Higgs and CP violation

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UC Santa Cruz

Experimental Particle & Astroparticle Physics (EPAP) seminar

Kings College, London
May 23, 2022

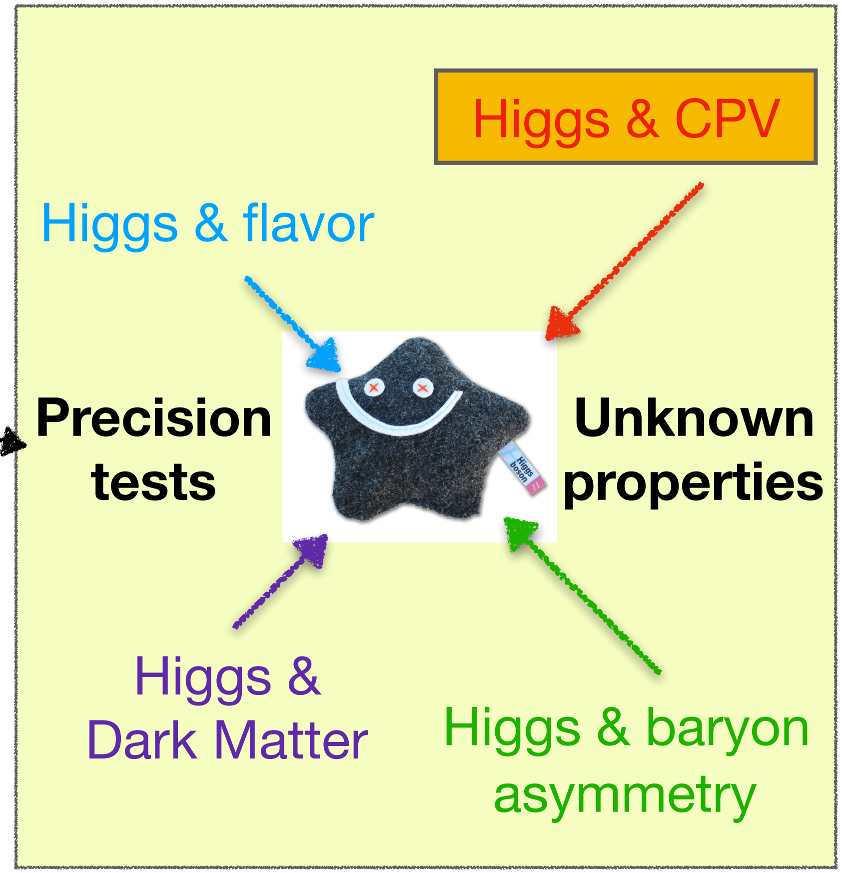
Outline of the seminar

1. (Brief) overview on the status of Higgs physics

- Higgs precision program
- Unknown properties of the Higgs boson

2. Higgs and CP violation (CPV)

- LHC direct and indirect bounds on a CPV Higgs
- Are new sources of CPV still allowed? electric-dipole-moments
- New LHC searches to probe Higgs and CPV

