Direct and indirect probes of Higgs CP violation

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LHC Higgs Working Group - Common WG2 and WG3
CP violation and Higgs Sector

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Higgs and CP violation

In the Standard Model,

- The only source of CP violation comes from the electroweak sector (CKM phase).
- The Higgs has scalar couplings with SM particles.

We need to test these two statements!

From the experimental point of view,

- The Higgs CP nature is one of the **least known properties** of the Higgs boson.
- By now, the CP-odd hypothesis is strongly disfavored.

What if the Higgs is a CP even - CP odd admixture?

Generically, UV scenarios (e.g. 2HDMs) involve extended Higgs sectors and the possibility of CPV Higgs couplings.
Constraints from electric dipole moments?

Baryon asymmetry (typically) requires new sources of CPV

EDMs, experimental status & prospects

$$\mathcal{L}_{\text{eff}} = -\sum_f \frac{i d_f}{2} (\bar{f} \sigma^{\mu\nu} \gamma_5 f) F_{\mu\nu}$$

from Altmannshofer, SG, Patel, Profumo, Tuckler, 2002.01400

observable	SM theory	current exp.	projected sens.
d_e	$< 10^{-44}\ e$ cm	$< 1.1 \times 10^{-29}\ e\,$cm	$\sim 10^{-30}\ e\,$cm
d_μ	$< 10^{-42}\ e$ cm	$< 1.9 \times 10^{-19}\ e\,$cm	$\sim 10^{-23}\ e\,$cm
d_τ	$< 10^{-41}\ e$ cm	$< 4.5 \times 10^{-17}\ e\,$cm	$\sim 10^{-19}\ e\,$cm
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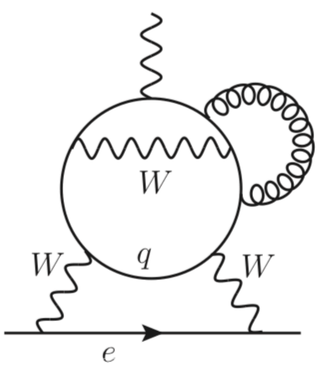
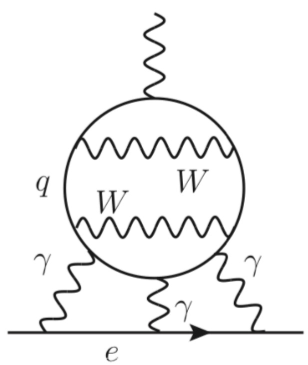
example diagrams
in the Standard Model:





d_e: ACME collaboration

d_μ: g-2 collaboration

d_τ: Belle collaboration

ACME collaboration

EDM experiment @ PSI

Belle II & e^+e^- experiments

EDMs, experimental status & prospects

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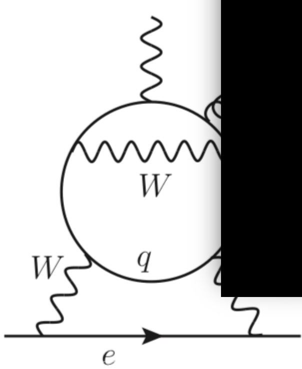
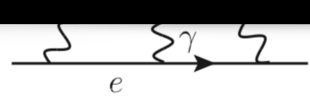
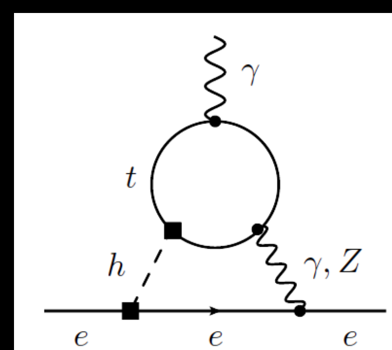
exa
in the





Any room left for
Higgs CPV couplings?



CME
llaboration

M experiment
PSI

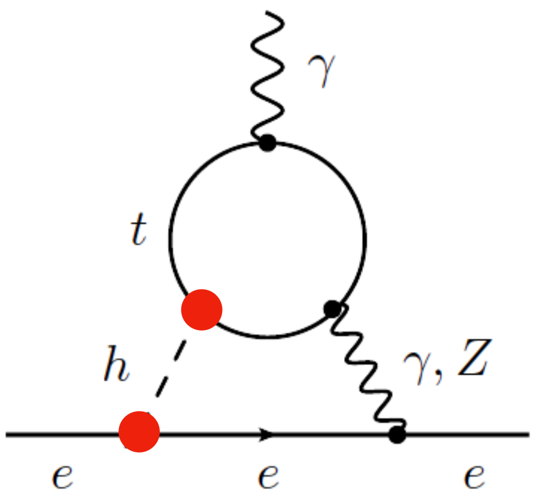
elle II &
e^+e^- experiments

EDMs, naive bounds on Higgs CPV couplings
(EFT approach)

If the **Higgs has CP violating couplings**:

$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$

for example from dim. 6 operators:
$\frac{c}{M^2}|H|^2 \bar{e}_L H e_R$



$$\frac{d_e}{e} = \frac{16}{3}\frac{\alpha}{(4\pi)^3}\sqrt{2}G_F m_e\left[\kappa_e\tilde{\kappa}_t f_1(x_{t/h}) + \tilde{\kappa}_e\kappa_t f_2(x_{t/h})\right]$$

electron EDM bound →

$$|\tilde{\kappa}_e| \lesssim 1.7 \times 10^{-3}$$
$$|\tilde{\kappa}_t| \lesssim 1.0 \times 10^{-3}$$

The complex 2HDM

Most general Higgs potential for a 2HDM with a softly broken Z_2 symmetry:

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \frac{1}{2}(m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}(\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.})$$

Only one independent phase

125 GeV Higgs → h_1

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \mathcal{R} \begin{pmatrix} \rho_1 \\ \rho_2 \\ A \end{pmatrix}$$

mass eigenstates — basis used above

$$\mathcal{R} = \begin{pmatrix} -s_\alpha c_{\alpha_2} & c_\alpha c_{\alpha_2} & s_{\alpha_2} \\ s_\alpha s_{\alpha_2} s_{\alpha_3} - c_\alpha c_{\alpha_3} & -s_\alpha c_{\alpha_3} - c_\alpha s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ s_\alpha s_{\alpha_2} c_{\alpha_3} + c_\alpha s_{\alpha_3} & s_\alpha s_{\alpha_3} - c_\alpha s_{\alpha_2} c_{\alpha_3} & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

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Set of free parameters (phenomenological):

$$m_{h_1},\ m_{h_2},\ m_{h_3},\ m_{H^\pm},\ \alpha\ (\text{or } x),\ \alpha_2,\ \nu,\ \tan\beta$$

$$\nu \equiv \frac{\text{Re}(m_{12}^2)}{v^2 \sin 2\beta}, \quad \alpha = \beta - \pi/2 + x$$

α_3 will be a function of these parameters

CPV couplings & Higgs rate measurements

$$\mathcal{L}_{\rm Yuk} = -\frac{m_{f_i}}{v}(\bar{f}_i \kappa_f^{(1)} f_i + i \bar{f}_i \gamma_5 \tilde{\kappa}_f^{(1)} f_i) h_1$$

Free parameters for the Higgs pheno:

$\alpha_2, \ x, \ \tan\beta, \ \nu$ ← only mildly entering through the Higgs self-coupling & Higgs coupling to the other Higgs bosons

	Type I	Type II
$\kappa_u^{(1)}$	$\frac{c_{\alpha_2} c_\alpha}{s_\beta}$	$\frac{c_{\alpha_2} c_\alpha}{s_\beta}$
$\kappa_{d,\ell}^{(1)}$	$\frac{c_{\alpha_2} c_\alpha}{s_\beta}$	$-\frac{c_{\alpha_2} s_\alpha}{c_\beta}$
$\tilde{\kappa}_u^{(1)}$	$-\frac{s_{\alpha_2}}{t_\beta}$	$-\frac{s_{\alpha_2}}{t_\beta}$
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Free parameters for the Higgs pheno:

$\alpha_2, \; x, \; \tan\beta, \; \nu$

only mildly entering through the Higgs self-coupling & Higgs coupling to the other Higgs bosons

