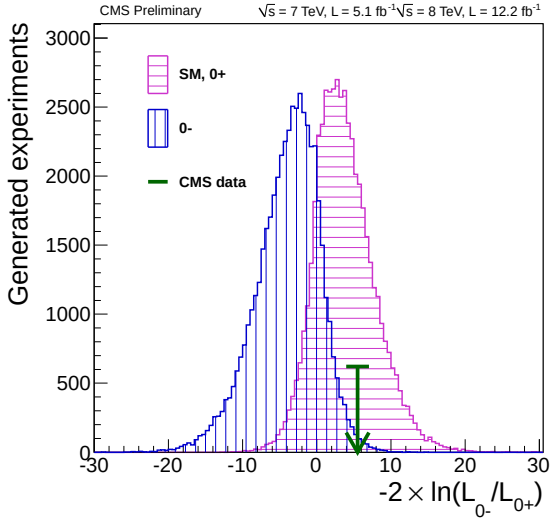
ATLAS-CONF-2012-169



- 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 99.7% (Atlas) / 97.6% (CMS)



CMS-PAS-HIG-12-041

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

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

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

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

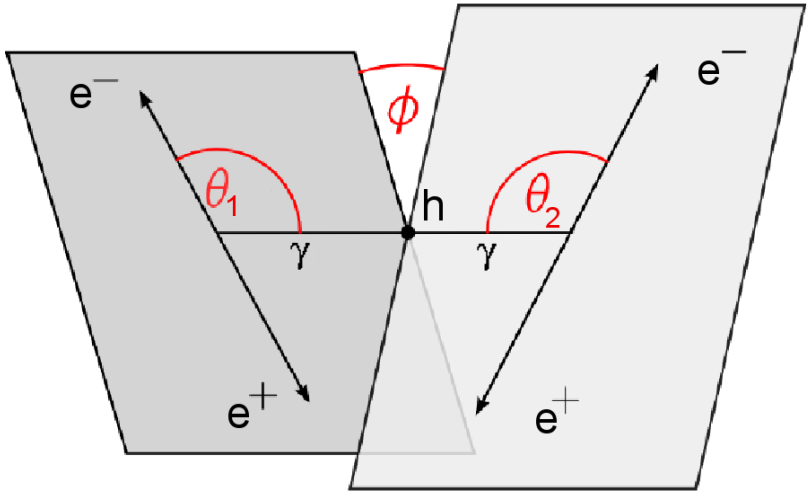
CP Properties from $h \to \gamma\gamma$

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

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

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

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

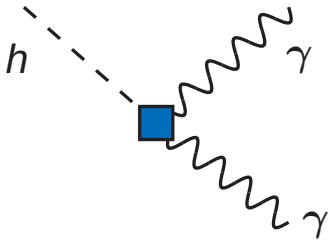


Voloshin '12

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

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

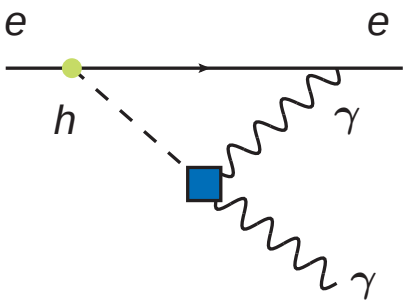
$$\frac{\tilde{C}v}{\Lambda^2}\, h\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$



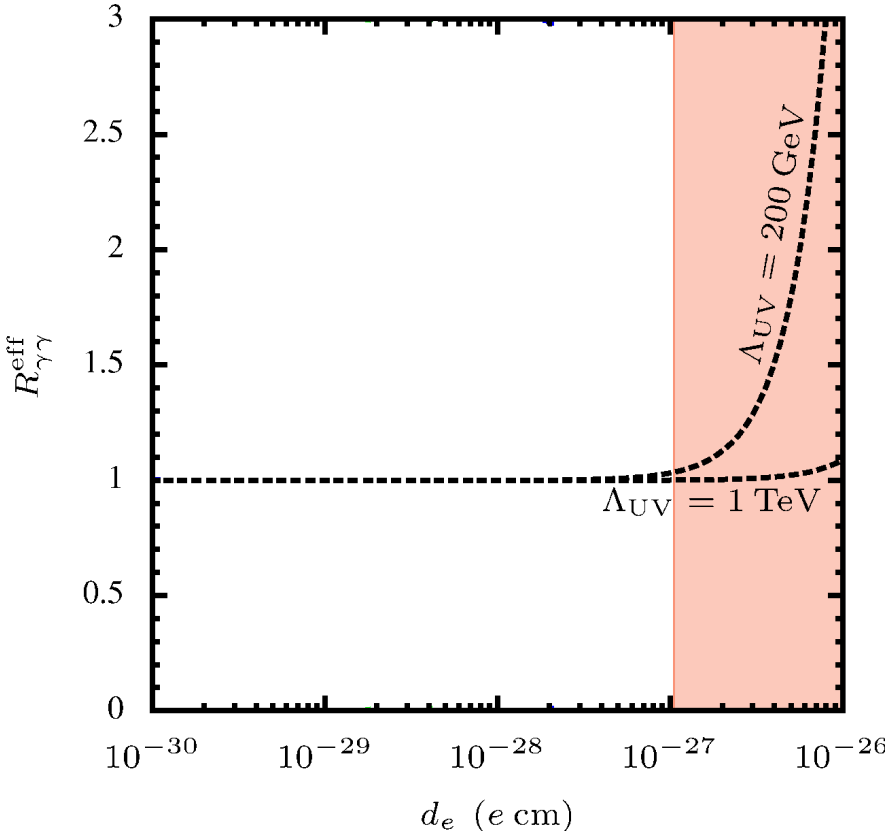
$h \to \gamma\gamma$ and EDMs (I)