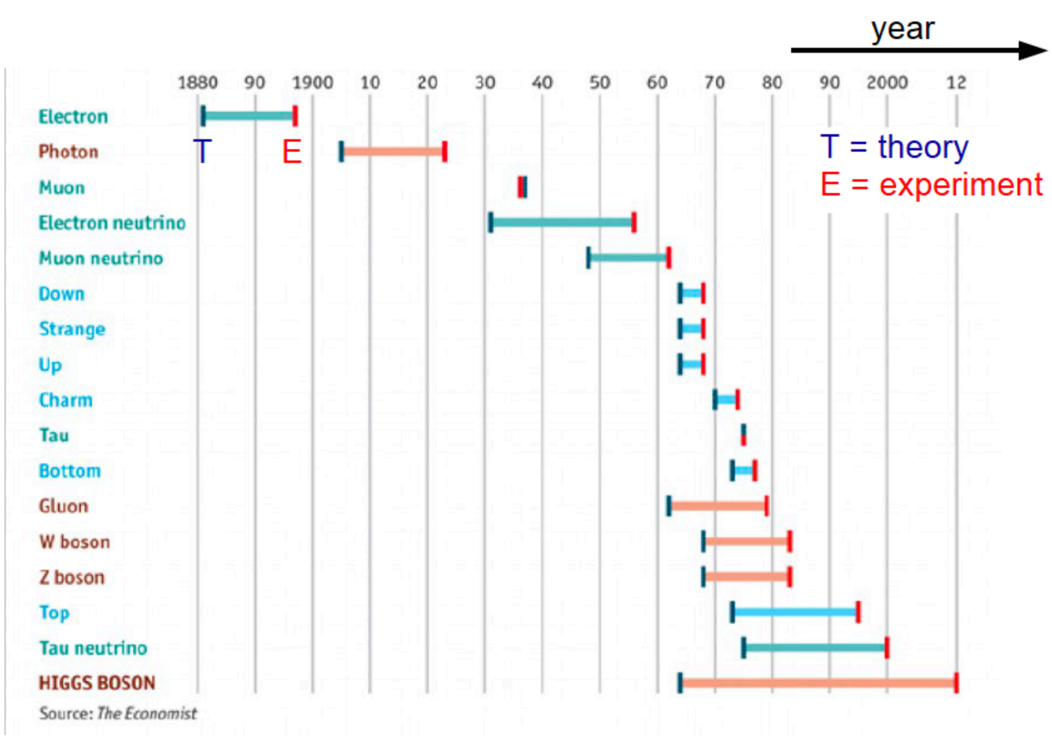


Main references for this talk

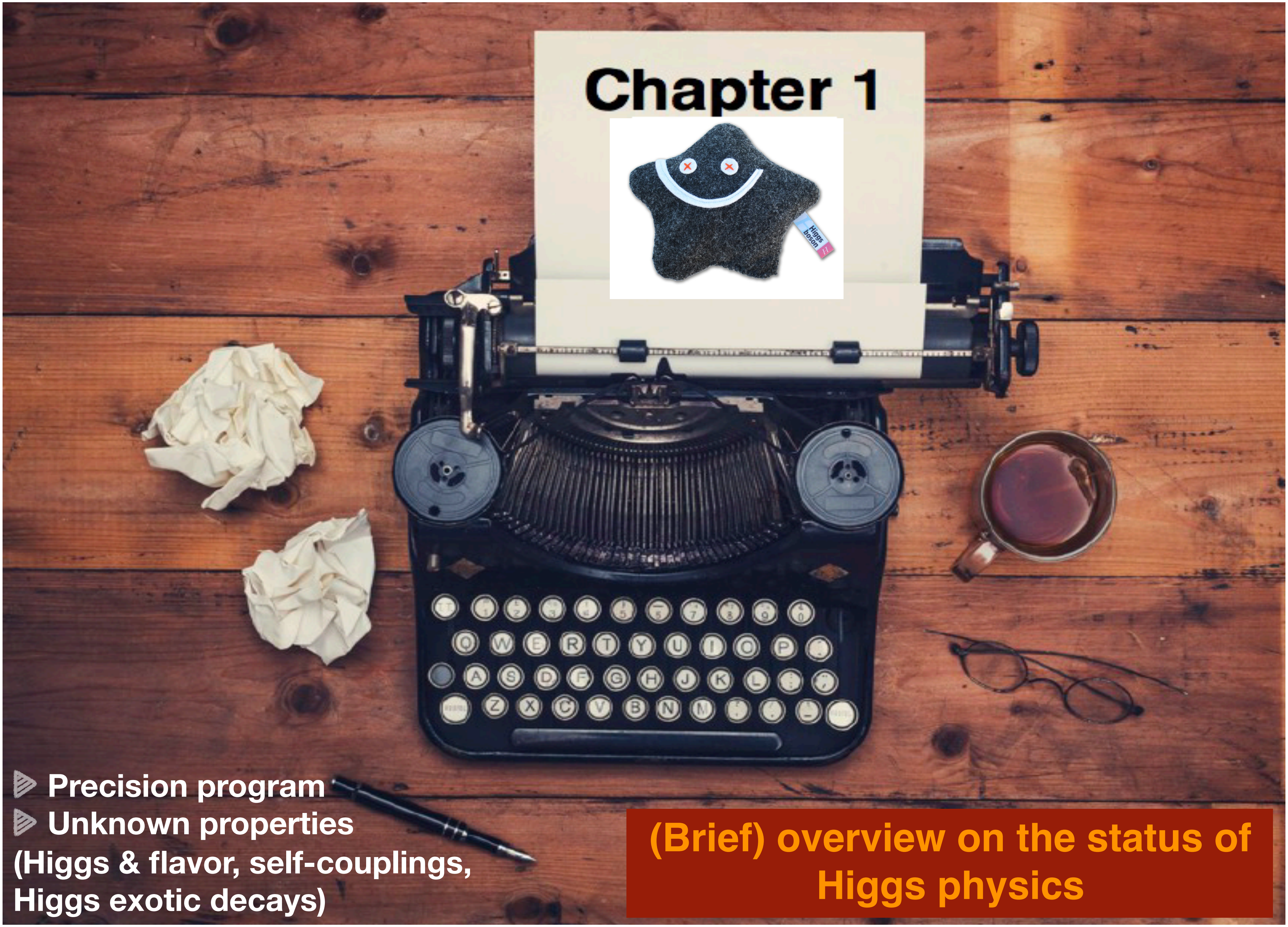
Altmannshofer, SG, Hamer, Patel, 2009.01258

SG, Hamer, appearing soon

The Higgs is (almost) 10 years old!