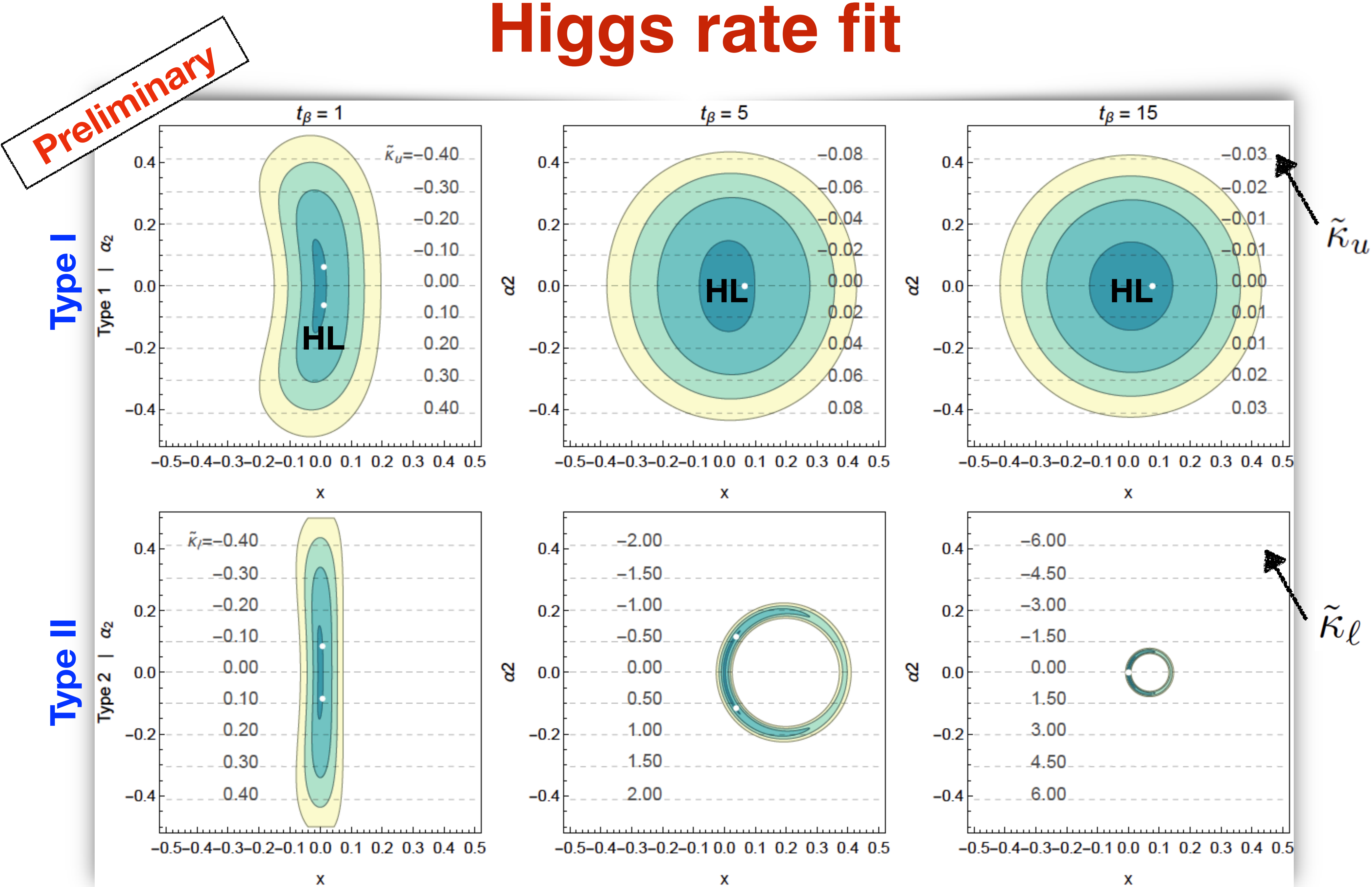
Some rates are easily scaled from the SM predictions:

e.g. $$\Gamma(h_1 \to b\bar{b}) \simeq \Gamma(h \to b\bar{b})_{\rm SM}(|\kappa_d|^2 + |\tilde{\kappa}_d^{(1)}|^2)$$

Some other rates are more complicated: e.g.

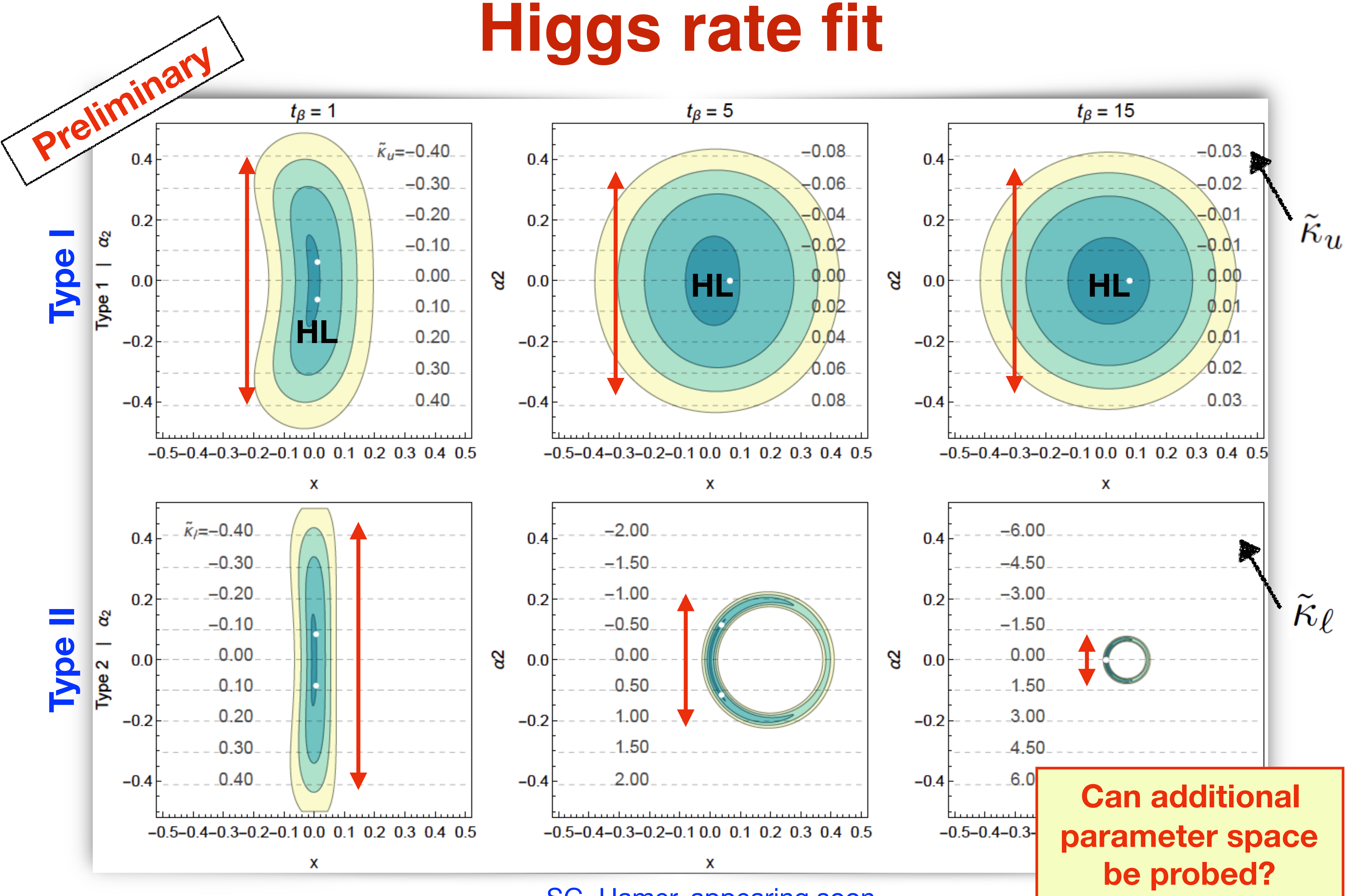
$$\sigma(gg \to h) \simeq \sigma(gg \to h)_{\rm SM} \times$$
$$\times \left(1.1\kappa_u^2 + 3.6 \times 10^{-3}\kappa_d^2 - 0.12\kappa_u\kappa_d + 2.5(\tilde{\kappa}_u^{(1)})^2 + 3.6 \times 10^{-3}(\tilde{\kappa}_d^{(1)})^2 + 0.19\tilde{\kappa}_u^{(1)}\tilde{\kappa}_d^{(1)}\right)$$

