Testing the CP nature of the Higgs boson

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Plan of the talk

1. Main question & Introduction :

Can the Higgs still 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
- Di-boson production

Focusing on 2HDMs

3. Direct constraints on CPV Higgs couplings

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

Main references for this talk

Altmannshofer, SG, Hamer, Patel, 2009.01258

SG, Hamer, in preparation (2104.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

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

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

observable	SM theory	current exp.	projected sens.
d_e	$< 10^{-44}$ e cm	$< 1.1 \times 10^{-29}\, e\,\text{cm}$	$\sim 10^{-30}\, e\,\text{cm}$
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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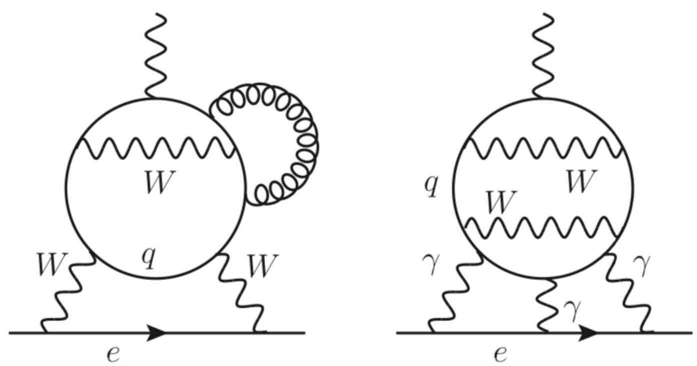
example diagrams in the Standard Model:



d_e: ACME collaboration

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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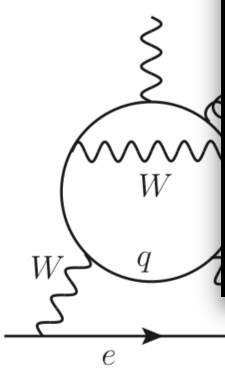
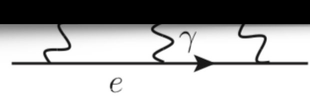
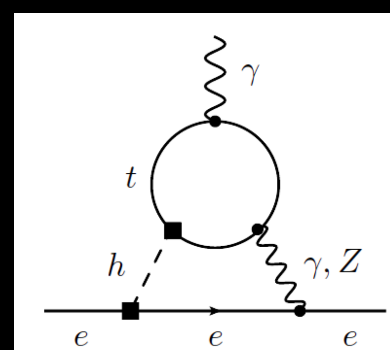
exa
in the





Any room left for
Higgs CPV couplings?



CME
llaboration

M experiment
PSI

lle II &
e^+e^- experiments

Chapter 2:

Indirect probes of Higgs CPV couplings

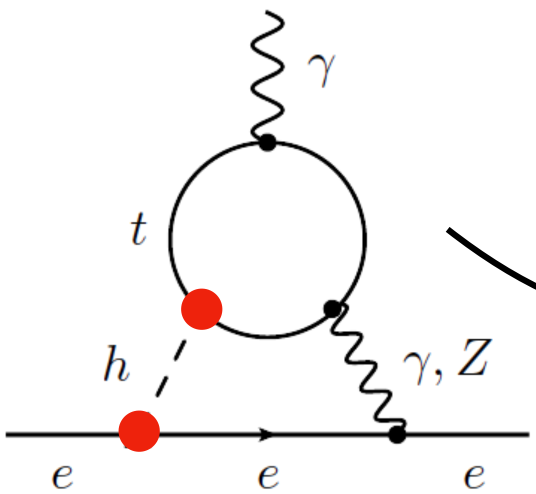
- Electron EDM
- Higgs rate measurements
- Di-boson measurements

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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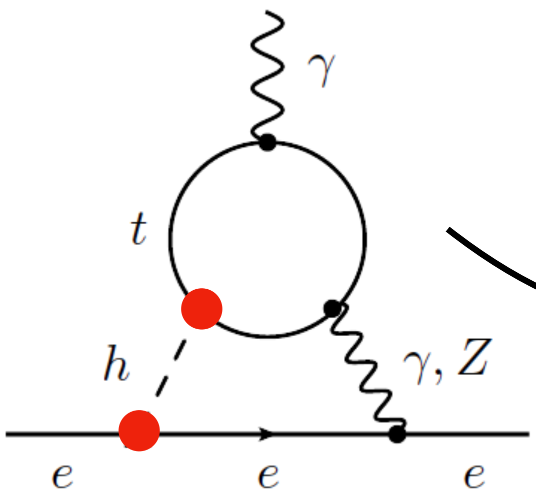

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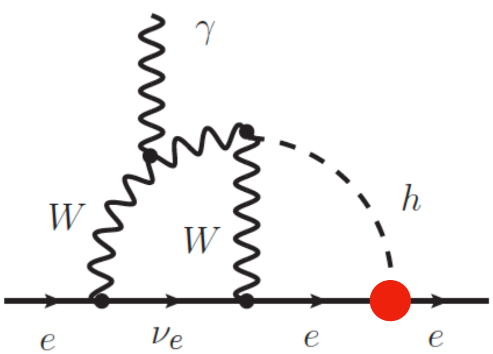
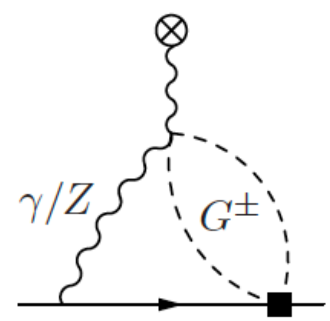


For the first time computed in Altmannshofer et al, 1503.04830

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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$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}(\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.})$$

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125 GeV Higgs → h_1

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Set of free parameters (phenomenological):