- ✱ What have we learned?
- ✱ What do we still need to learn?
- ✱ Connection to the broader picture: can the Higgs help us addressing the most important **open problems in particle physics**? (dark matter, baryogengesis, flavor puzzle, …)



Chapter 1

- Precision program
- Unknown properties

(Higgs & flavor, self-couplings, Higgs exotic decays)

(Brief) overview on the status of Higgs physics

Towards a Higgs precision program

Now that we have measured the mass of the Higgs boson (last free parameter of the Standard Model (SM)), we can make **accurate SM predictions** for the Higgs phenomena

"k framework":

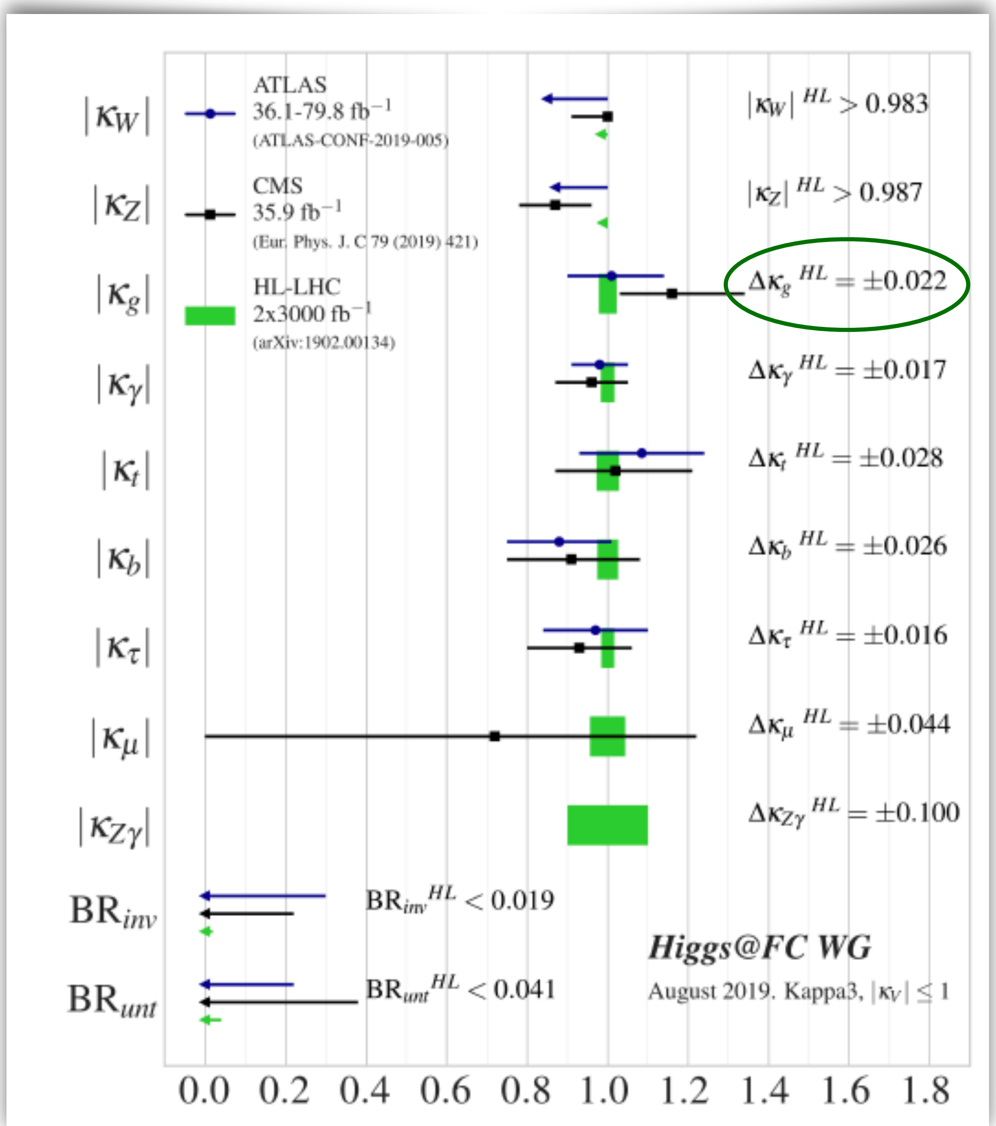
all New Physics (NP) is encoded in the modification of the Higgs couplings to SM particles

In any NP model,

$$\kappa \equiv \frac{\text{Coupling}^{\text{NP}}_{\text{Higgs}}}{\text{Coupling}^{\text{SM}}_{\text{Higgs}}}$$

We can extract these via measuring the Higgs rates at the LHC

Towards a Higgs precision program



"Physics briefing book", European physics strategy, 1910.11775

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Expected precision with HL-LHC:
$k_g \rightarrow$ 2 % TH+STAT+SYS.

Enormous challenge for TH to reach this level!

