Higgs and CP violation

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UC Santa Cruz

Higgs hunting 2021

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Plan of the talk

1. Main question & Introduction :

Can the Higgs have (hidden) CP violating (CPV) couplings?

Experimental status of the searches for an electron EDM

2. Indirect constraints on CPV Higgs couplings

- EDM constraints: a complete (gauge invariant) calculation
- Higgs rate measurements

3. Direct constraints on CPV Higgs couplings

- Differential distributions in Higgs boson productions / decays
- Possible new searches for heavy CPV Higgs bosons

Focusing on 2HDMs

Main references for this talk

Altmannshofer, SG, Hamer, Patel, 2009.01258

SG, Hamer, in preparation (21xx.xxxxx)

Higgs and CP violation

In the Standard Model (SM),

- 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.

Baryon asymmetry (typically) requires new sources of CPV

EDMs, experimental status & prospects

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

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

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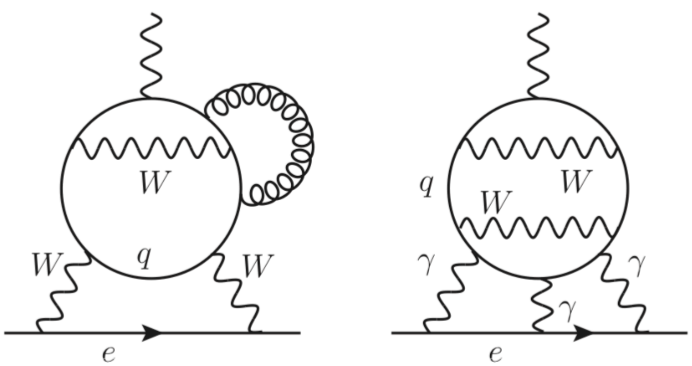
example diagrams in the Standard Model:



d_e: ACME collaboration — ACME collaboration

d_μ: g-2 collaboration — EDM experiment @ PSI

d_τ: Belle collaboration — Belle II & e^+e^- experiments

EDMs, experimental status & prospects

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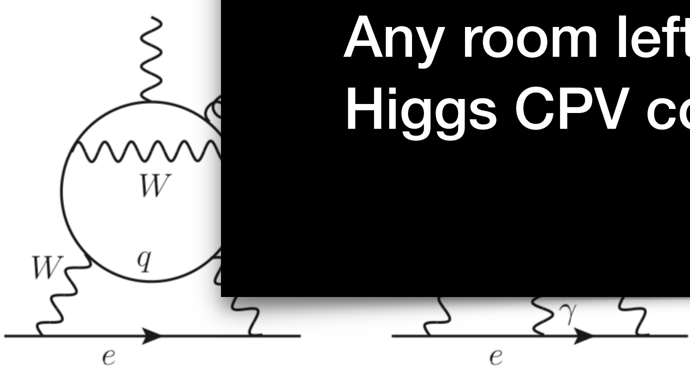
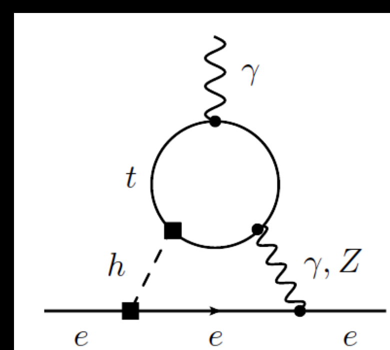
exa
in the



Any room left for
Higgs CPV couplings?



CME
llaboration

M experiment
PSI

lle II &
e^+e^- experiments

Chapter 2:

Indirect probes of Higgs CPV couplings

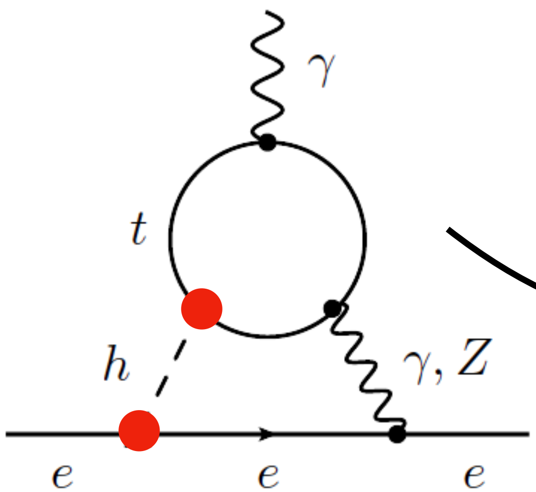
- Electron EDM
- Higgs rate measurements

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

$$|\tilde{\kappa}_e| \lesssim 1.7 \times 10^{-2}$$
$$|\tilde{\kappa}_t| \lesssim 1.0 \times 10^{-2}$$

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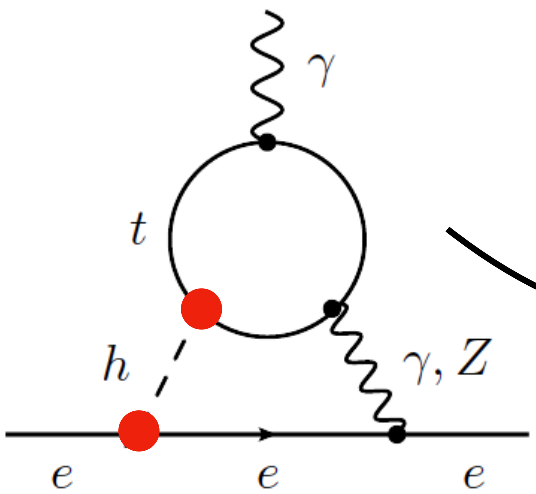

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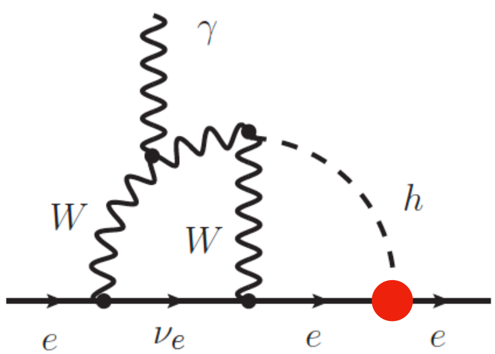
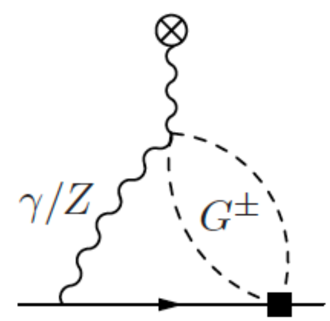


For the first time computed in Altmannshofer et al, 1503.04830

Gauge-dependent contributions to the EDM.