Higgs rate fit



SG, Hamer, appearing soon

Higgs rate fit



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Direct searches for Higgs CPV (bosonic)

$$\mathcal{L}_{\rm eff} \supset -\frac{\tilde{g}_{hZZ}}{2}\, hZ_{\mu\nu}\tilde{Z}^{\mu\nu} - \tilde{g}_{hWW}\, hW^{+}_{\mu\nu}\tilde{W}^{-\mu\nu}$$

CP-odd couplings

(arise at **one loop** in the complex 2HDM)

$$\tilde{g}_{hZZ} \simeq -\frac{\sin\alpha_2}{\tan\beta}\,\frac{1}{8\times 10^5\ \mathrm{GeV}}$$

$$\tilde{g}_{hWW} \simeq \frac{\sin\alpha_2}{\tan\beta}\,\frac{1}{7\times 10^5\ \mathrm{GeV}}$$

(*)

CP-even coupling: $hZ_{\mu\nu}Z^{\mu\nu}$

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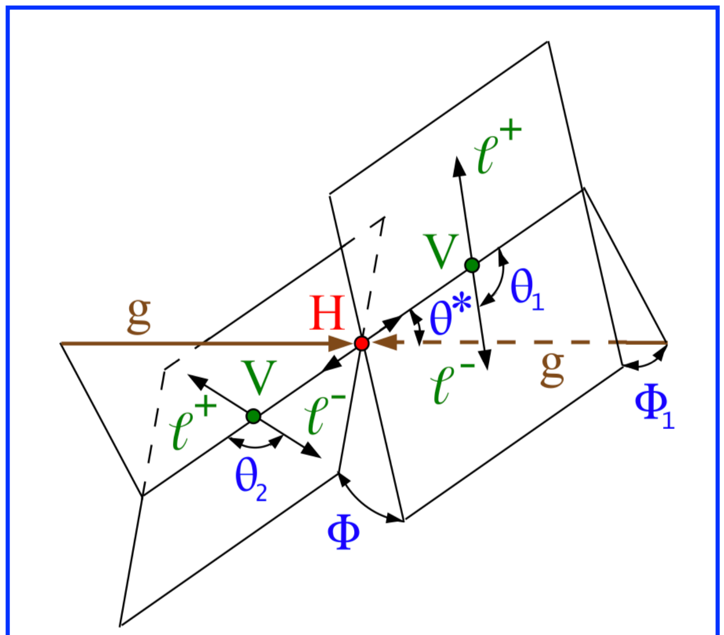
CP-even coupling: $hZ_{\mu\nu}Z^{\mu\nu}$

Searches for:

- h→ZZ* →4l, h→WW* →lvlv;
- h→ττ with the Higgs produced in vector boson fusion;
- h → bb with the Higgs produced in association with a vector boson

$$\begin{cases} \tilde{g}_{hZZ} \lesssim \dfrac{1}{3\times 10^3~\text{GeV}} & \text{(137 fb}^{-1}\text{, CMS PAS HIG-19-009)} \\ \tilde{g}_{hZZ} \lesssim \dfrac{1}{8\times 10^3~\text{GeV}} & \text{(HL-LHC, 1902.00134)} \end{cases}$$



(*) Challenging to probe CPV Higgs mixing angles arising from this minimal 2HDM

Direct searches for Higgs CPV (fermionic)

$$\mathcal{L}_{\rm Yuk} \supset -\frac{m_f}{v}\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$

(arise at **tree level** in the complex 2HDM)

	Type I	Type II
$\tilde{\kappa}_u$	$-\frac{s_{\alpha_2}}{t_\beta}$	$-\frac{s_{\alpha_2}}{t_\beta}$
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- Search for tth, h→γγ: $\left|\frac{\tilde{\kappa}_t}{\kappa_t}\right| \lesssim 0.93$ (139 fb^{-1}, ATLAS, 2004.04545; CMS, 2003.10866)
- Search for $h \to \tau^\pm\tau^\mp$: $\left|\frac{\tilde{\kappa}_\tau}{\kappa_\tau}\right| \lesssim 0.87$ (137 fb^{-1}, CMS PAS HIG-20-006)

Collider E(GeV) $\mathcal{L}$(1/fb)	pp 14.000 300	pp 14.000 3000	e^+e^- 250 250	e^+e^- 350 350	e^+e^- 500 500	e^+e^- 1000 1000
$h\bar{t}t$ $(\tilde{\kappa}_t/\kappa_t)$	0.49	0.22	–	–	0.53	0.28
$h\bar{\tau}\tau$ $(\tilde{\kappa}_\tau/\kappa_\tau)$	0.26	0.09	0.1	0.1	0.14	0.24

adapted from Gritsan et al., 2205.07715

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(arise at **tree level** in the complex 2HDM)

$$\left\{\begin{array}{lcc} \tilde{\kappa}_u & -\frac{s_{\alpha_2}}{t_\beta} & -\frac{s_{\alpha_2}}{t_\beta} \\ \tilde{\kappa}_{d,\ell} & \frac{s_{\alpha_2}}{t_\beta} & -s_{\alpha_2} t_\beta \end{array}\right.$$

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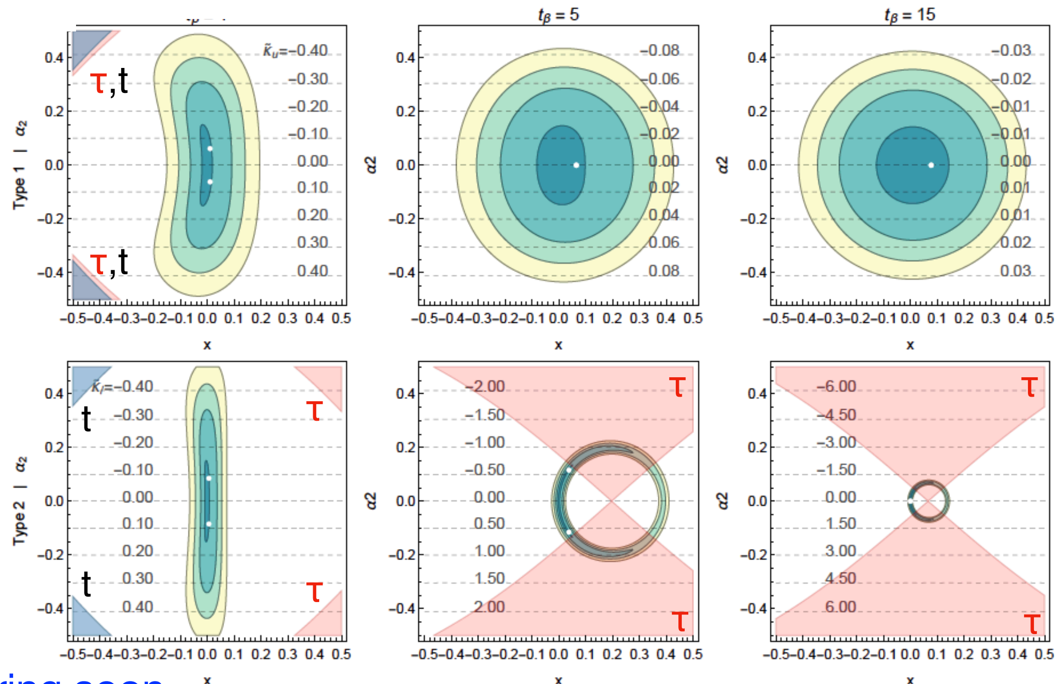
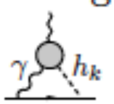
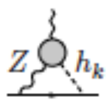
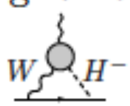
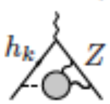
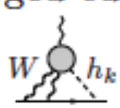


SG, Hamer, appearing soon

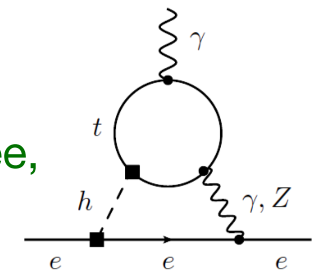
EDMs, a complete 2HDM study

Many contributions to the electron EDM:

Barr-Zee	Fermion loop	Charged Higgs loop	Gauge boson loop
Electromagnetic 	$\delta_f^{\rm EM}$ (24)	$\delta_{H^+}^{\rm EM}$ (27)	$\delta_W^{\rm EM}(\xi)$ (30)
Neutral current 	$\delta_f^{\rm NC}$ (25)	$\delta_{H^+}^{\rm NC}$ (28)	$\delta_W^{\rm NC}(\xi)$ (31)
Charged current 	–	$\delta_{H^+}^{\rm CC}$ (29)	$\delta_W^{\rm CC}(\xi)$ (35)
Kite			
Neutral current 	–	–	$\delta_{\rm kite}^{\rm NC}$ (38)
Charged current 	–	–	$\delta_{\rm kite}^{\rm CC}(\xi)$ (39)

Altmannshofer, SG, Hamer, Patel, 2009.01258

Barr-Zee, 1990



Computed more recently:
Abe et al, 1311.4704

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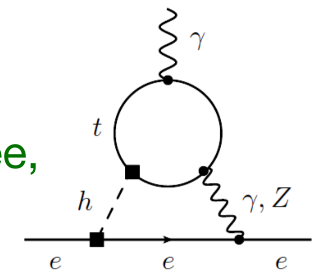
Altmannshofer, SG, Hamer, Patel, 2009.01258

Notice the gauge dependence

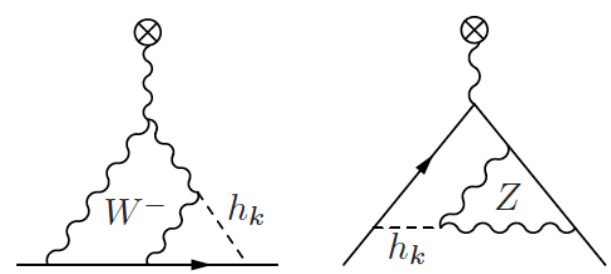
Barr-Zee, 1990



Computed more recently: Abe et al, 1311.4704

New set of diagrams computed for the first time "Kite contributions"

representative diagrams:



EDMs, a complete 2HDM study, gauge dependence

Barr-Zee	Fermion loop	Charged Higgs loop	Gauge boson loop
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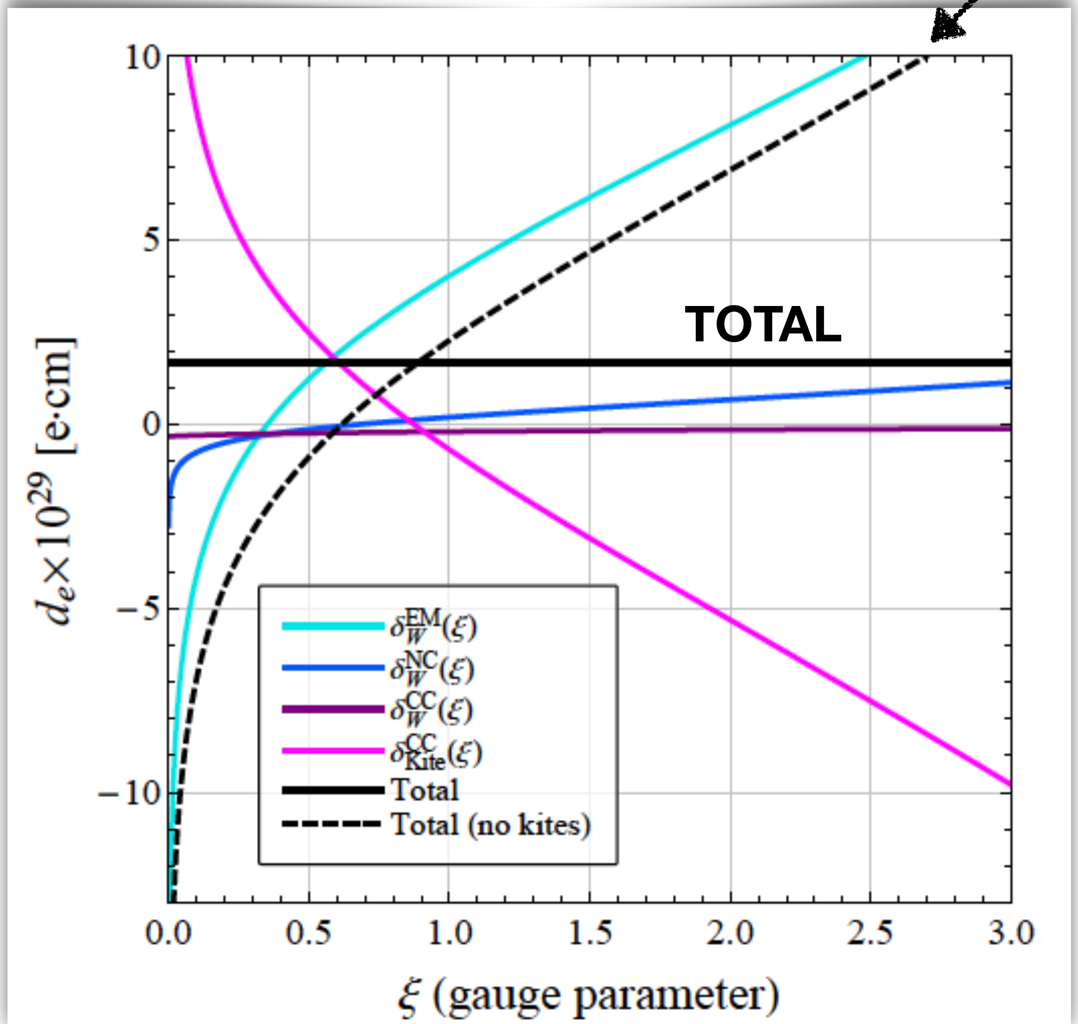
Kite			
Neutral current	–	–	δ_{kite}^{NC} (38)
Charged current	–	–	$\delta_{kite}^{CC}(\xi)$ (39)

Altmannshofer, SG, Hamer, Patel, 2009.01258

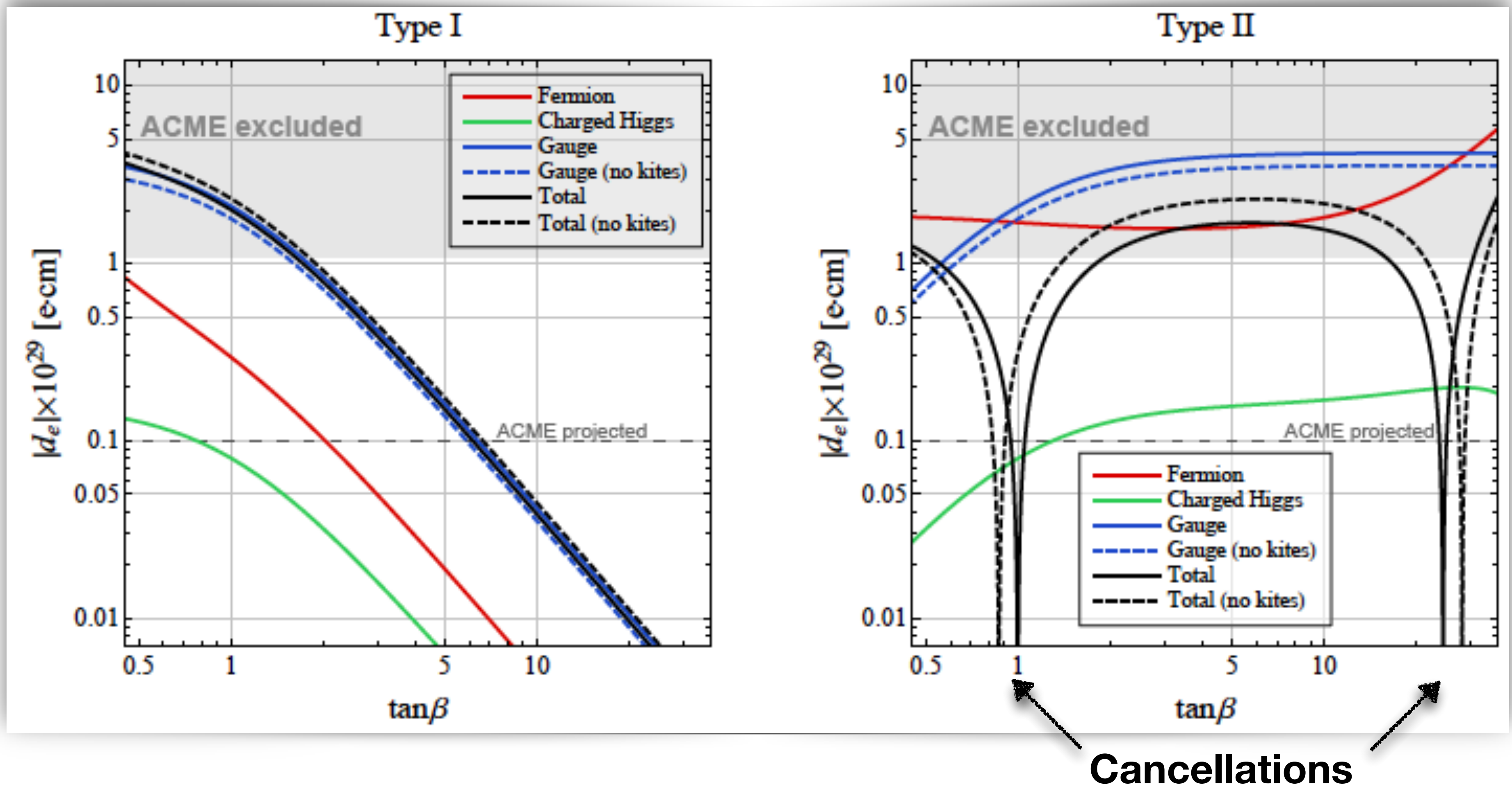
Notice the **gauge dependence** if we do not include the Kite diagrams