Probing Higgs distributions

The LHC not only measures Higgs rates but also Higgs event distributions

These can be used to set bounds on the SMEFT Lagrangian.
(The idea is to write the most general Lagrangian containing SM particles up to dimension 6 satisfying the SU(2) gauge symmetry and flavor universal)

EWPO:	$\mathcal{O}_{HWB}\,,\,\mathcal{O}_{HD}\,,\,\mathcal{O}_{ll}\,,\,\mathcal{O}_{Hl}^{(3)}\,,\,\mathcal{O}_{Hl}^{(1)}\,,\,\mathcal{O}_{He}\,,\,\mathcal{O}_{Hq}^{(3)}\,,\,\mathcal{O}_{Hq}^{(1)}\,,\,\mathcal{O}_{Hd}\,,\,\mathcal{O}_{Hu}\,,$
Bosonic:	$\mathcal{O}_{H\Box}\,,\,\boxed{\mathcal{O}_{HG}}\,,\,\mathcal{O}_{HW}\,,\,\mathcal{O}_{HB}\,,\,\mathcal{O}_{W}\,,\,\mathcal{O}_{G}\,,$
Yukawa:	$\mathcal{O}_{\tau H}\,,\,\mathcal{O}_{\mu H}\,,\,\mathcal{O}_{bH}\,,\,\mathcal{O}_{tH}\,.$

Example:

$$\boxed{\mathcal{O}_{HG}} = H^\dagger H G^A_{\mu\nu} G^{\mu\nu A}$$

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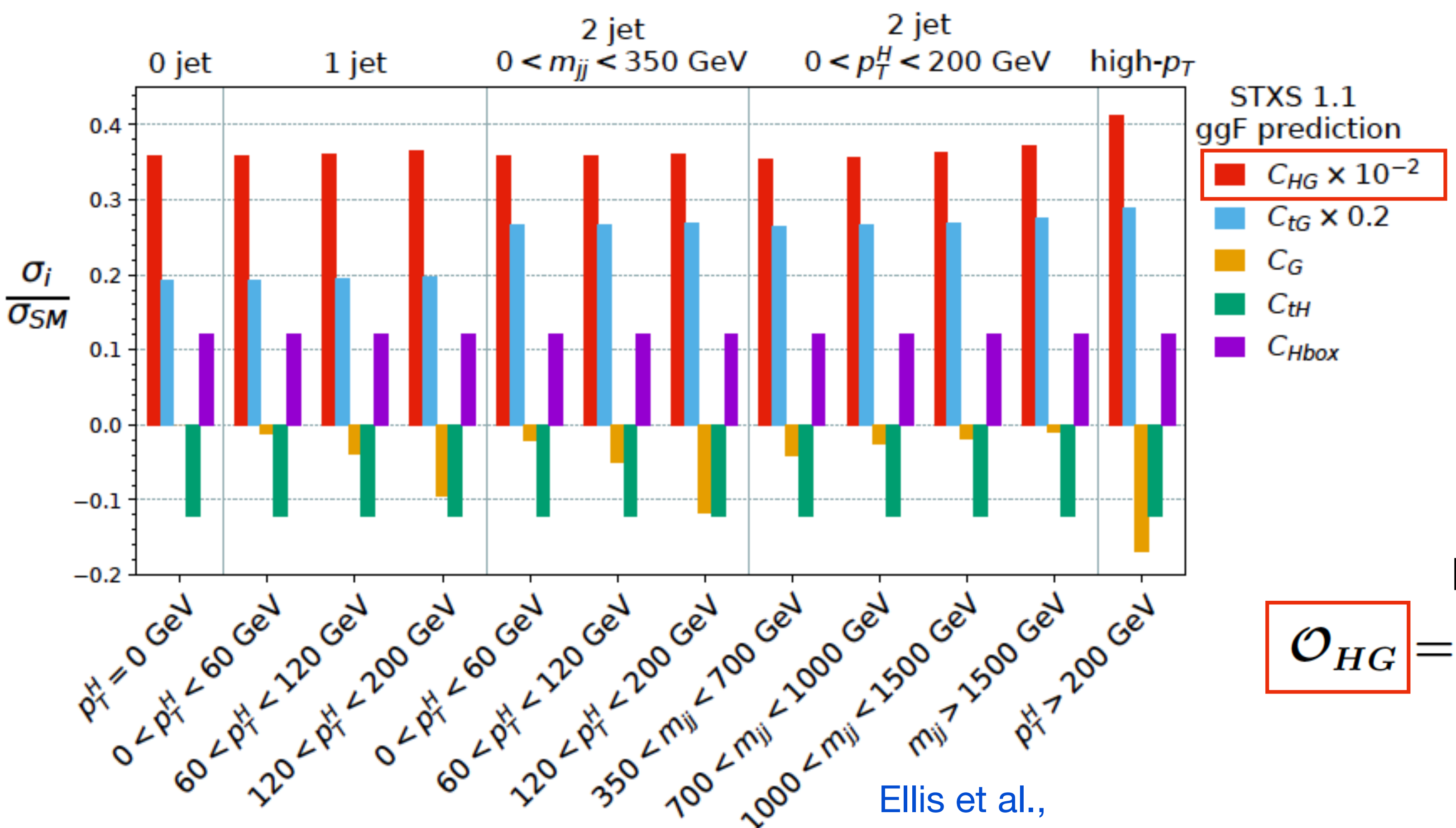