To achieve a gauge invariant result, one needs to add diagrams like:



UV-divergent.

Problem of EFT approach

Altmannshofer, SG, Hamer, Patel, 2009.01258

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

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

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):

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

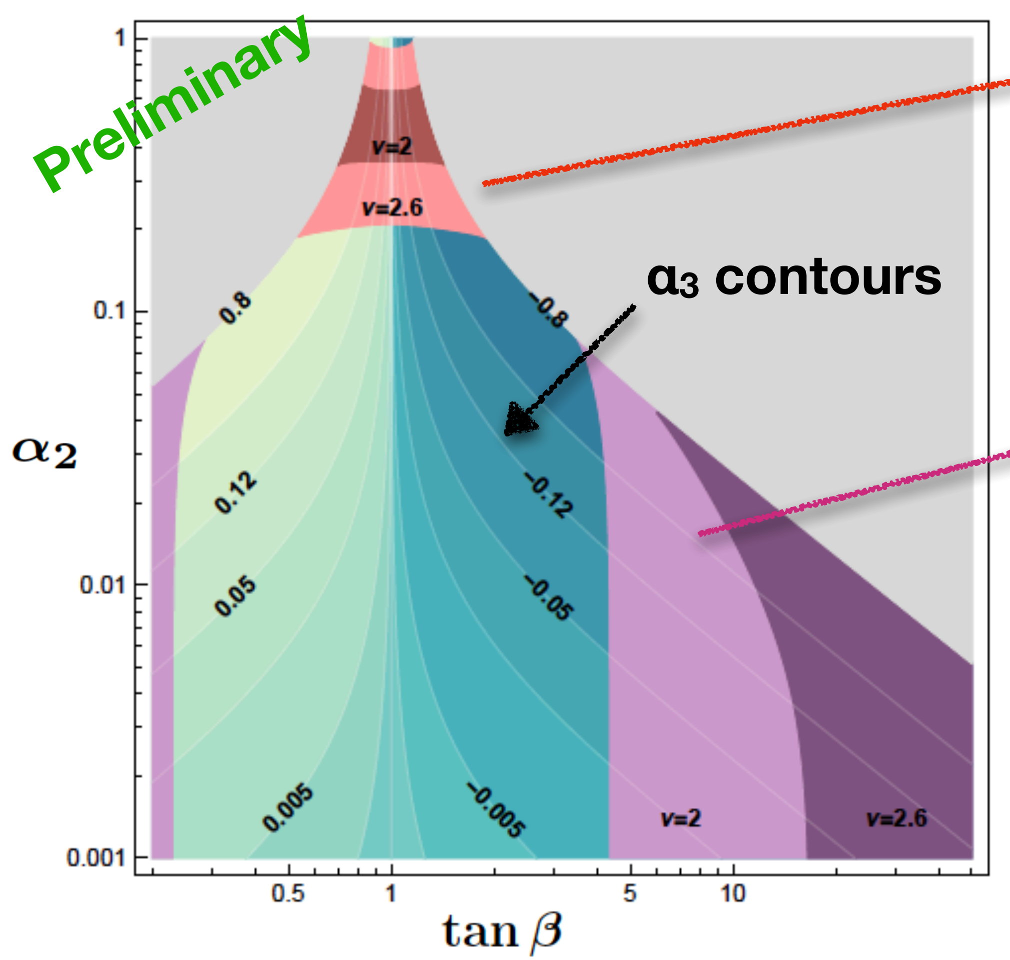
$$\nu \equiv \frac{\text{Re}(m_{12}^2)}{v^2 \sin 2\beta}, \quad \alpha = \beta - \pi/2 + x$$

α_3 will be a function of these parameters

Not all parameters are good parameters

Once the spectrum is fixed, the mixing angles cannot be arbitrary.

SG, Hamer, in progress



α₃ contours

Vacuum (absolute) stability

Perturbativity

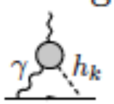
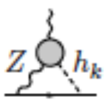
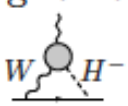
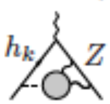
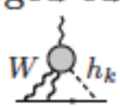
$$\lambda_1 = \frac{m_{h_1}^2 \sin^2\alpha \cos^2\alpha_2 + m_{h_2}^2 \mathcal{R}_{21}^2 + m_{h_3}^2 \mathcal{R}_{31}^2}{v^2\cos^2\beta} - \nu \tan^2\beta$$

$$\lambda_2 = \frac{m_{h_1}^2 \cos^2\alpha \cos^2\alpha_2 + m_{h_2}^2 \mathcal{R}_{22}^2 + m_{h_3}^2 \mathcal{R}_{32}^2}{v^2\sin^2\beta} - \nu \cot^2\beta$$

$$(m_{h_1}, m_{h_2}, m_{h_3}, m_{H^\pm}) = (125, 400, 450, 420)\,\mathrm{GeV}, \quad x = 0$$

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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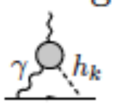
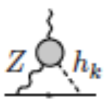
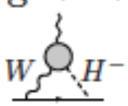
Electromagnetic 	$\delta_f^{\rm EM}$ (24)	$\delta_{H+}^{\rm EM}$ (27)	$\delta_W^{\rm EM}(\xi)$ (30)
Neutral current 	$\delta_f^{\rm NC}$ (25)	$\delta_{H+}^{\rm NC}$ (28)	$\delta_W^{\rm NC}(\xi)$ (31)
Charged current 	–	$\delta_{H+}^{\rm CC}$ (29)	$\delta_W^{\rm CC}(\xi)$ (35)
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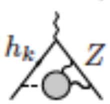
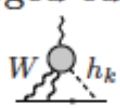
Neutral current 	–	–	$\delta_{\rm kite}^{\rm NC}$ (38)
Charged current 	–	–	$\delta_{\rm kite}^{\rm CC}(\xi)$ (39)