- 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)

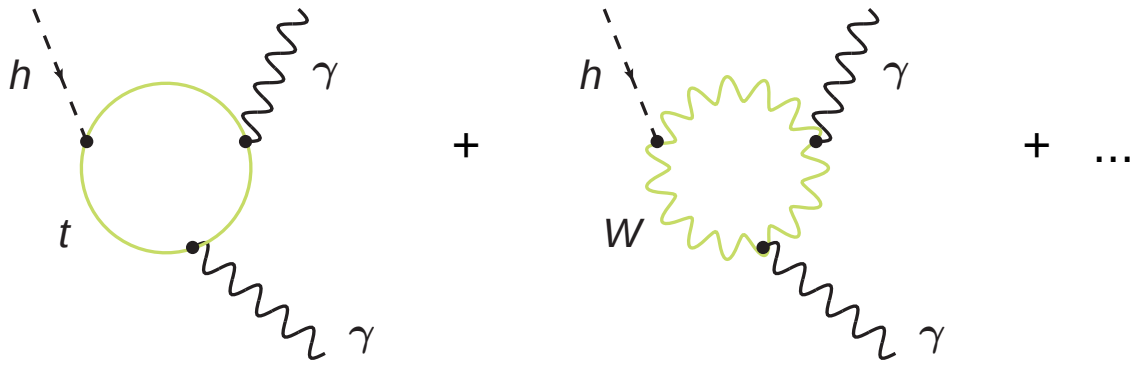
$\Rightarrow$ possible effects of the $hF\tilde{F}$ operator in $h \to \gamma\gamma$ are highly constrained by EDMs

$h \to \gamma\gamma$ 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 $h \to \gamma\gamma$

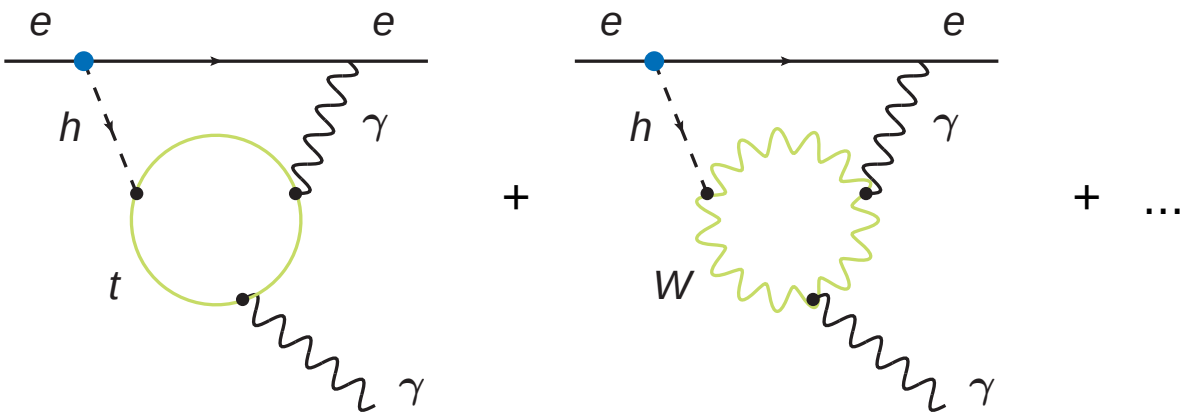


$h \to \gamma\gamma$ and EDMs (II)

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

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

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



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

$\Rightarrow \quad y_e' < 2 \times 10^{-7} \quad ,$ (compare to SM Yukawa coupling $y_e^{\rm SM} \simeq 3 \times 10^{-6}$)