Ellis et al.,
2012.02779

Example:

$$\mathcal{O}_{HG} = H^\dagger H G^A_{\mu\nu} G^{\mu\nu A}$$

(1) Higgs & flavor

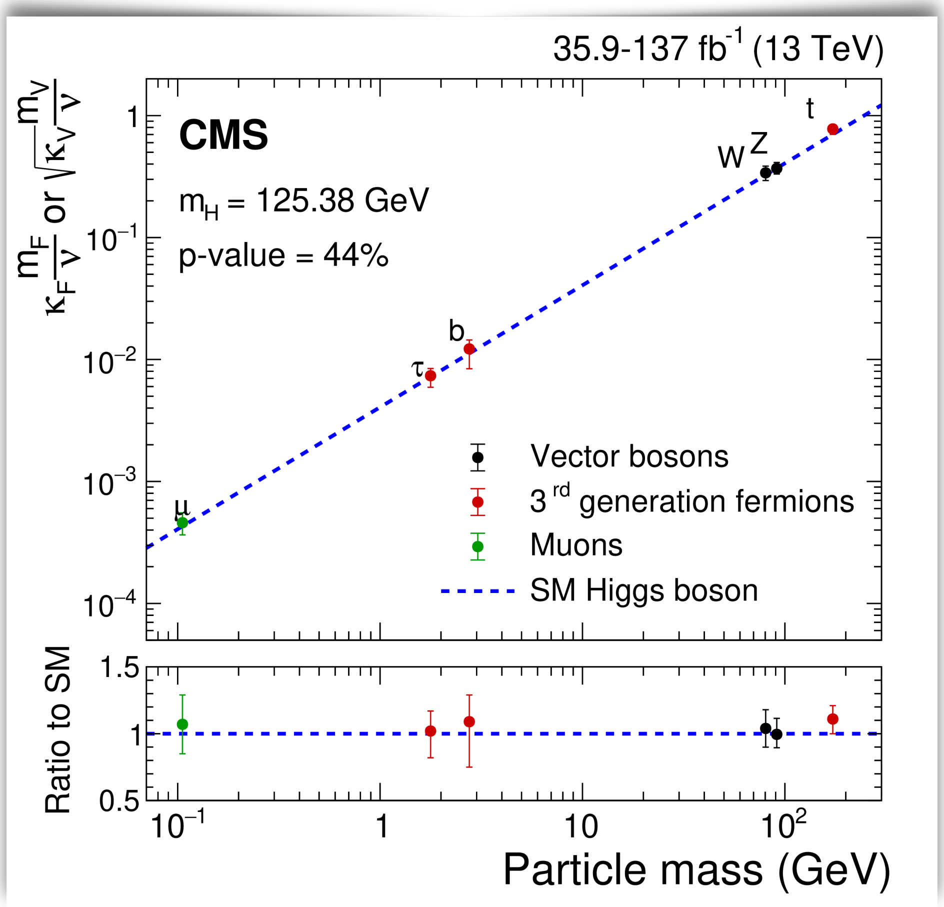
We do not know if the 125 GeV Higgs couples/gives mass to all flavors

Evidence for the Higgs decaying into muons!

$$\mu = 1.2 \pm 0.6$$ (ATLAS, 2007.07830)

$$\mu = 1.19^{+0.40}_{-0.39}(\mathrm{stat})^{+0.15}_{-0.14}(\mathrm{syst})$$ (CMS, 2009.04363)

Run III discovery?



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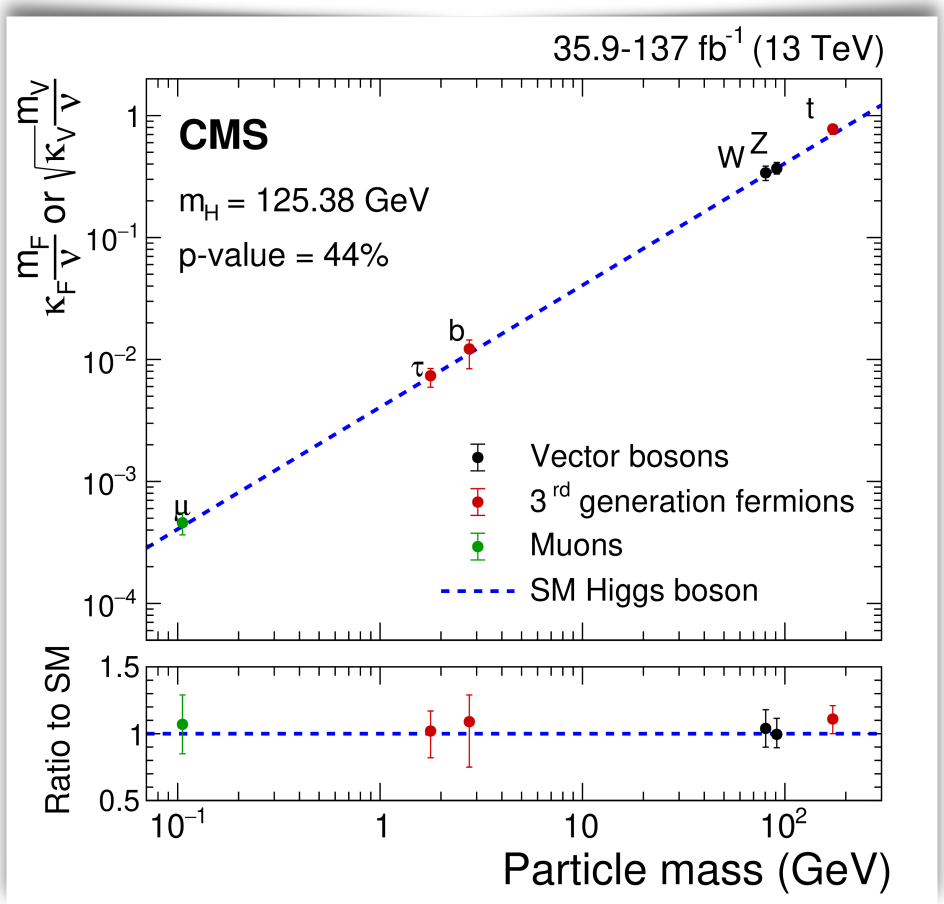