Altmannshofer, SG, Hamer, Patel, 2009.01258

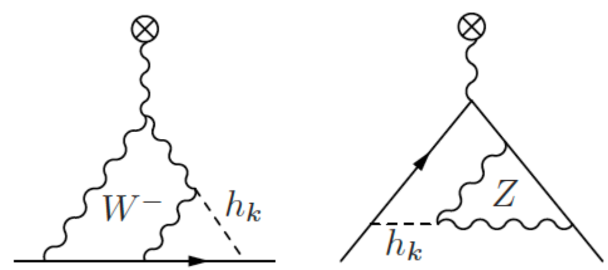
◯ Note the gauge dependence

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

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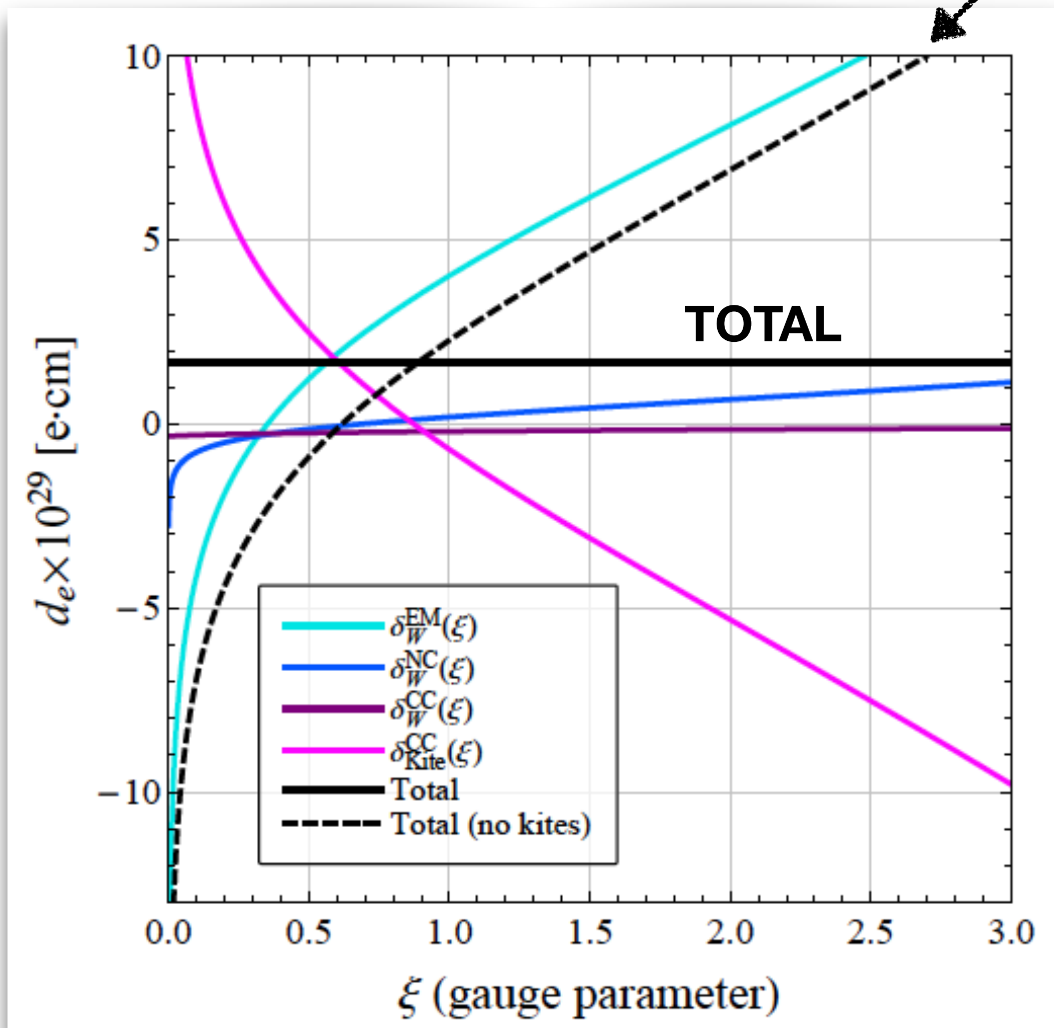
Altmannshofer, SG, Hamer, Patel, 2009.01258

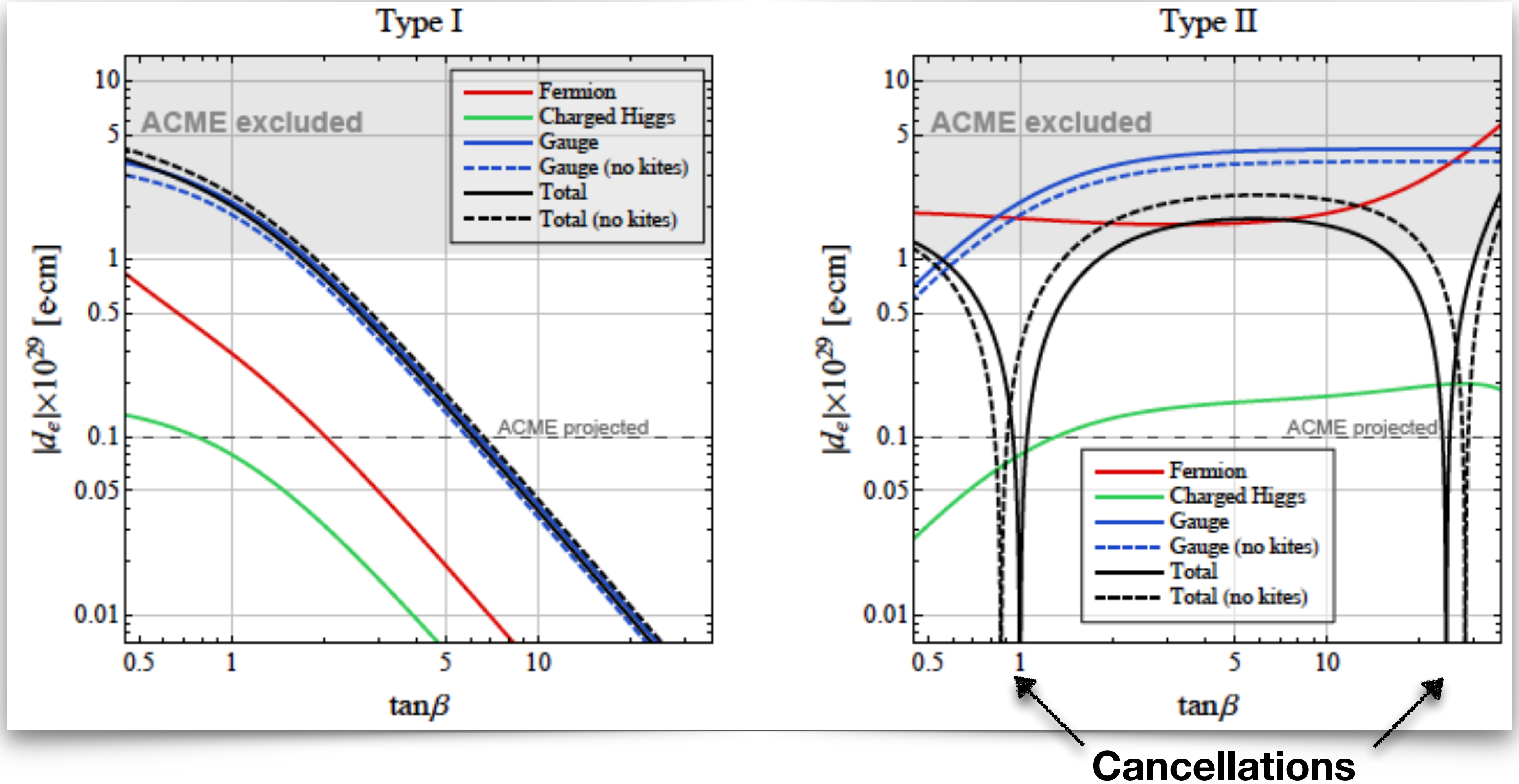
Notice the **gauge dependence** if we do not include the Kite diagrams