EDMs, 2HDM results

Example benchmark:

Altmannshofer, SG, Hamer, Patel, 2009.01258



In the decoupling limit:

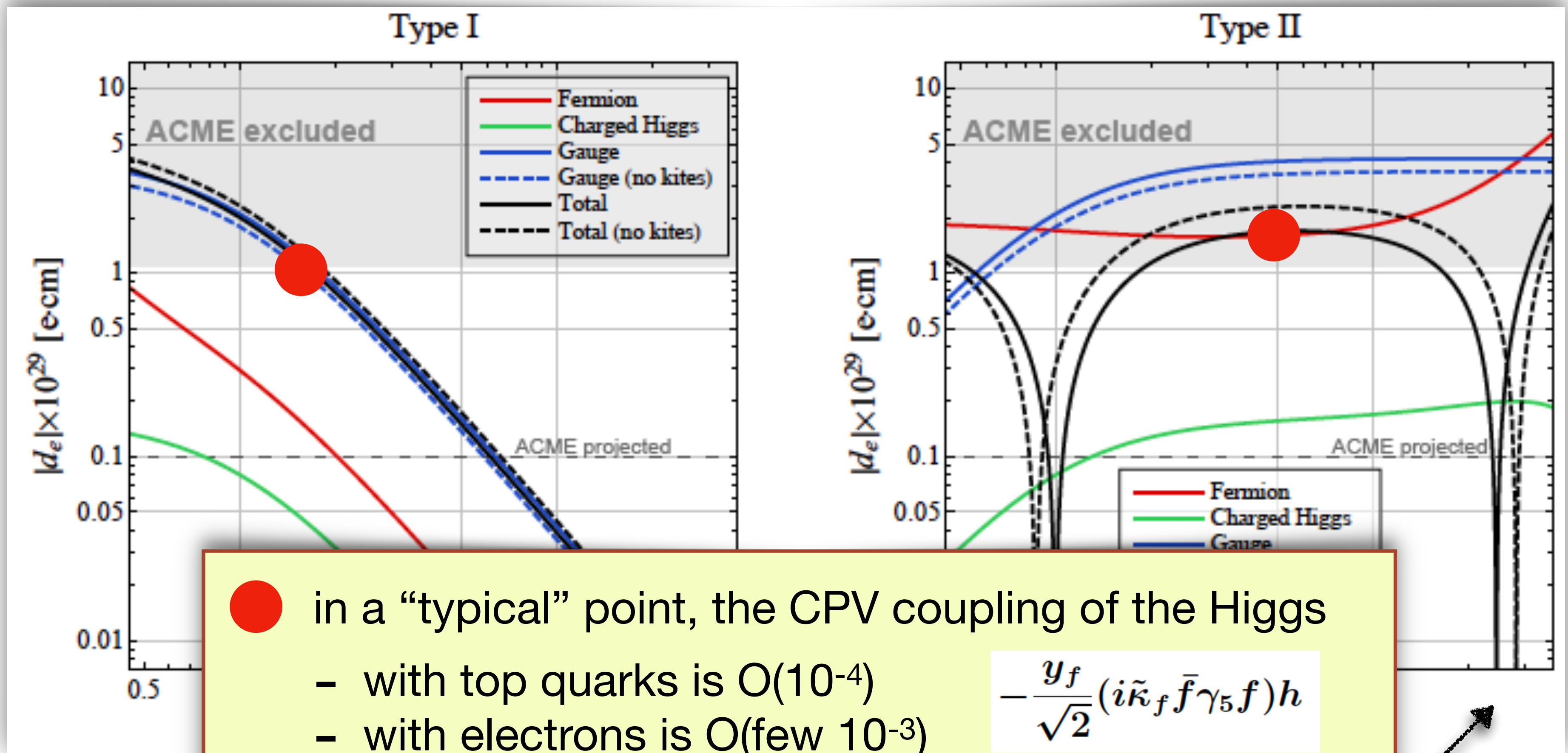
$$\text{Type I:}\quad d_e = -1.06\times 10^{-27}\,e\,\text{cm}\times\left(\frac{1\,\text{TeV}}{M}\right)^2 \text{Im}(\lambda_5)\quad \cos^2\beta\left[1+0.07\ln\left(\frac{M}{1\,\text{TeV}}\right)\right],$$

$$\text{Type II:}\quad d_e = \quad 0.47\times 10^{-27}\,e\,\text{cm}\times\left(\frac{1\,\text{TeV}}{M}\right)^2 \text{Im}(\lambda_5)\left\{\sin^2\beta\left[1+0.16\ln\left(\frac{M}{1\,\text{TeV}}\right)\right]-1.26\cos^2\beta\right\}$$

EDMs, 2HDM results

Example benchmark:

Altmannshofer, SG, Hamer, Patel, 2009.01258



in a “typical” point, the CPV coupling of the Higgs

- with top quarks is O(10^{-4})
- with electrons is O(few 10^{-3})

$$-\frac{y_f}{\sqrt{2}}(i\tilde{\kappa}_f \bar{f}\gamma_5 f)h$$

Cancellations

In the decoupling limit:

$$\text{Type I:} \quad d_e = -1.06 \times 10^{-27} e\,\text{cm} \times \left(\frac{1\,\text{TeV}}{M}\right)^2 \text{Im}(\lambda_5) \quad \cos^2\beta \left[1 + 0.07 \ln\left(\frac{M}{1\,\text{TeV}}\right)\right],$$

$$\text{Type II:} \quad d_e = \quad 0.47 \times 10^{-27} e\,\text{cm} \times \left(\frac{1\,\text{TeV}}{M}\right)^2 \text{Im}(\lambda_5) \left\{\sin^2\beta \left[1 + 0.16 \ln\left(\frac{M}{1\,\text{TeV}}\right)\right] - 1.26 \cos^2\beta\right\}$$

Additional EDM bounds: neutron EDM

$$d_n = (\zeta_n^u \delta_u + \zeta_n^d \delta_d) + (\tilde{\zeta}_n^u \tilde{\delta}_u + \tilde{\zeta}_n^d \tilde{\delta}_d) + \beta_n^G C_{\tilde{G}}$$

Light quark EDMs

Light quark chromo-EDMs

$$\frac{\tilde{\delta}_q}{\Lambda^2} m_q g_s \bar{q} \sigma_{\mu\nu} \gamma_5 T^a q G^{a\mu\nu}$$

Weinberg operator

$$\frac{C_{\tilde{G}}}{2\Lambda^2} g_s f^{abc} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\lambda} G^{b\,\lambda}_{\nu} G^c_{\rho\sigma}$$