What about light quarks? (electrons?)

Strategies to probe light quark Yukawas
(warning: not exhaustive)

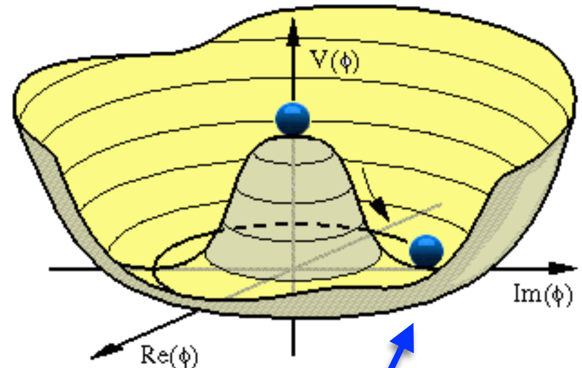
- ✱ Higgs + charm production
  (Brivio, Isidori, Goertz 1507.02916)
- ✱ Higgs + jet production
  (Bishara, Haisch, Monni, Re, 1606.09253)
- ✱ Higgs η & p_T distributions
  (Soreq, Zhu, Zupan, 1606.09621)
- ✱ Rare Higgs decays
  (Bodwin, Petriello, Stoynev, Velasco,1306.5770)
- ✱ Charge asymmetry in $W^\pm h$ production
  (Yu,1609.06592) discovery with 300/fb
- ✱ Higgs + photon production
  (Aguilar-Saavedra, Cano, No, 2008.12538)

(2) Higgs self-interactions

In the SM, the Higgs **self-interactions are fully determined**:

$$\frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4$$

v, m_h are the only two free parameters of the Higgs potential



What's the shape of the potential at around the minimum?

Well motivated theories beyond the SM predict **modifications** to this picture.
Classic example: theories to explain the baryon-antibaryon asymmetry

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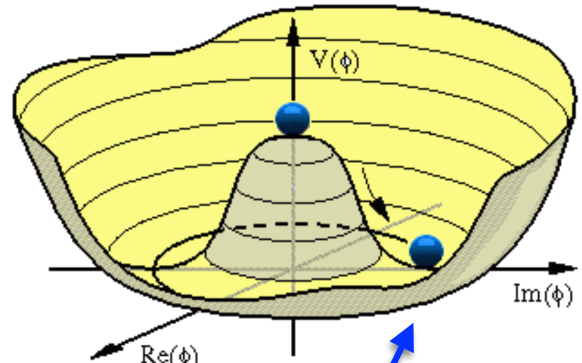

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It is very important to test the Higgs self-interactions!

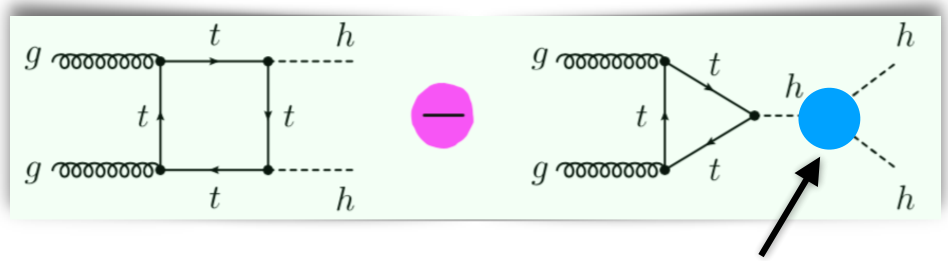
How to measure it?