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

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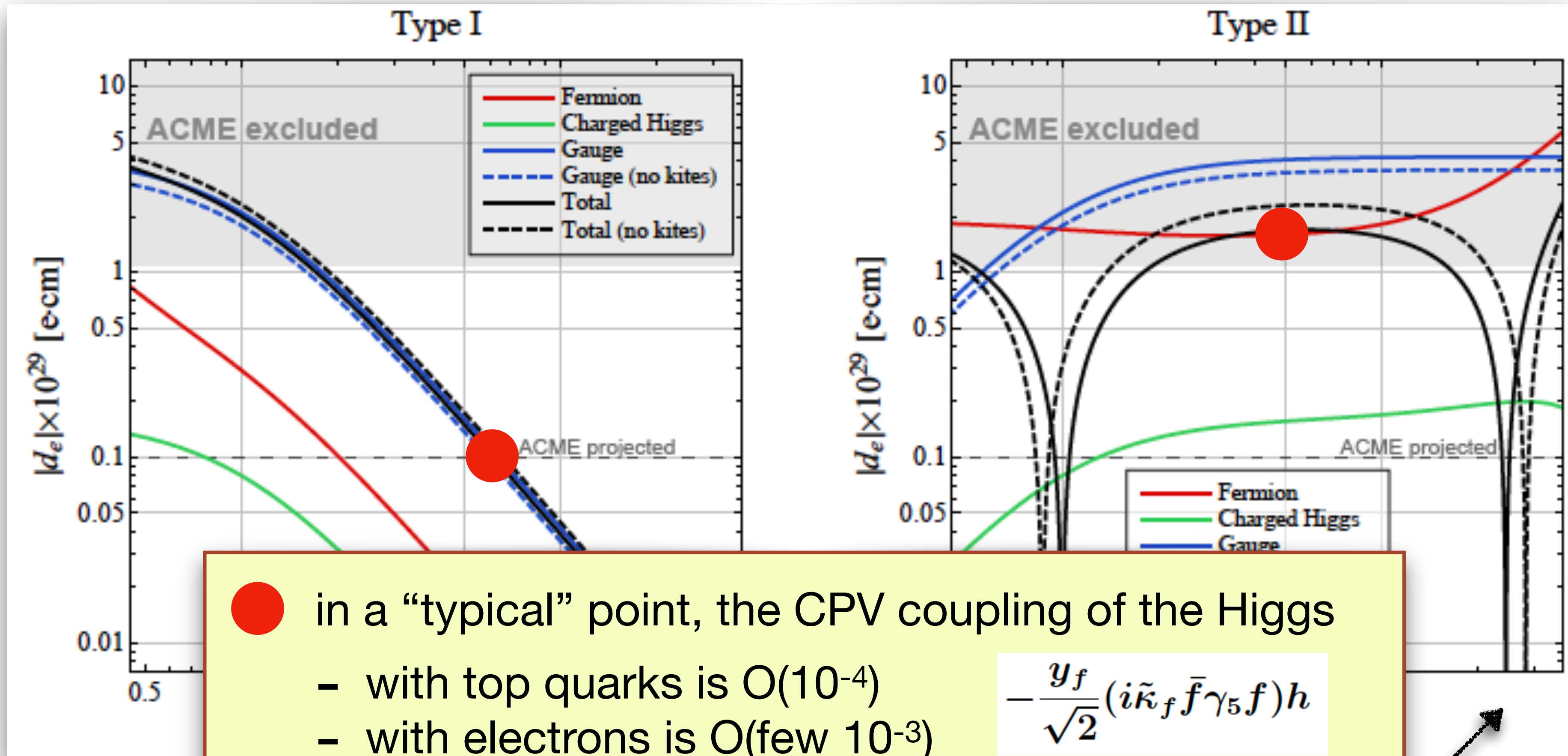

- in a "typical" point, the CPV coupling of the Higgs
  - with top quarks is O(10^{-4})
  - with electrons is O(few 10^{-3})

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

Cancellations

In the decoupling limit:

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Other indirect probes: Higgs rate measurements (1)

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

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
$\kappa_u^{(1)}$	$\frac{c_{\alpha_2} c_\alpha}{s_\beta}$	$\frac{c_{\alpha_2} c_\alpha}{s_\beta}$
$\kappa_{d,\ell}^{(1)}$	$\frac{c_{\alpha_2} c_\alpha}{s_\beta}$	$-\frac{c_{\alpha_2} s_\alpha}{c_\beta}$
$\tilde{\kappa}_u^{(1)}$	$-\frac{s_{\alpha_2}}{t_\beta}$	$-\frac{s_{\alpha_2}}{t_\beta}$
$\tilde{\kappa}_{d,\ell}^{(1)}$	$\frac{s_{\alpha_2}}{t_\beta}$	$-s_{\alpha_2} t_\beta$