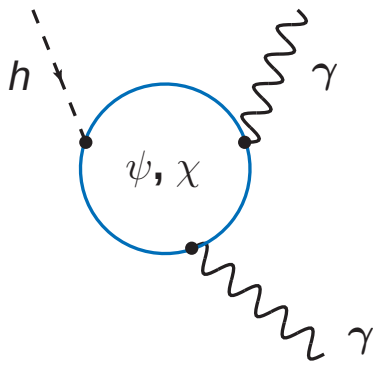
Enhanced $h \to \gamma\gamma$ and EDMs (I)

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

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

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

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



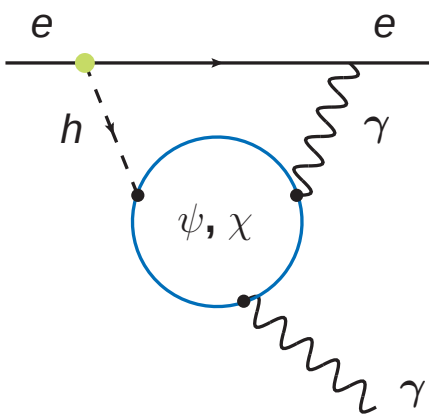
Enhanced $h \to \gamma\gamma$ and EDMs (I)

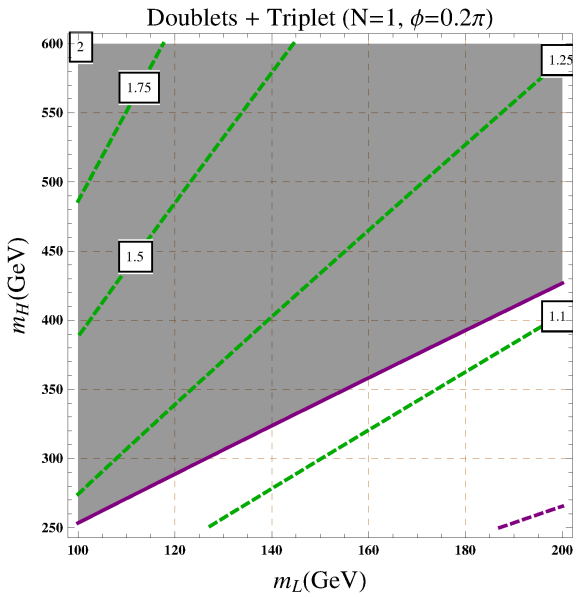
- simple extensions of the SM that can accommodate an enhanced $h \to \gamma\gamma$ rate:
  $\to$ one generation of vector-like "leptons"
  $\psi, \psi^c, \chi, \chi^c$

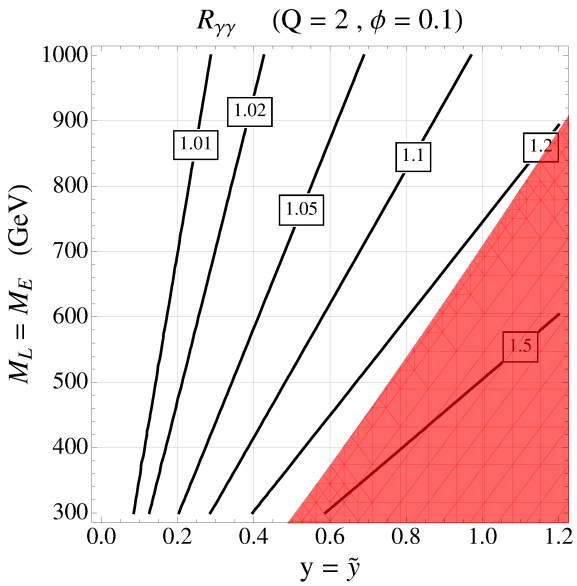
$$M = \begin{pmatrix} m_L & yv \\ \tilde{y}v & m_E \end{pmatrix}$$

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

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







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

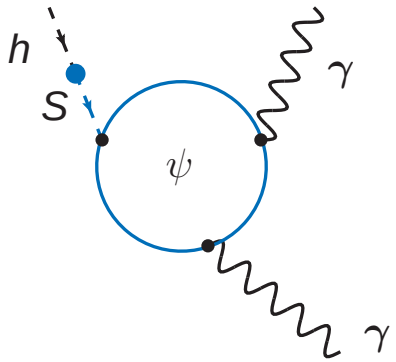
WA, Bauer, Carena, in preparation

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

- another model:

  charged vector-like
  SU(2) singlet ψ, ψ^c

  + scalar singlet S
  that mixes with the Higgs



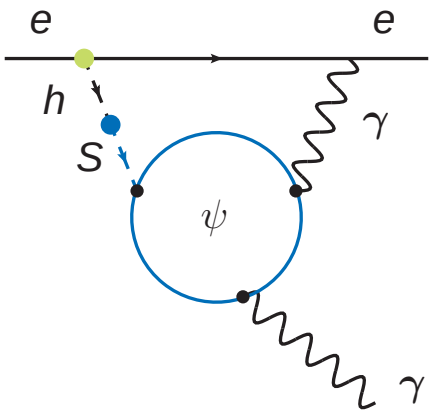
Enhanced $h \to \gamma\gamma$ and EDMs (II)