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

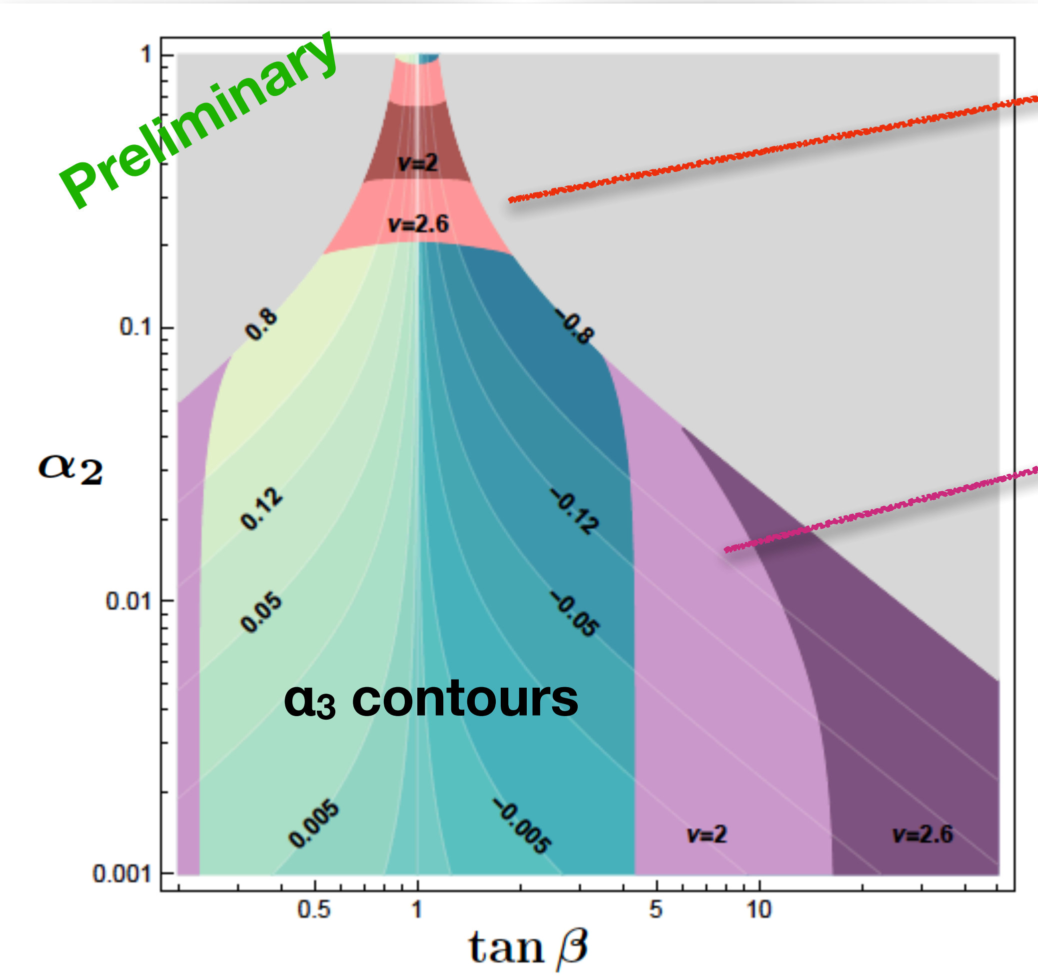
$$\nu \equiv \frac{\text{Re}(m_{12}^2)}{v^2 \sin 2\beta},\quad \alpha = \beta - \pi/2 + x$$

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



Vacuum (absolute) stability

Perturbativity

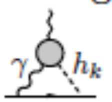
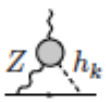
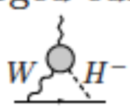
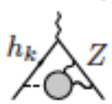
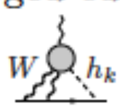
$$\lambda_1 = \frac{m_{h_1}^2 \sin^2\alpha \cos^2\alpha_2 + m_{h_2}^2 \mathcal{R}_{21}^2 + m_{h_3}^2 \mathcal{R}_{31}^2}{v^2\cos^2\beta} - \nu \tan^2\beta$$

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

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

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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Charged current	–	$\delta_{H+}^{\rm CC}$ (29)	$\delta_W^{\rm CC}(\xi)$ (35)
Kite			
Neutral current	–	–	$\delta_{\rm kite}^{\rm NC}$ (38)
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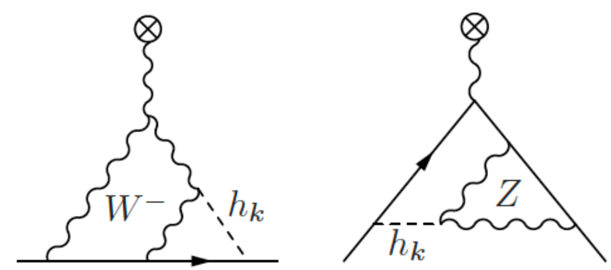
Altmannshofer, SG, Hamer, Patel, 2009.01258

Barr-Zee, 1990

Computed more recently: Abe et al, 1311.4704

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

representative diagrams:



◯ Note the gauge dependence

EDMs, a complete 2HDM study, gauge dependence

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Neutral current	δ_f^{NC} (25)	δ_{H+}^{NC} (28)	$\delta_W^{NC}(\xi)$ (31)
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Kite			
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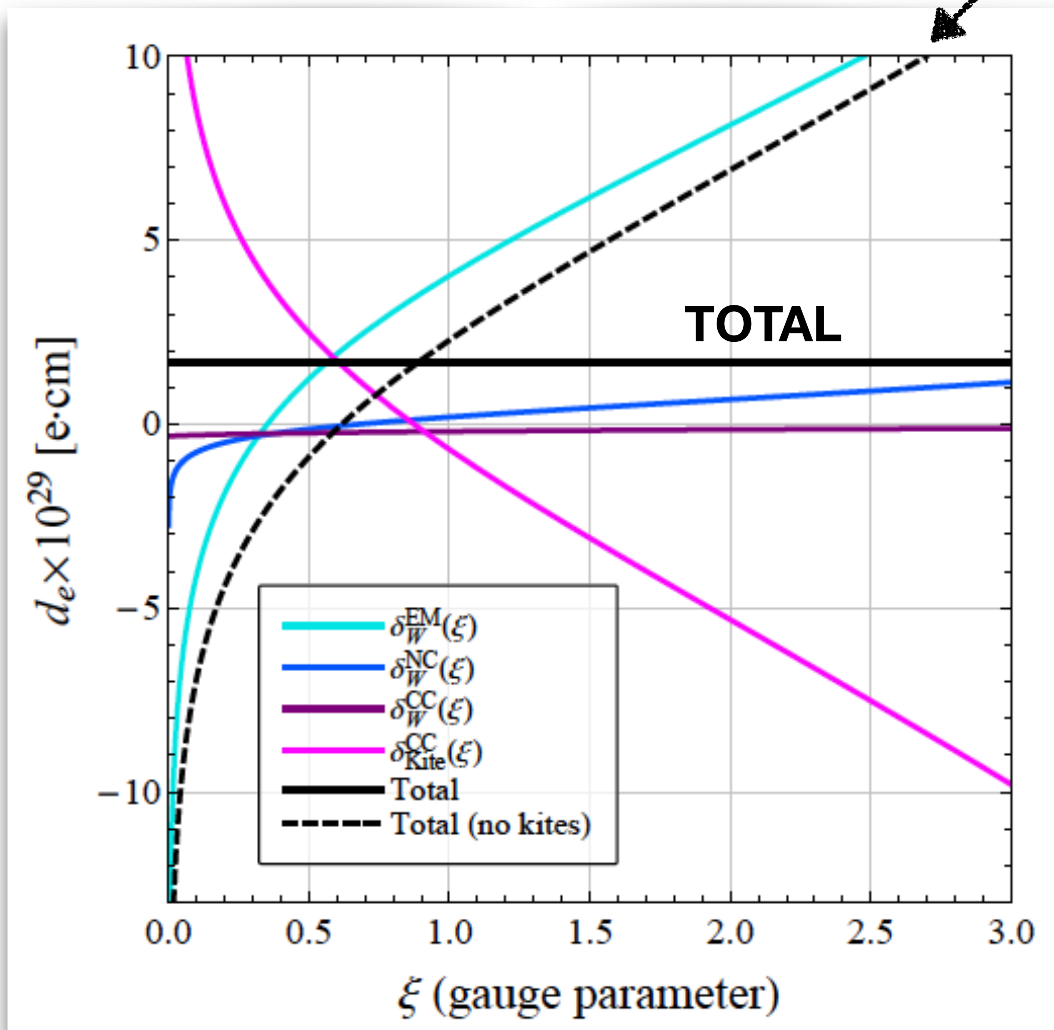
Altmannshofer, SG, Hamer, Patel, 2009.01258

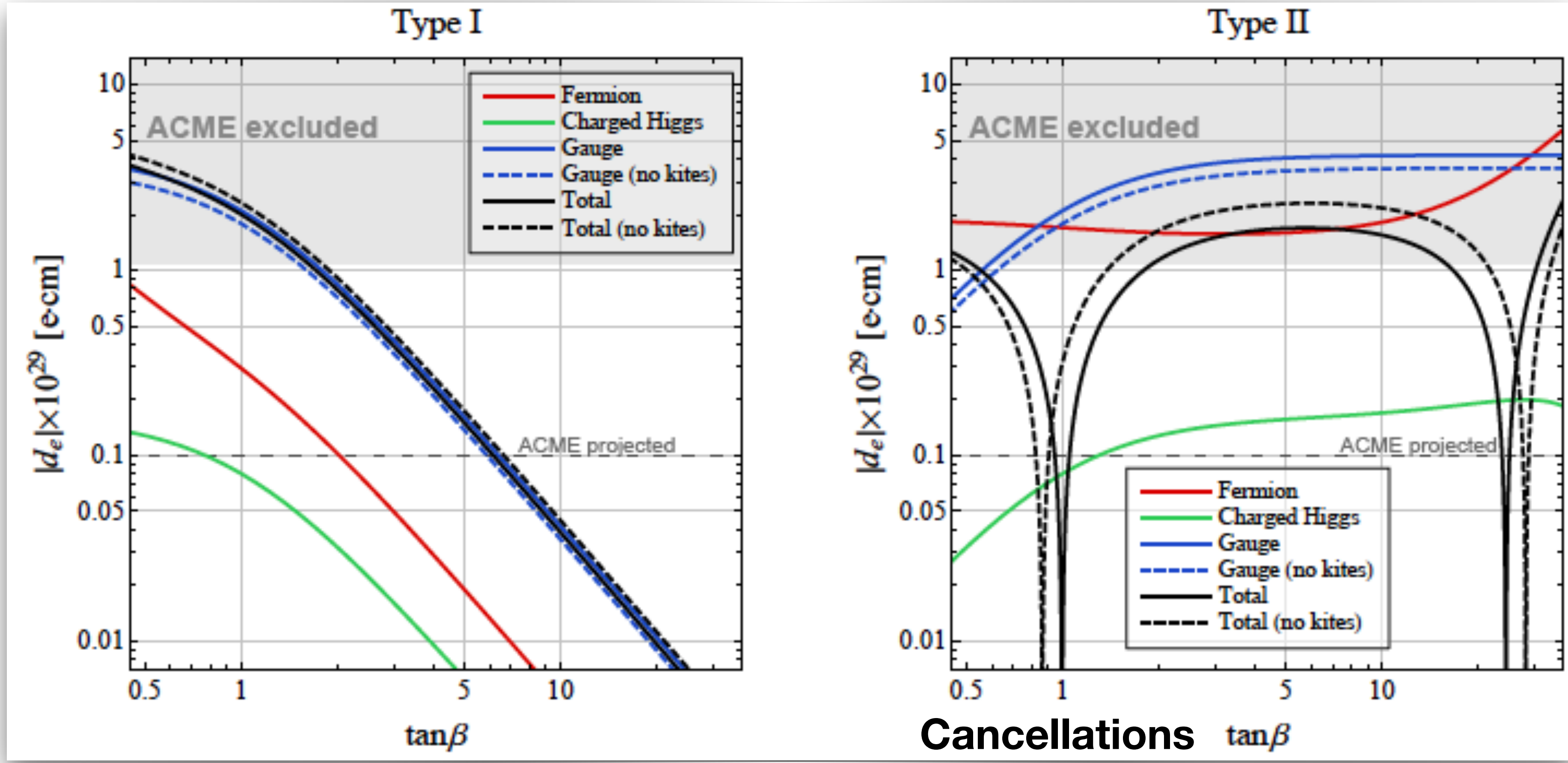
Notice the **gauge dependence** if we do not include the Kite diagrams