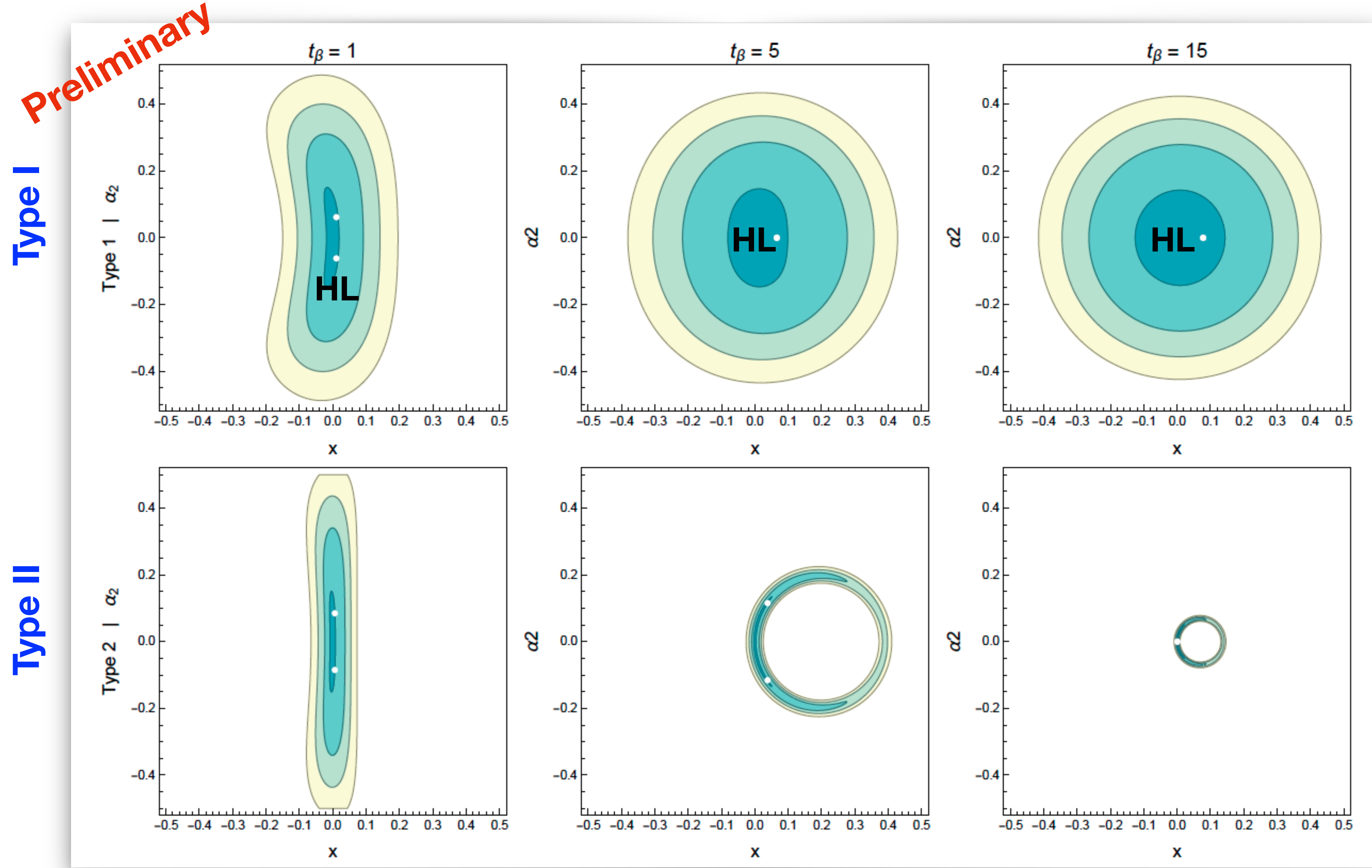
Some rates are easily scaled from the SM predictions:

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.

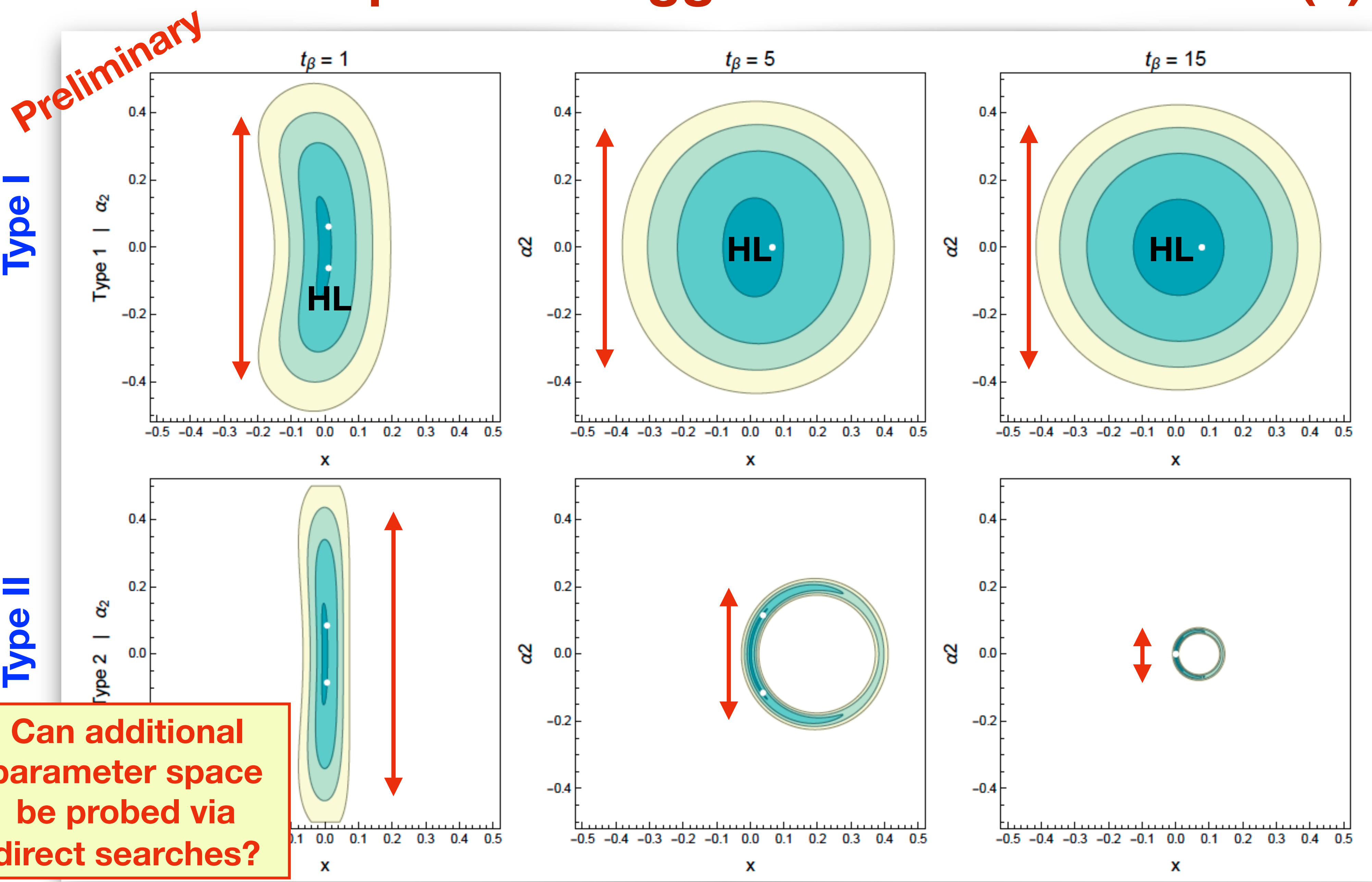
$$\sigma(gg \to h) \simeq \sigma(gg \to h)_{\rm SM} \times$$
$$\times\,(1.1\kappa_u^2 + 3.6 \times 10^{-3}\kappa_d^2 - 0.12\kappa_u\kappa_d + 2.5(\tilde{\kappa}_u^{(1)})^2 + 3.6 \times 10^{-3}(\tilde{\kappa}_d^{(1)})^2 + 0.19\tilde{\kappa}_u^{(1)}\tilde{\kappa}_d^{(1)})$$