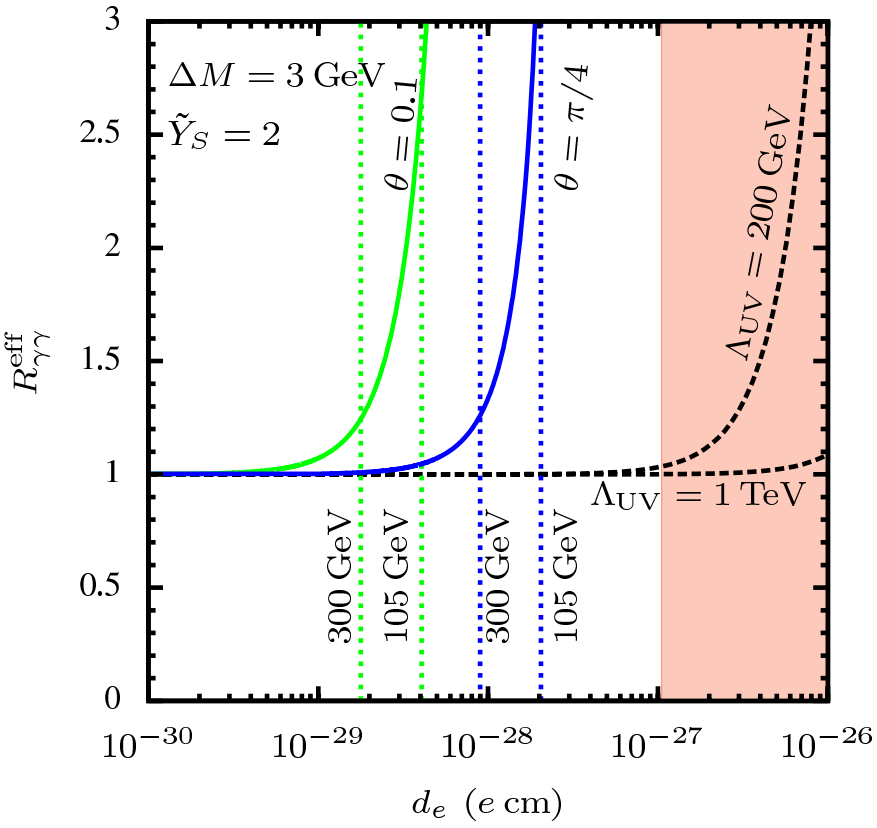
- another model:

  charged vector-like SU(2) singlet ψ, ψ^c

  + scalar singlet S that mixes with the Higgs

- EDMs $\propto \sin(2\theta)(m_S^2 - m_h^2)$

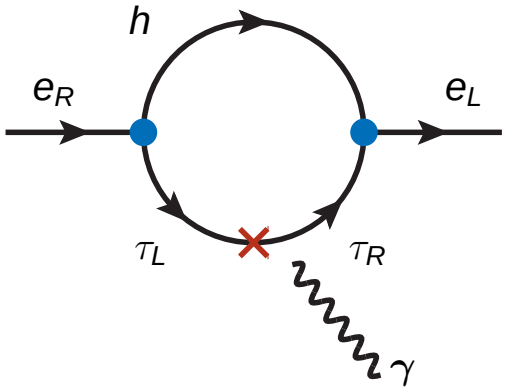


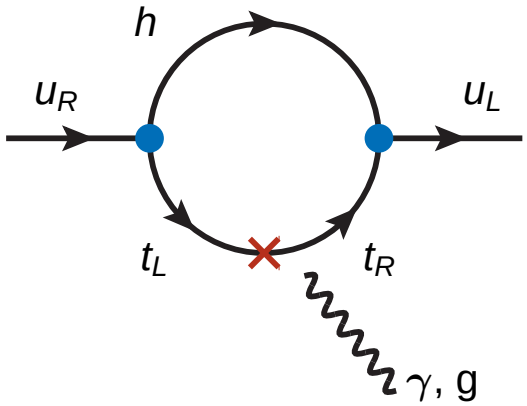


McKeen, Pospelov, Ritz '12

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

$$|\mathrm{Im}(Y_{e\tau}Y_{\tau e})| < 1.1\times 10^{-8} \qquad \text{compare to } Y_e^{\mathrm{SM}}Y_\tau^{\mathrm{SM}} \simeq 3\times 10^{-8}$$

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

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

Summary (II)

- EDMs give strong constraints on CP violation in $h \to \gamma\gamma$ (assuming SM like couplings of the Higgs to light fermions)
- EDMs give constraints on CP violating couplings of the Higgs to light fermions
- 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

- 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 couplings of the Higgs to light fermions