Very large theoretical uncertainties

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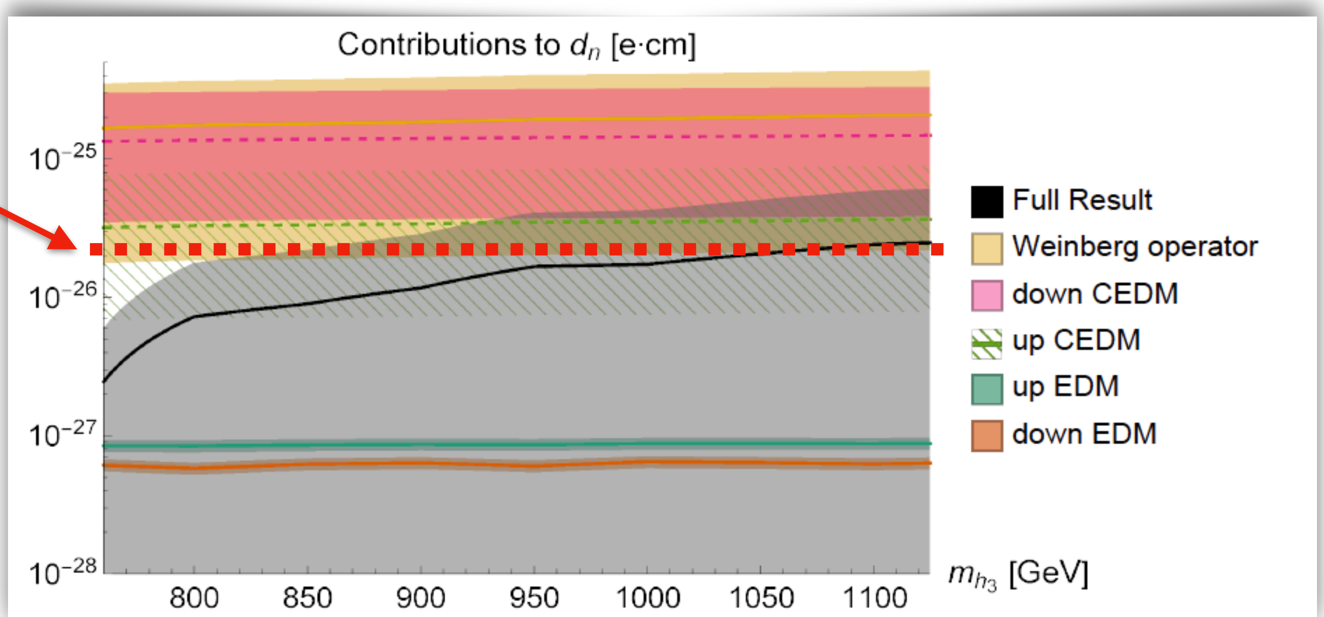
Very large theoretical uncertainties

This is for a benchmark scenario with

$$|\tilde{\kappa}_t| \sim |\tilde{\kappa}_\tau| \sim 0.1$$

exp bound



SG, Hamer, appearing soon

Heavy Higgs pheno. CPV signatures

H_3 and H_2 can lead to striking CPV signatures

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Examples:

- both H_3 and H_2 decaying to WW and ZZ
- $H_3 \to H_2 Z$, $H_2 \to H_1 Z$
- $H_3 \to H_1 H_2$
- …

Signatures not yet looked for: $H_3 \to H_2 Z$, $H_2 \to H_1 Z$ and $H_3 \to H_1 H_2$

Large mass splittings between H_2 and H_3 are needed (for the same two)

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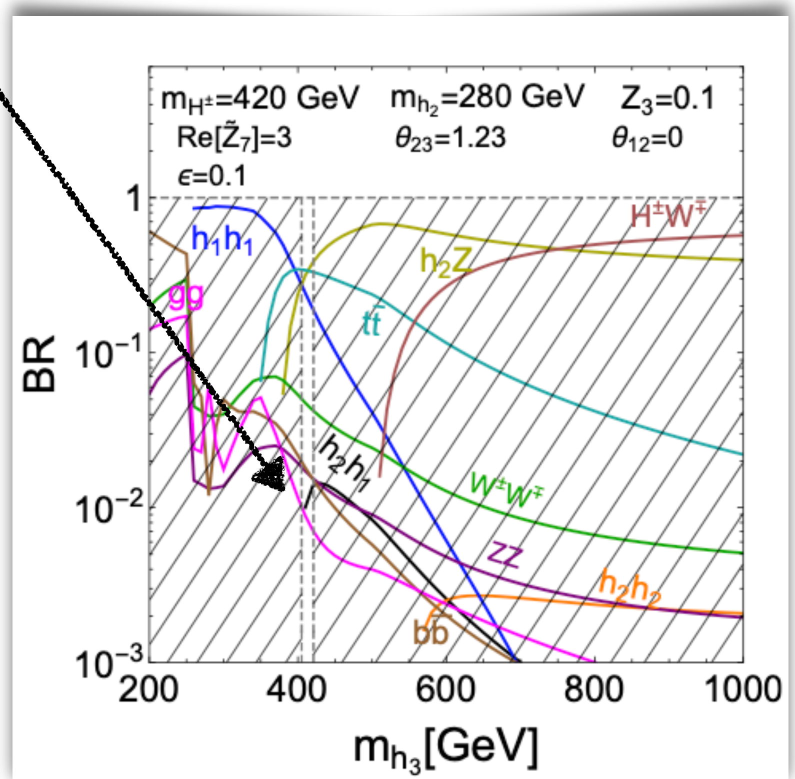

Low, Shah, Wang, 2012.00773.

Theory & pheno constraints on large mass splittings

A large mass splitting between h_3 and h_2 requires **large Higgs quartic couplings**

$$m_{h_3} = m_{h_2} + F[\lambda_i, \beta]\frac{v^2}{m_{h_2}}$$

Constraints from
- perturbativity
- vacuum stability

Possible constraints from **electroweak precision tests**: **m_W!**
However, no New Physics effect on m_W if

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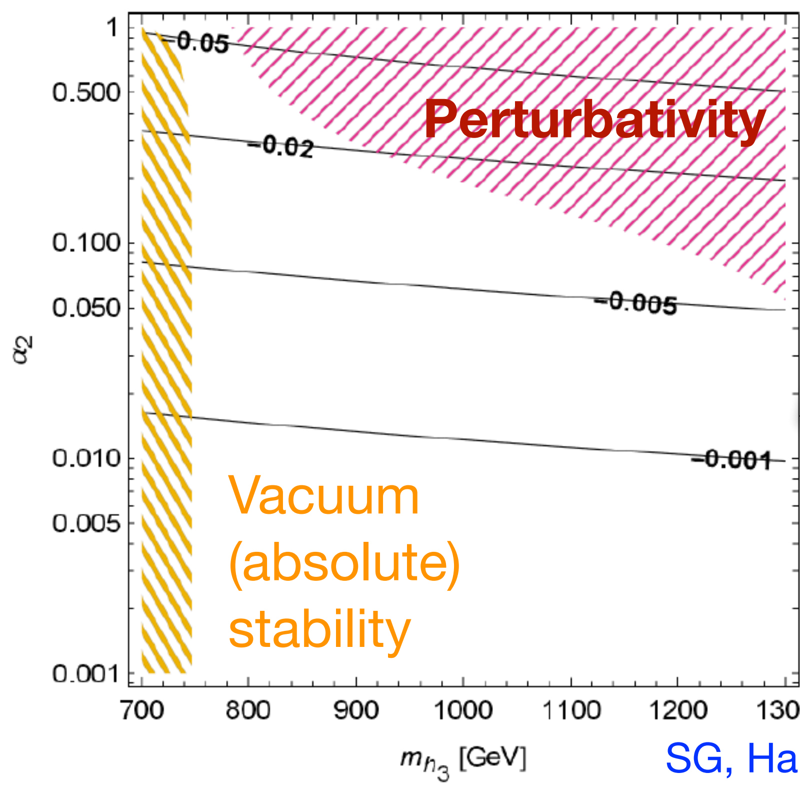