Other indirect probes: Higgs rate measurements (2)



SG, Hamer, in progress

Other indirect probes: Higgs rate measurements (2)



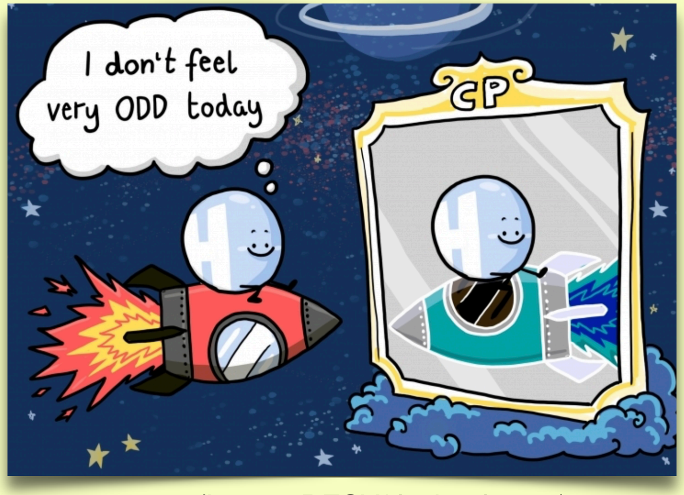
Can additional parameter space be probed via direct searches?

SG, Hamer, in progress

Chapter 3:

Direct probes of Higgs CPV couplings

- Higgs distributions
- Signals of CPV from additional Higgs bosons



(image: DESY/designdoppel)

Direct searches for Higgs CPV (bosonic)

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

(arising at one loop in the complex 2HDM)

$$\begin{cases} \tilde{g}_{hZZ} \simeq -\frac{\sin\alpha_2}{\tan\beta} \frac{1}{6\times 10^5 \text{ GeV}} \\ \tilde{g}_{hWW} \simeq \frac{\sin\alpha_2}{\tan\beta} \frac{1}{5\times 10^5 \text{ GeV}} \end{cases}$$ (*)

Direct searches for Higgs CPV (bosonic)

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

(arising at one loop in the complex 2HDM)

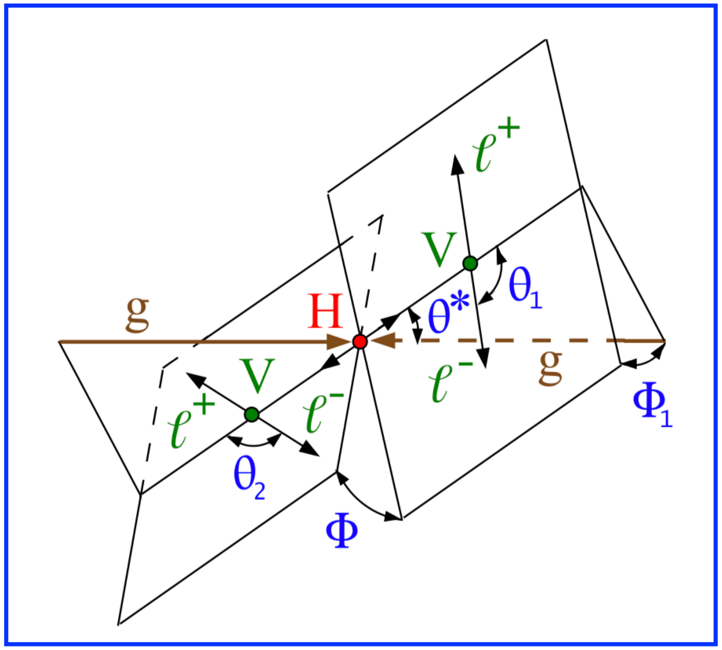
$$\begin{cases} \tilde{g}_{hZZ} \simeq -\dfrac{\sin\alpha_2}{\tan\beta}\dfrac{1}{6\times 10^5\ \mathrm{GeV}} \\ \tilde{g}_{hWW} \simeq \dfrac{\sin\alpha_2}{\tan\beta}\dfrac{1}{5\times 10^5\ \mathrm{GeV}} \end{cases} \quad (*)$$

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

$$\tilde{g}_{hZZ} \lesssim \frac{1}{3\times 10^3\ \mathrm{GeV}}$$ (137 fb^{-1}, CMS PAS HIG-19-009)

$$\tilde{g}_{hZZ} \lesssim \frac{1}{8\times 10^3\ \mathrm{GeV}}$$ (HL-LHC, 1902.00134)



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

Direct searches for Higgs CPV (fermionic)

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

(arising at tree level in the complex 2HDM)

	Type I	Type II
$\tilde{\kappa}_u$	$-\frac{s_{\alpha_2}}{t_\beta}$	$-\frac{s_{\alpha_2}}{t_\beta}$
$\tilde{\kappa}_{d,\ell}$	$\frac{s_{\alpha_2}}{t_\beta}$	$-s_{\alpha_2} t_\beta$

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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 $h \to \tau^\pm\tau^\mp$: $\left|\frac{\tilde{\kappa}_\tau}{\kappa_\tau}\right| \lesssim 0.73$ (137 fb−1, CMS PAS HIG-20-006)

1804.01241

ILC, 250 GeV, 2ab-1:
angle can be measured with a 4.3° precision
$\sim |\tilde{\kappa}/\kappa|$

1703.04855

CEPC, 250 GeV, 5ab-1:
angle can be measured with a 2.9° precision
$\sim |\tilde{\kappa}/\kappa|$