EDMs, 2HDM results

Example benchmark:

Altmannshofer, SG, Hamer, Patel, 2009.01258



Cancellations

In the decoupling limit:

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

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

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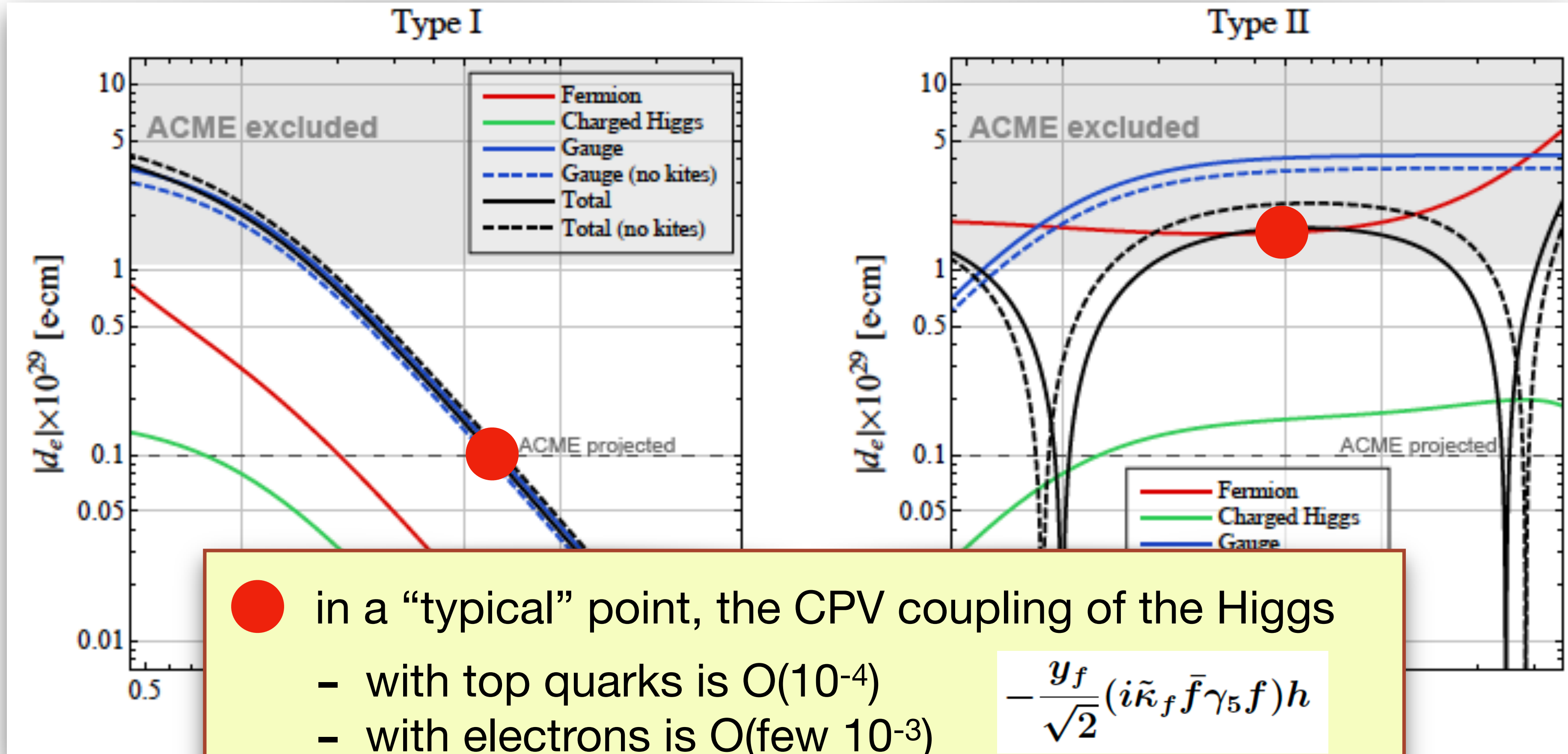

- in a "typical" point, the CPV coupling of the Higgs
  - with top quarks is $O(10^{-4})$
  - with electrons is $O(\text{few } 10^{-3})$

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

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

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

Free parameters for the Higgs pheno:

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

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

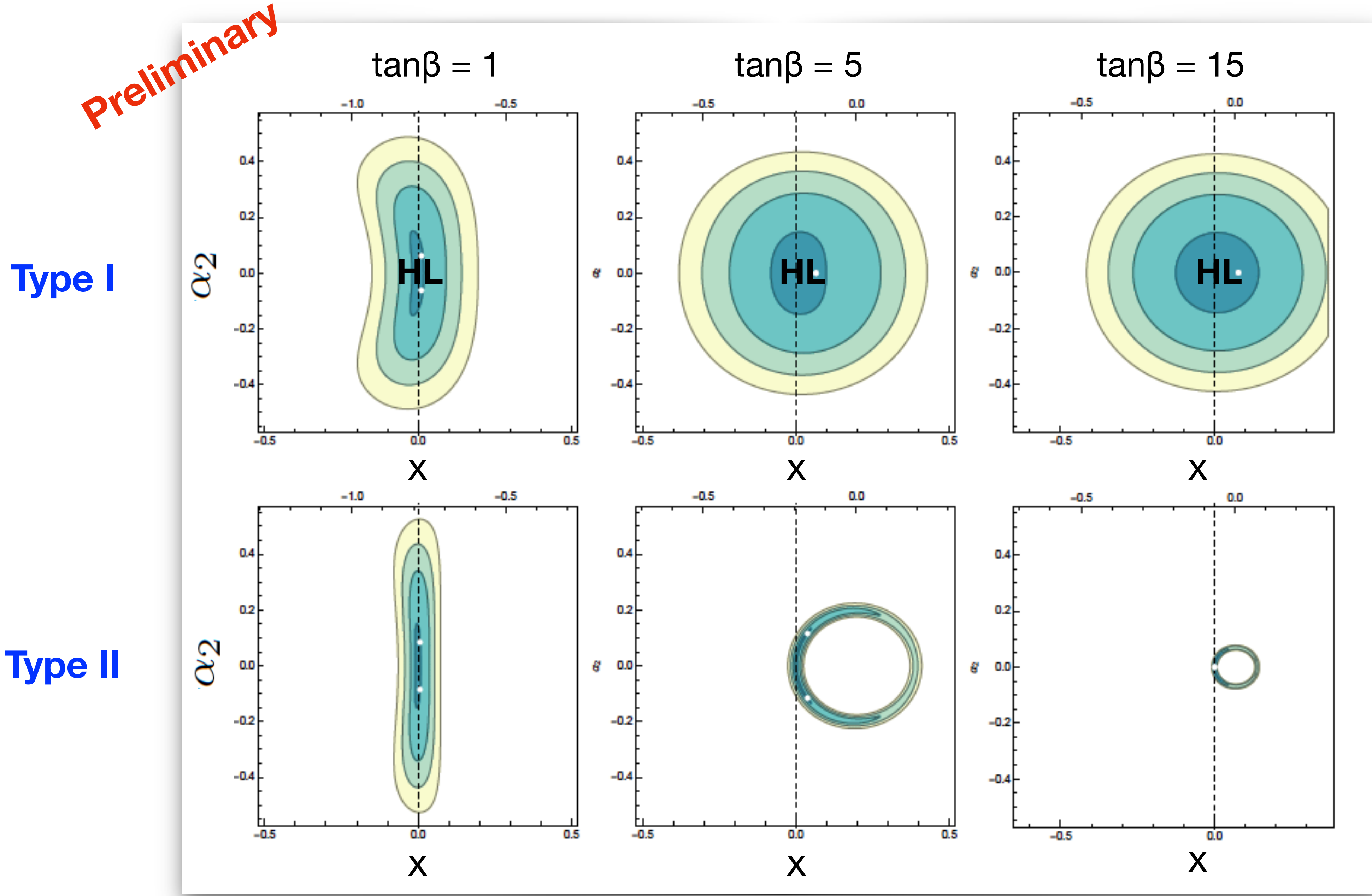
Some rates are easily scaled from the SM predictions:

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

Some other rates are more complicated:

$$\sigma(gg \to h) \simeq \sigma(gg \to h)_{\rm SM} \times$$
$$\times\,(1.1\kappa_t^2 + 3.6\times 10^{-3}\kappa_b^2 - 0.12\kappa_t\kappa_b + 2.5(\tilde{\kappa}_t^{(1)})^2 + 3.6\times 10^{-3}(\tilde{\kappa}_b^{(1)})^2 + 0.19\tilde{\kappa}_t^{(1)}\tilde{\kappa}_b^{(1)})$$

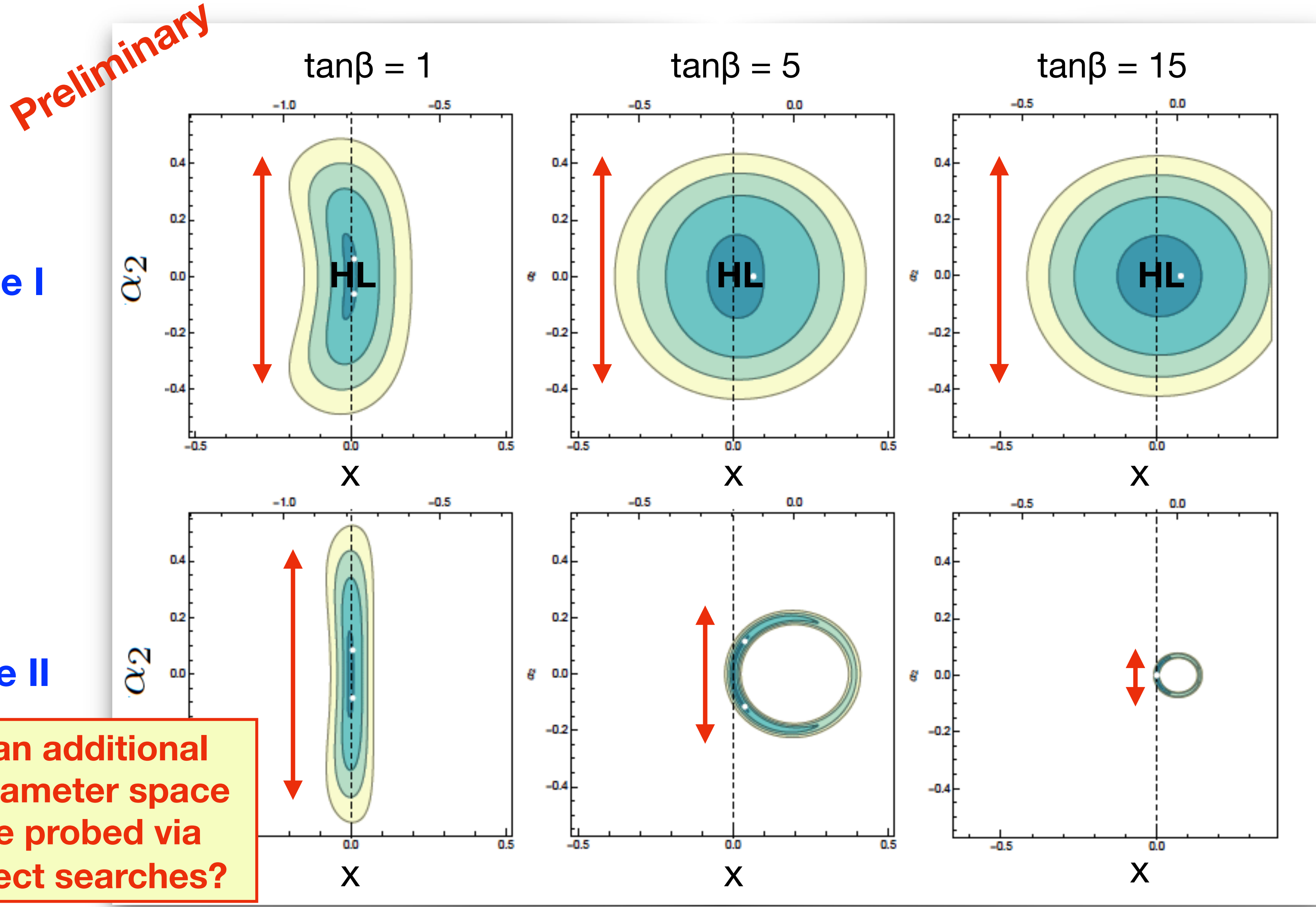
Other indirect probes: Higgs rate measurements (2)



SG, Hamer, in progress

See also Inoue et al, 1403.4257

Other indirect probes: Higgs rate measurements (2)



Can additional parameter space be probed via direct searches?