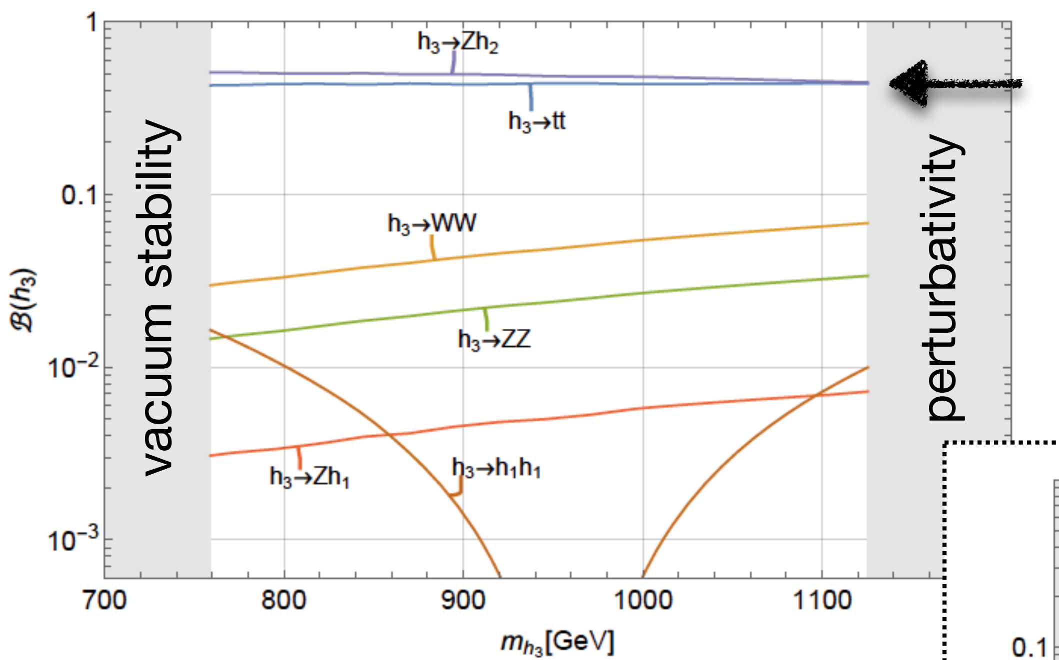
α_3 contours

$$m_{h_2} = m_{h_3} - 320 \text{ GeV}$$
$$x = -0.04$$
$$\tan\beta \sim 1$$

SG, Hamer, appearing soon

New signature: $H_3 \to H_2 Z$, $H_2 \to H_1 Z$ (1)

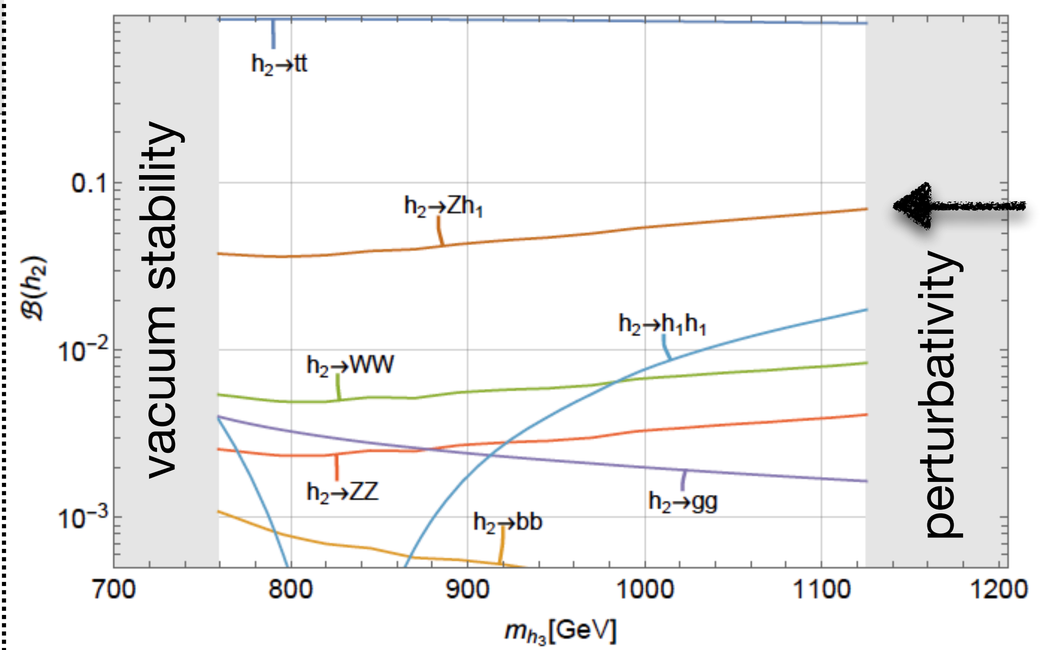
h_3 mainly CP odd



$$\begin{aligned} m_{h_2} &= m_{h_3} - 320 \text{ GeV} \\ x &= -0.04 \\ \tan\beta &\sim 1 \end{aligned}$$

(benchmark allowed by EDMs)

h_2 mainly CP even



$$\mathcal{L}_{\text{gauge}} = \frac{g^2 v}{4} \sum_k g_{h_k VV} \left[2 W_\mu^+ W^{\mu -} + \frac{1}{\cos^2\theta} Z_\mu Z^\mu \right] h_k + \frac{g}{2\cos\theta} Z_\mu \sum_{i<j} g_{Z h_i h_j} \left[h_i \partial^\mu h_j \right]$$

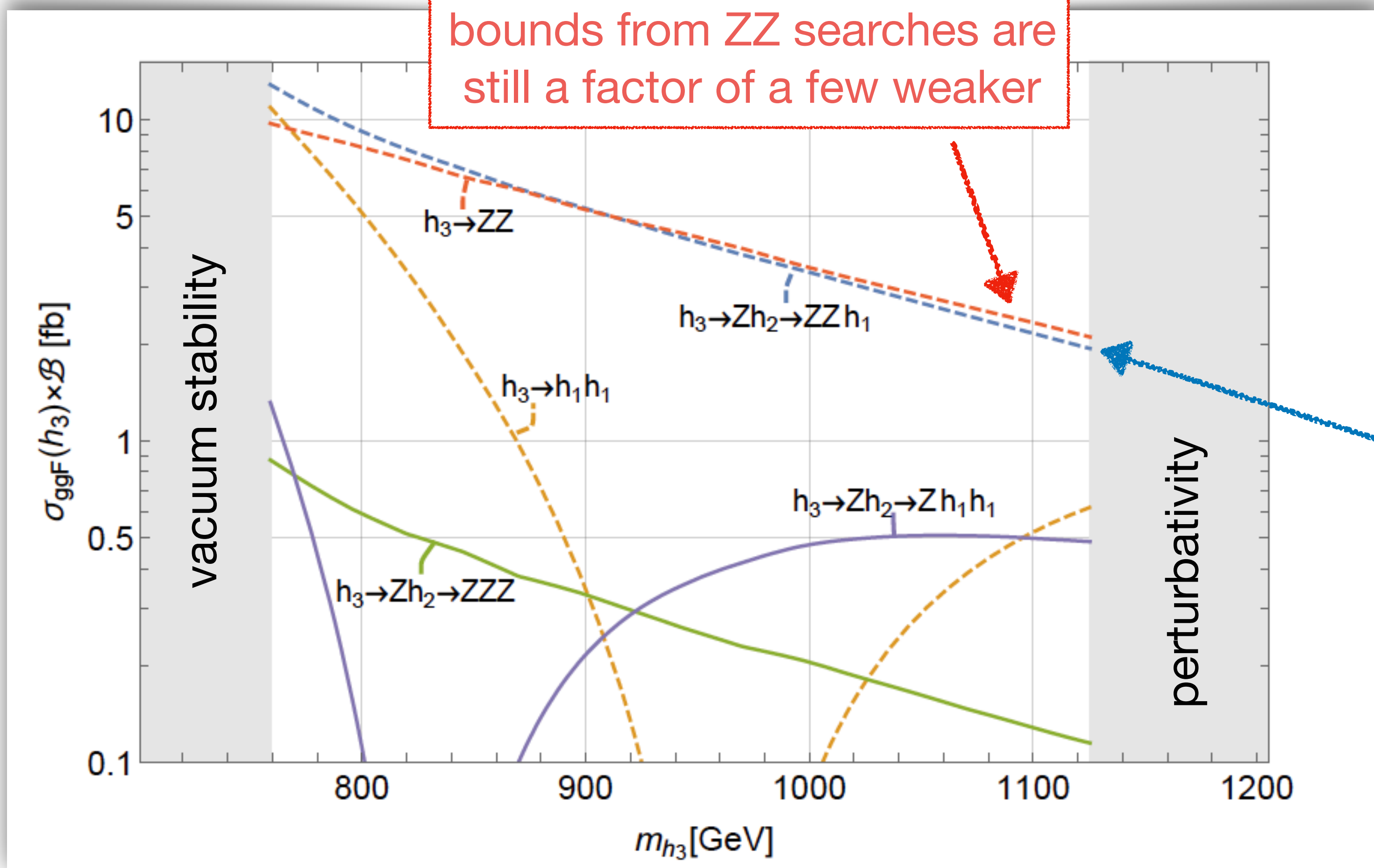
$$g_{Z h_2 h_3} = g_{h_1 VV} \sim 1$$

$$g_{Z h_1 h_2} = g_{h_3 VV}$$

SG, Hamer, appearing soon

New signature: $H_3 \rightarrow H_2 Z$, $H_2 \rightarrow H_1 Z$ (2)