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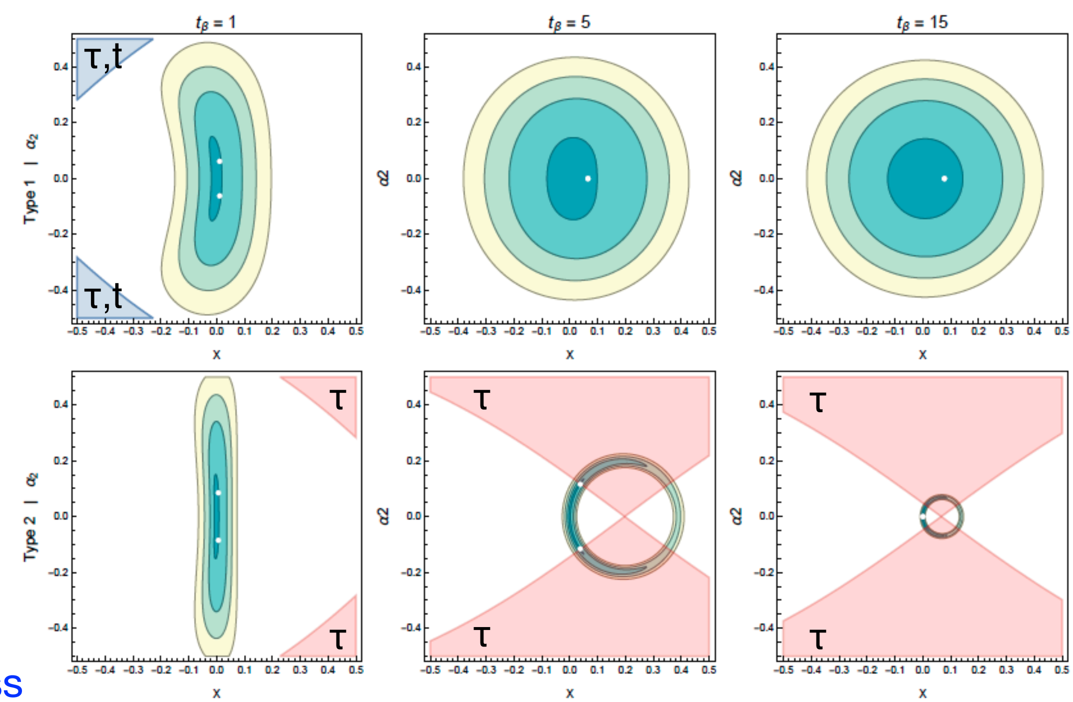

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SG, Hamer, in progress

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.

Heavy Higgs pheno. CPV signatures

H_3 and H_2 can lead to striking CPV signatures

Examples:

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

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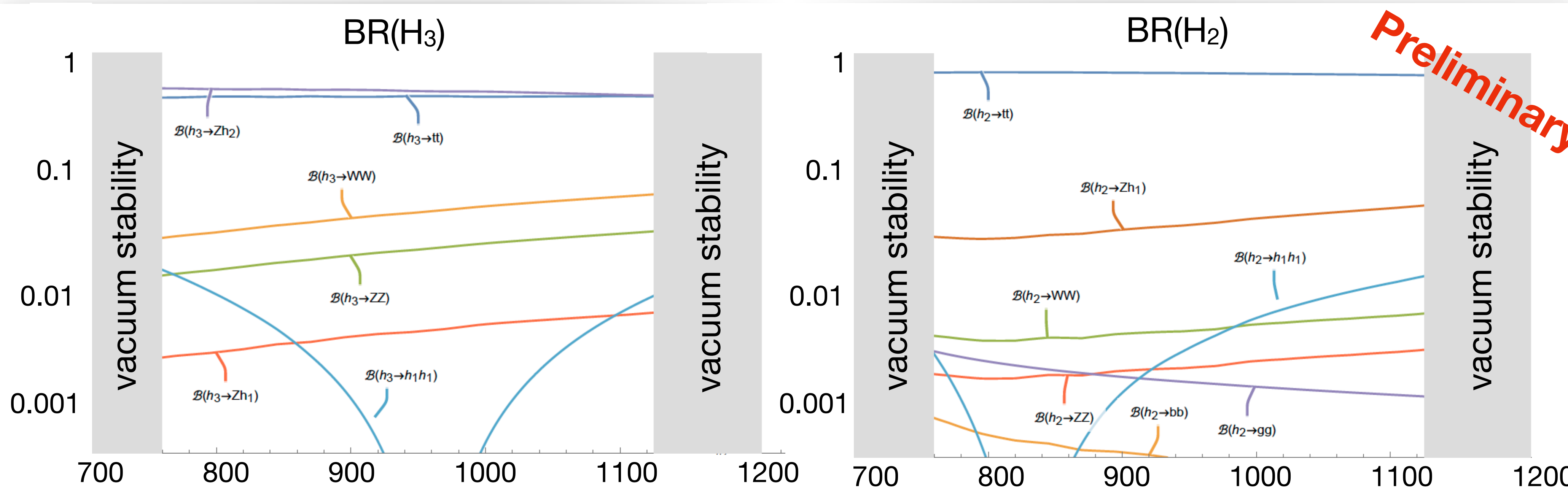
- $H_3 \to H_1 H_2$
- …

Electroweak precision tests ✓
Higgs rates ✓
Electron EDM ✓

Example benchmark (type II): $m_{h_2} = m_{h_3} - 320\ \text{GeV},\ m_{H^\pm} = m_{h_3} + 7\ \text{GeV},$
$x = -0.04,\ \alpha_2 = 0.125,\ \lambda_2 = 3,\ \tan\beta \sim 1$