SG, Hamer, in progress

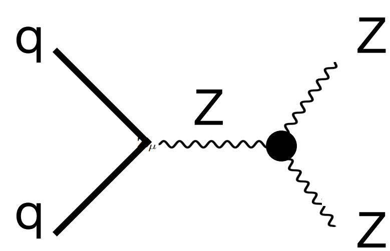
See also Inoue et al, 1403.4257

Other indirect probes: di-boson production

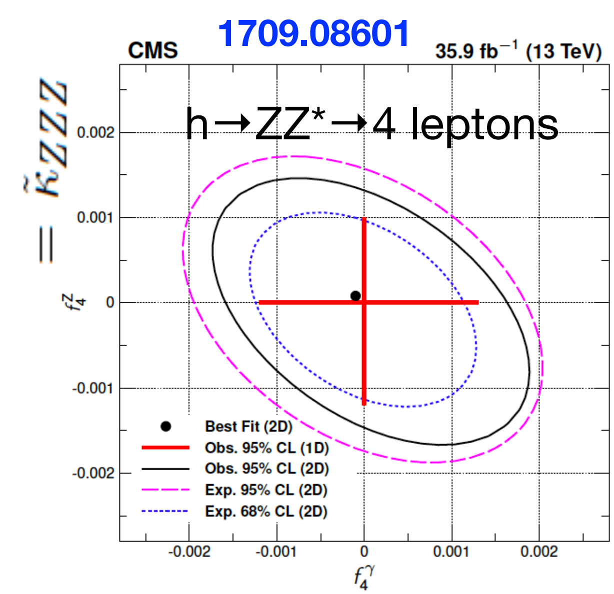
Beyond Higgs measurements, measurements of di-boson production can unveil the existence of new sources of CPV in triple gauge couplings

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)



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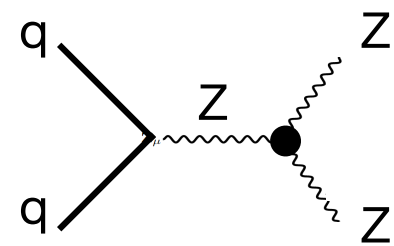

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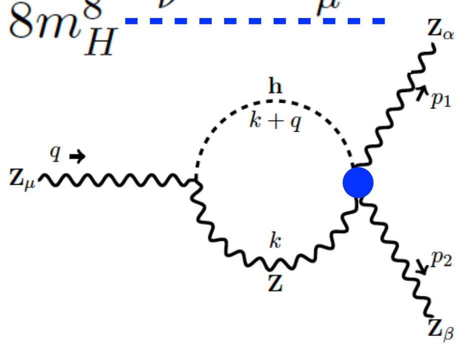
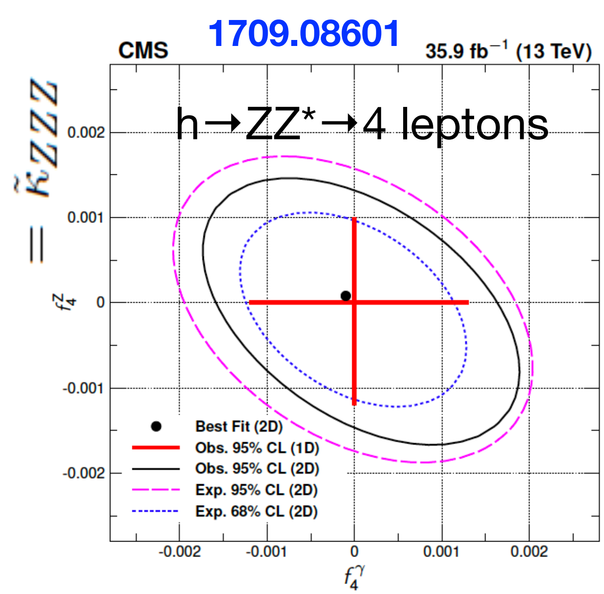
For a 2HDM realization,
see Belusca-Maito et al. 1710.05563:

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

Parameters of the 2HDM potential

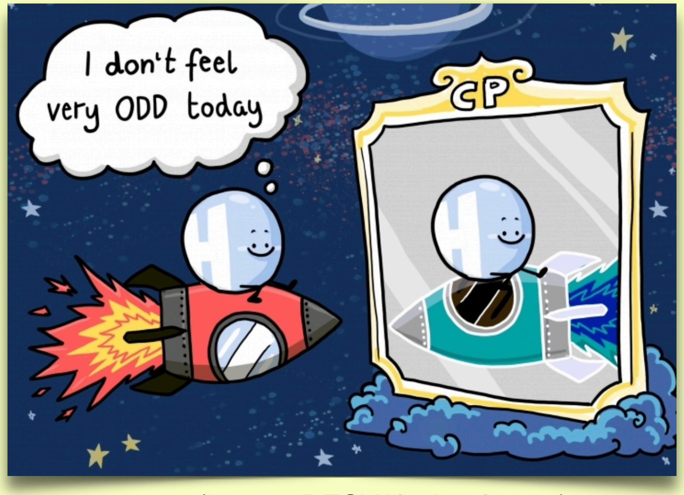




Chapter 3:

Direct probes of Higgs CPV couplings

- Higgs distributions
- Signals of CPV from additional Higgs bosons



(image: DESY/designdoppel)

Direct searches for Higgs CPV (bosonic)

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

(arising at one loop in the complex 2HDM)

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

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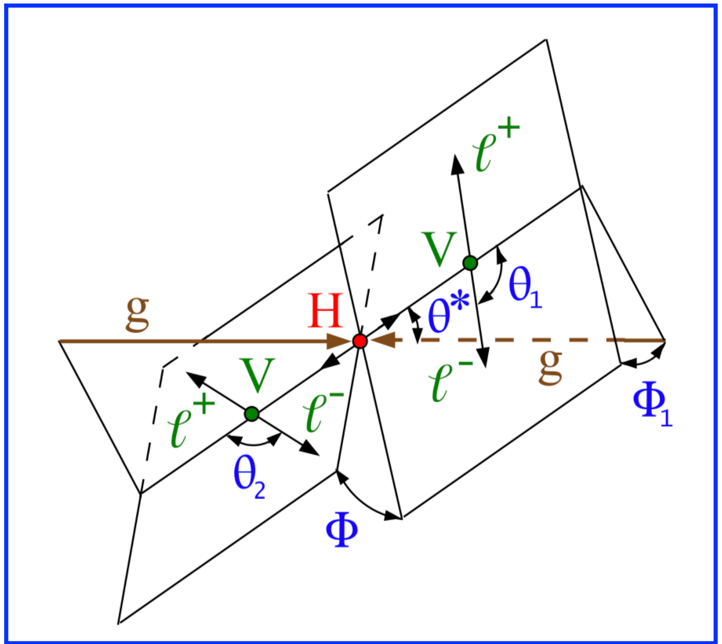
Searches for

- 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

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

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

(*) 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: $\tilde{\kappa}_t \lesssim 0.68$ (139 fb^{-1}, ATLAS, 2004.04545; CMS, 2003.10866)
- Search for $h \to \tau^\pm \tau^\mp$: $\tilde{\kappa}_\tau \lesssim 0.59$ (137 fb^{-1}, CMS PAS HIG-20-006)

1804.01241

ILC, 250 GeV, 2ab^{-1}: angle can be measured with a 4.3° precision

1703.04855

CEPC, 250 GeV, 5ab^{-1}: angle can be measured with a 2.9° precision

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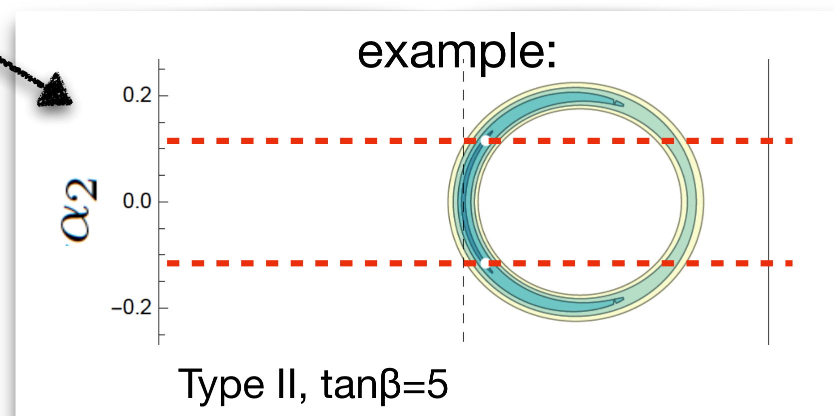

Additional CPV Higgs coupling probes

An (incomplete) list…

$Z\gamma$ 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]

$gg \to hjj$, $h \to \tau\,\tau$. Uses associated jets for angular analysis

$\gamma\gamma$ Bishara, Grossman, Harnik, Robinson, Shu, Zupan [1312.2955]

Requires converted photons and angular resolution on leptonic opening angles

bb, cc ?

Galanti, Giammanco, Grossman, Kats, Stamou, Zupan [1505.02771]

Can possible overcome QCD wash-out of quark polarization

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
- $H_3 \to H_2 Z$, $H_2 \to H_1 Z$
- $H_3 \to H_1 H_2$ (see Ian's talk yesterday)
- …

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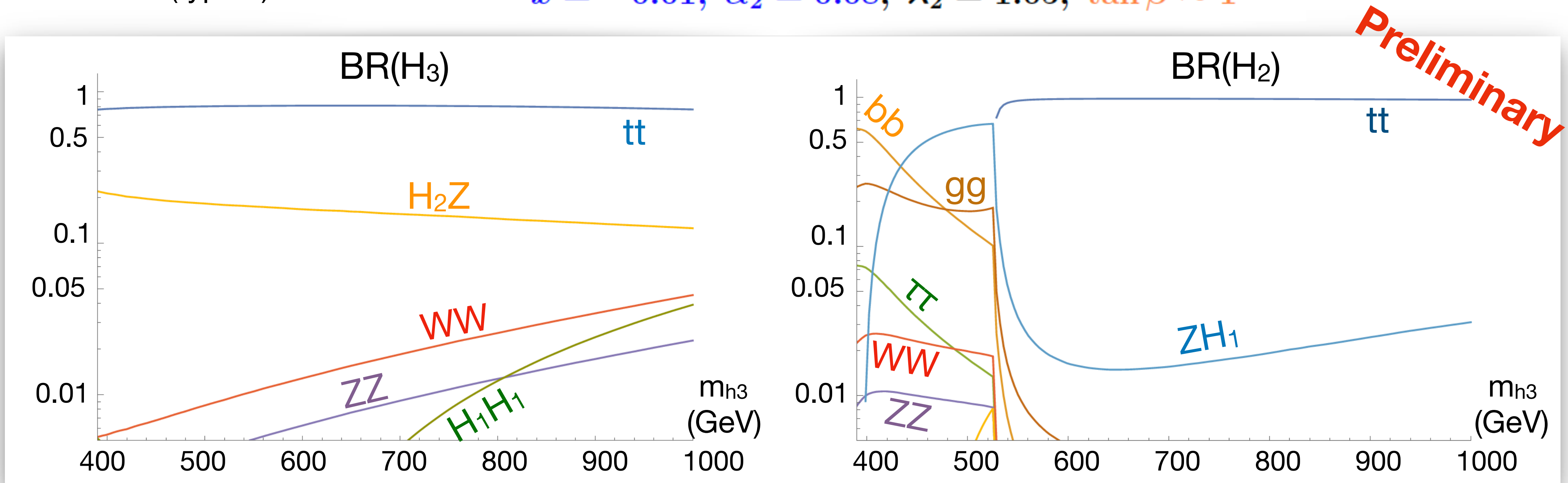
- …