bounds from ZZ searches are still a factor of a few weaker



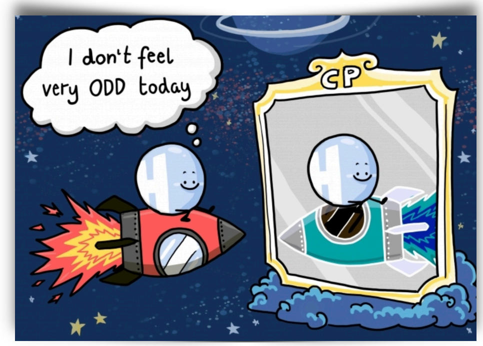
SG, Hamer, appearing soon

Sizable cross sections to be searched for

Dashed lines correspond to signatures that arise only if CPV

Conclusions and outlook

After 10 years since the Higgs boson discovery, there are still many open questions about the nature of the Higgs particle



(image: DESY/designdoppel)

Testing the CP nature of the Higgs should be a goal for the coming years.

Generically, searches for EDMs set very stringent constraints on CPV Higgs couplings

<u>However</u>, there are regions of parameters not probed by EDMs (the example discussed in this talk is the complex 2HDM)

indirect →
* Higgs rate measurements

direct →
* Higgs distributions
* Signals of CPV from additional Higgs bosons ($H_3 \to H_2 Z$, $H_2 \to H_1 Z$, $H_3 \to H_1 H_2$)

← **LHC probes**

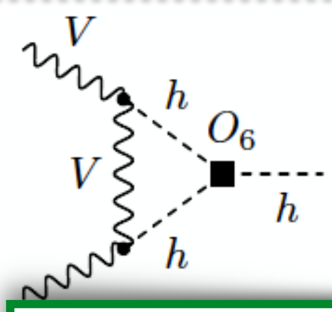
Complementarity

2. Higgs self-couplings and single Higgs

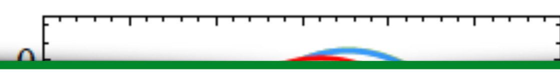
A value of k_λ different from the SM prediction will modify the Higgs couplings the other SM particles and, therefore, single Higgs measurements.

For example, the coupling to W and Z bosons:

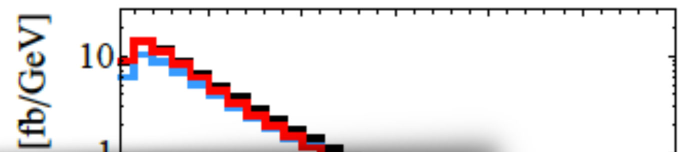
example diagram:



1. VBF and Z/W Higgs associated production cross section will be affected



2. NP effects in differential distributions, as well

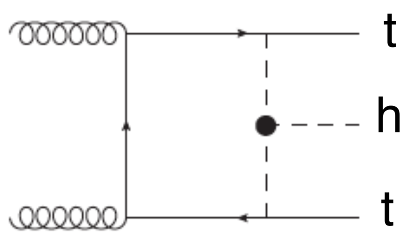


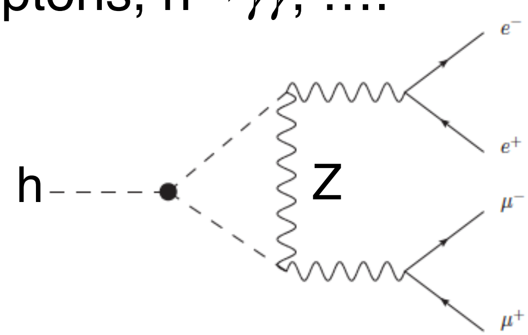
Bizon et al., 1610.05771

Extracted k_λ
with the one
from di-Higg

Maltoni et al., 1709.08649

Many additional single Higgs measurements will be affected:
tth production, h → 4leptons, h→$\gamma\gamma$, ….



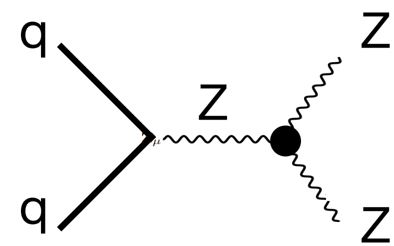


Other indirect probes: di-boson production

Beyond Higgs measurements, measurements of di-boson production can unveil the existence of new sources of CPV in triple gauge couplings

For example:

$$\mathcal{L}_{\rm eff} \supset \frac{\tilde{\kappa}_{ZZZ}}{m_Z^2} \partial_\mu Z_\nu \partial^\mu Z^\rho \partial_\rho Z^\nu$$

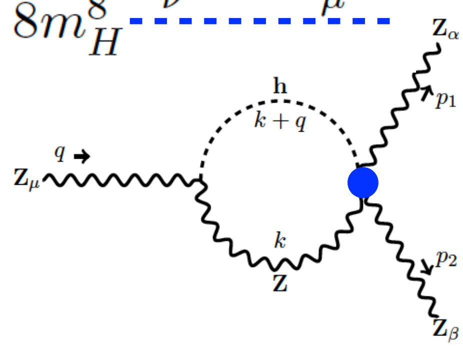


this CPV operator enters eg. the pp → ZZ production (together with CP conserving operators)

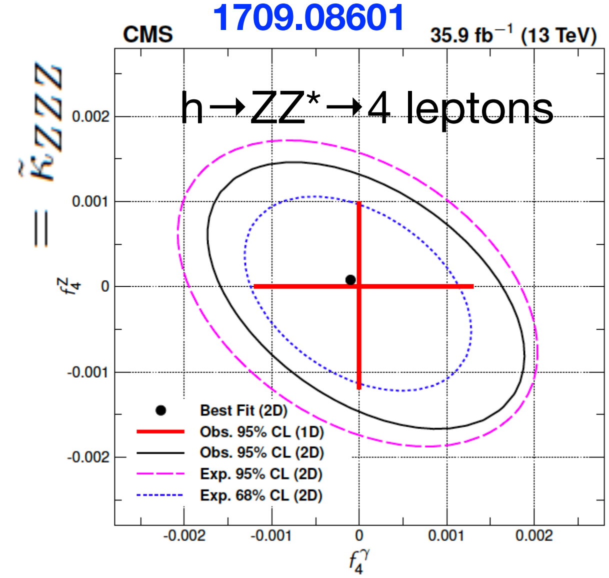
For a 2HDM realization,
see Belusca-Maito et al. 1710.05563:

$$\mathcal{L}_{\rm SMEFT} \supset {\rm Im}\left(Z_5^* Z_6^2\right) \left(\frac{g}{c_W}\right)^3 \frac{v^7}{8 m_H^8} \partial_\nu h Z^\nu Z_\mu Z^\mu$$

Parameters of the 2HDM potential



1709.08601



S.Gori

Backup

Additional CPV Higgs coupling probes

An (incomplete) list…

tt Goncalves, Kim, Kong, Wu [2108.01083]

htt, h →bb. Uses boosted Higgs regime and fat-jets to be Higgs-tagged via the BDRS algorithm.

Zγ Farina, Grossman, Robinson [1503.06470]

Takes advantage of interference between continuum background and signal from gluon initiated events.

gg Dolan, Harris, Jankowiak, Spannowsky [1406.3322]

gg → hjj, h → τ τ. Uses associated jets for angular analysis.

γγ Bishara, Grossman, Harnik, Robinson, Shu, Zupan [1312.2955]

Requires converted photons and angular resolution on leptonic opening angles.