SG, Hamer, in progress



Rates for the heavy Higgs CPV signatures

$m_{h_2} = m_{h_3} - 320$ GeV, $m_{H^\pm} = m_{h_3} + 7$ GeV,
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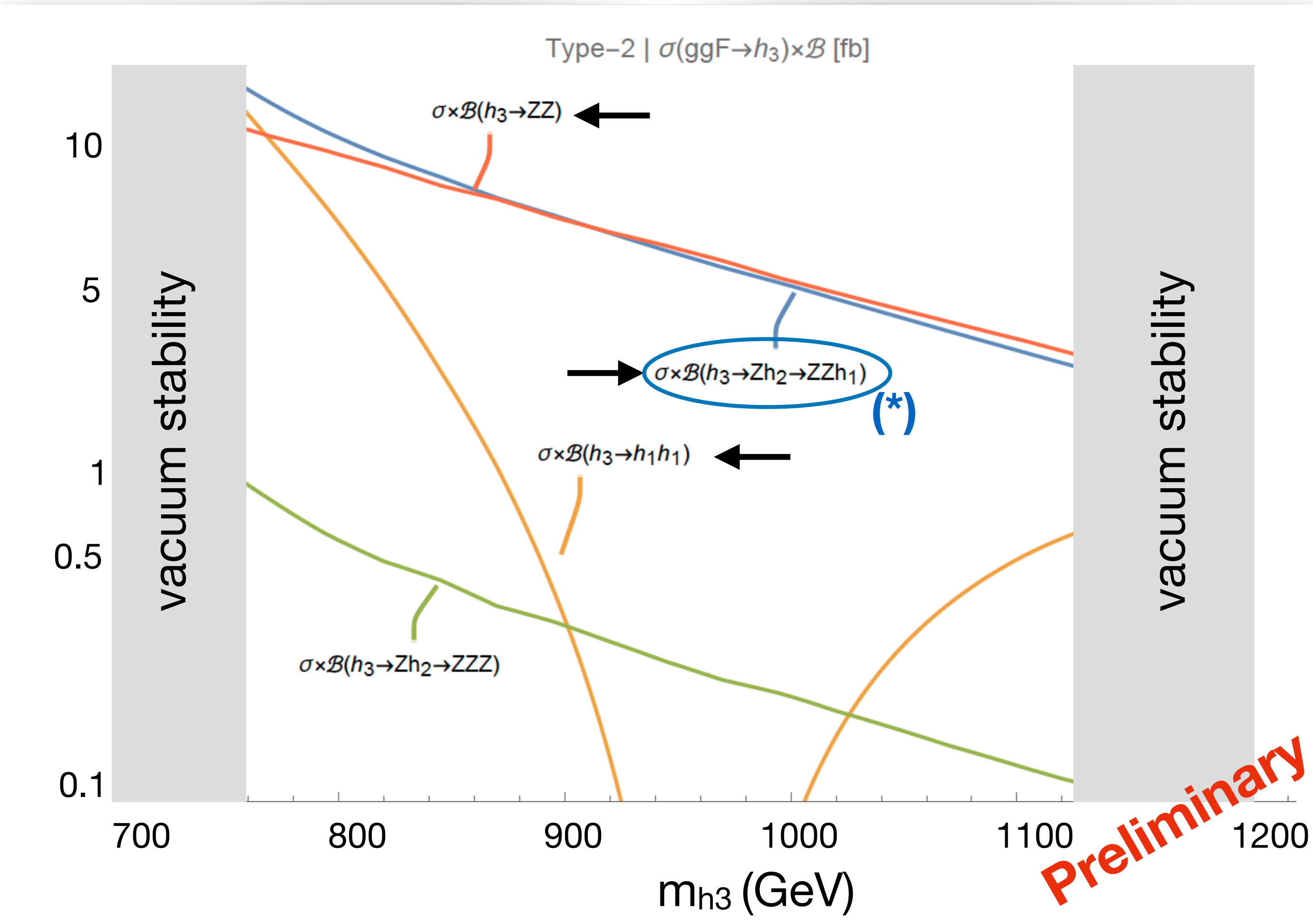


SG, Hamer, in progress

(*) new proposed search

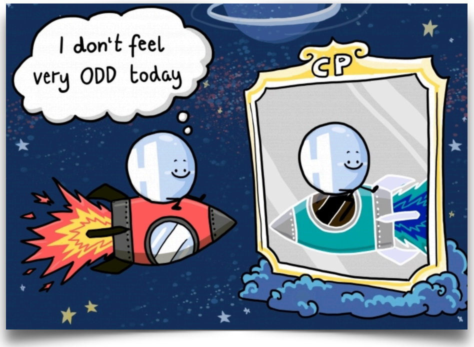
→ CPV decays

Some part of the parameter space is already probed by direct searches.

For the specific benchmark, the most relevant constraint comes from searches for pp→ttH$_{(2)}$, H$_{(2)}$ →tt

$$m_{H3} \gtrsim 700 \text{ GeV}$$

Conclusions and outlook



(image: DESY/designdoppel)

Testing the CP nature of the Higgs should be a high priority 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 → direct

- Higgs rate measurements

- Higgs distributions
- Signals of CPV from additional Higgs bosons

← **LHC probes**

($H_3 \to H_2 Z$, $H_2 \to H_1 Z$
$H_3 \to H_1 H_2$)

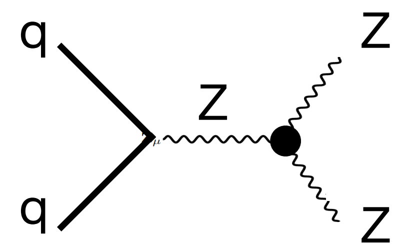
Complementarity

Other indirect probes: di-boson production

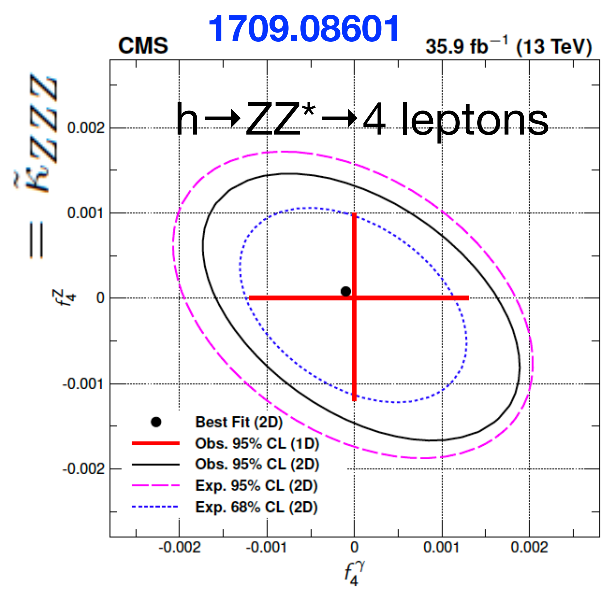
Beyond Higgs measurements, measurements of di-boson production can unveil the existence of new sources of CPV in triple gauge couplings

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)

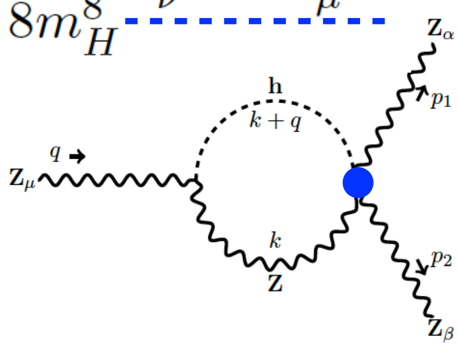


For a 2HDM realization,

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



S.Gori

Backup