Electroweak precision tests ✓
Higgs rates ✓
Electron EDM ✓

Example benchmark (type II):

$$m_{h_2} = m_{h_3} - 180\ \text{GeV},\ m_{H^\pm} = m_{h_3} + 25\ \text{GeV},$$
$$x = -0.01,\ \alpha_2 = 0.08,\ \lambda_2 = 1.05,\ \tan\beta \sim 1$$



SG, Hamer, in progress

Rates for the heavy Higgs CPV signatures

$m_{h_2} = m_{h_3} - 180$ GeV, $m_{H^\pm} = m_{h_3} + 25$ GeV,
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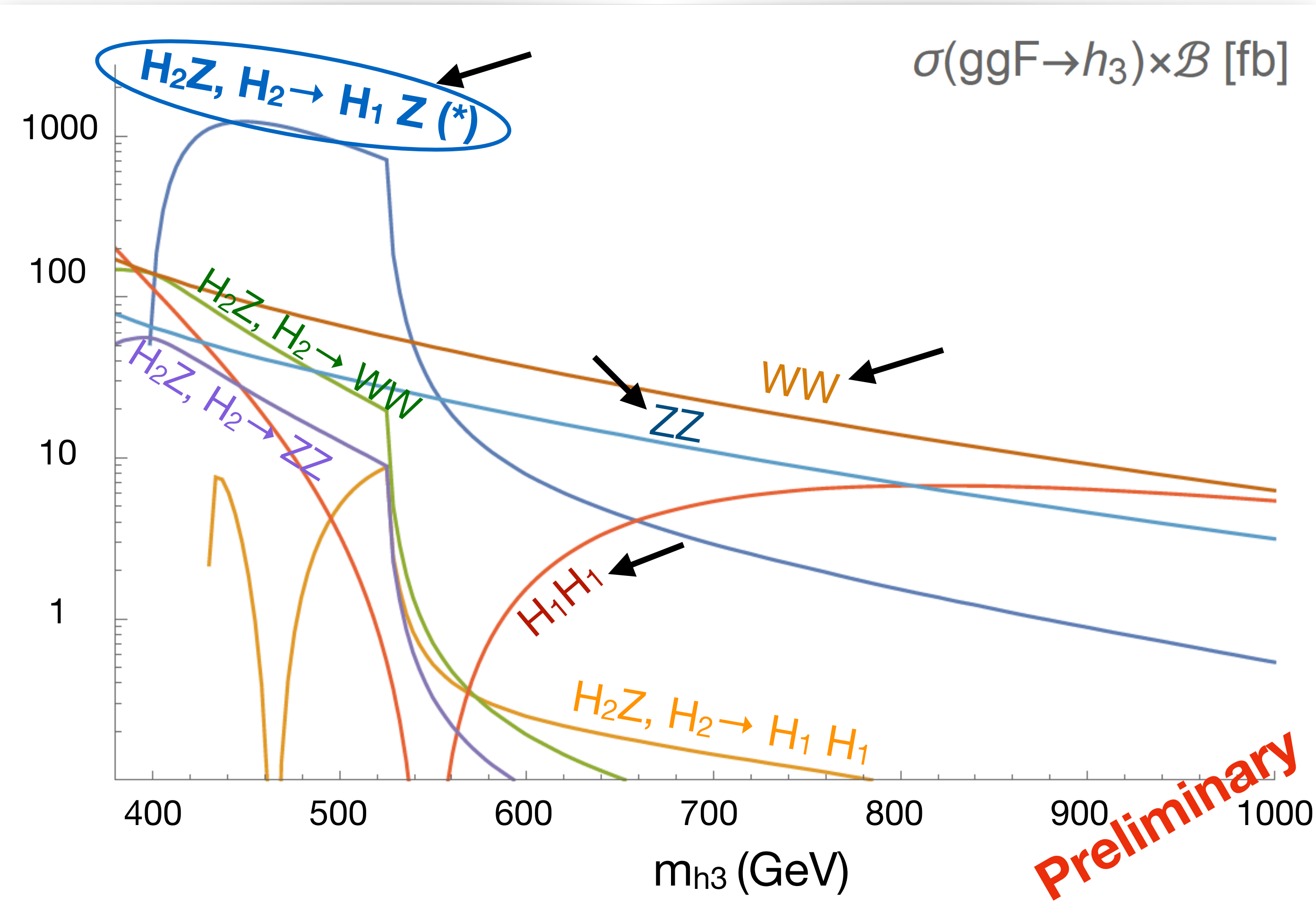


SG, Hamer, in progress

(*) new proposed search

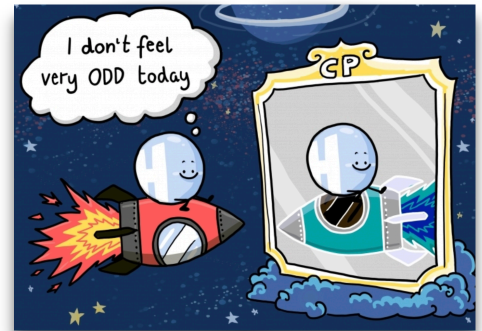
→ CPV decays

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

For the specific benchmark, the most relevant constraint comes from searches for $pp \to t\bar{t}H_{(2)}$, $H_{(2)} \to t\bar{t}$

$$m_{H_3} \gtrsim 550 \text{GeV}$$

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

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

indirect

- Higgs rate measurements
- Di-boson measurements

direct

- Higgs distributions
- Signals of CPV from additional Higgs bosons

LHC probes

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

Complementarity