1. Di-Higgs production

2. Higgs rate measurements

1. Di-Higgs production

The measurement is challenging since the **SM di-Higgs cross section is small**



σ ~ 30 fb
(~1000 smaller than single production)

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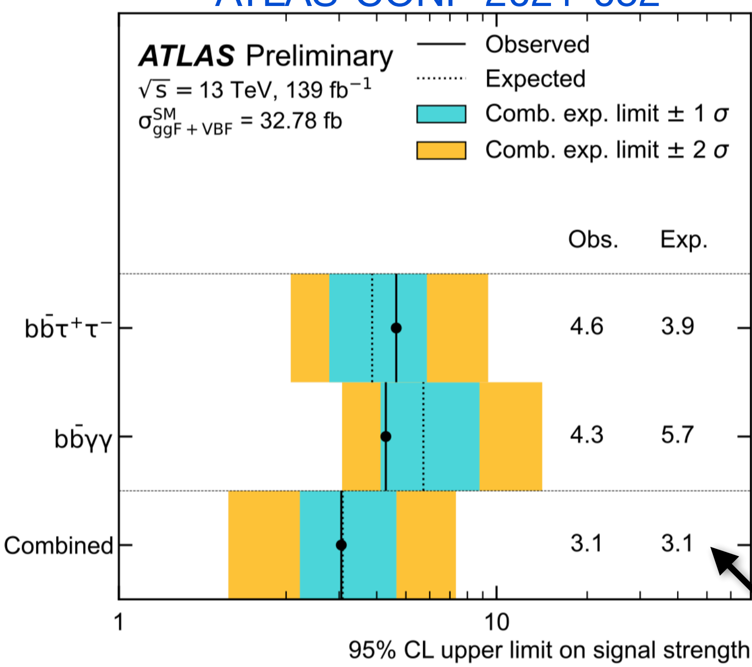
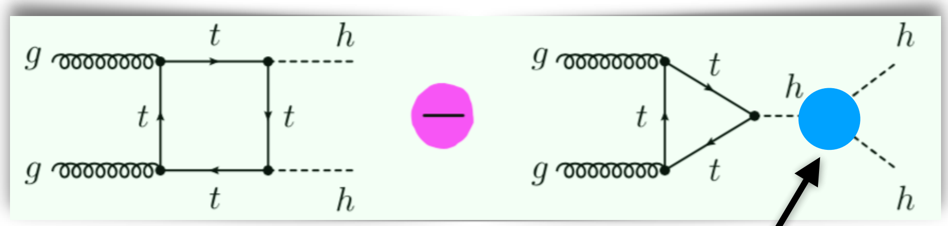
The measurement is challenging since the **SM di-Higgs cross section is small**

Several di-Higgs searches performed at Run II:

ATLAS-CONF-2021-052



times the SM cross section



σ ~ 30 fb
(~1000 smaller than single production)

HL: bbττ, bbγγ (and bbbb) will provide the best sensitivity (combined sensitivity of ~4-4.5σ)

We should prepare in view of the HL-LHC!

Improved b-tagging performance and improved b-jet triggers would be very important!

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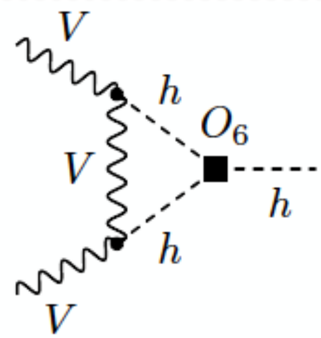
For example, the coupling to W and Z bosons:

example diagram:



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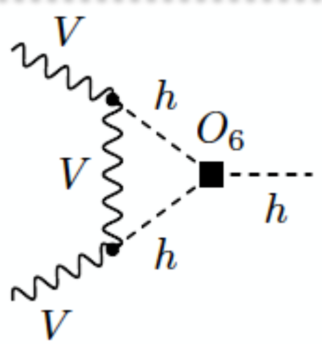
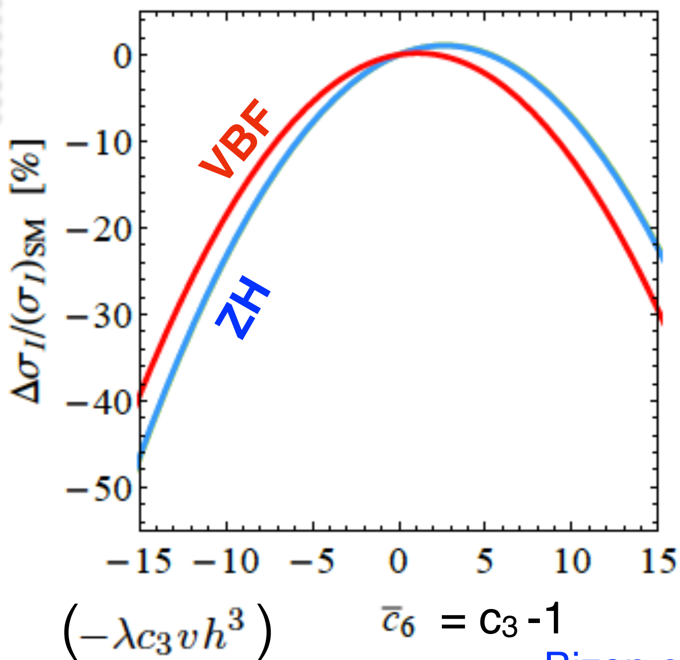
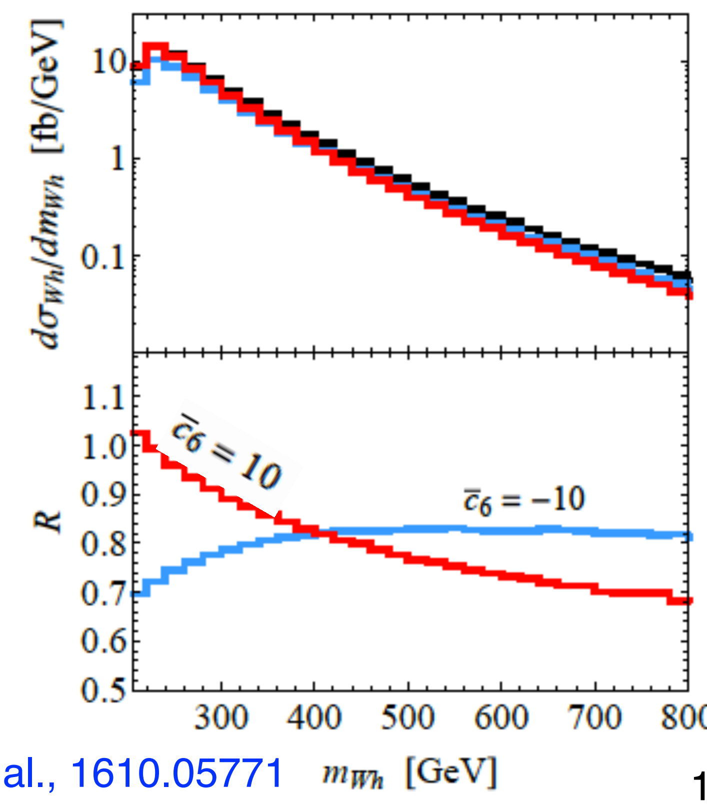


1. VBF and Z/W Higgs associated production cross section will be affected



2. NP effects in differential distributions, as well



Bizon et al., 1610.05771

Extracted k_λ is **competitive** with the one extracted from di-Higgs searches

(3) Higgs, dark sectors, and exotic decays

Dark sector particles (= particles not charged under any SM gauge interaction) are theoretically very well-motivated:

- Models for thermal Dark Matter with a mass below a few GeV
- Several anomalies in data can be addressed by dark sectors (eg. $(g-2)_\mu$ …)
- Neutrino mass model building

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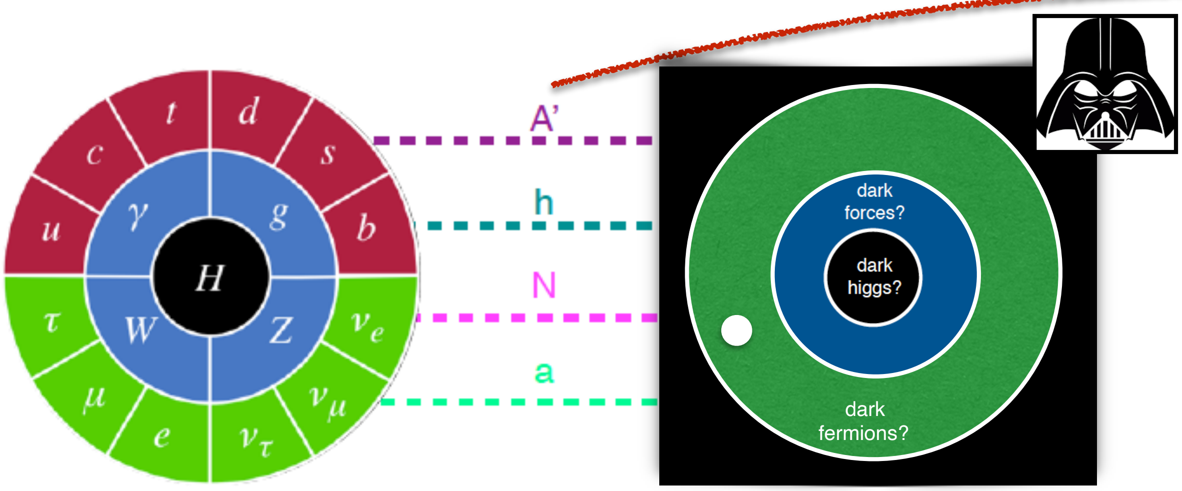
How to test this emerging paradigm?



"Portals":

Dark photon	$\epsilon Z^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$y H L N$

generically small parameters

Each portal can lead to a "Higgs exotic decay"

E.g. $\epsilon Z^{\mu\nu} A'_{\mu\nu} \Rightarrow h \to Z Z'$

$\kappa \lvert H \rvert^2 \lvert S \rvert^2 \Rightarrow h \to SS$

The least investigated Higgs exotic decays

Several searches for Higgs exotic decays have been performed at Run I-II.
Several big gaps:

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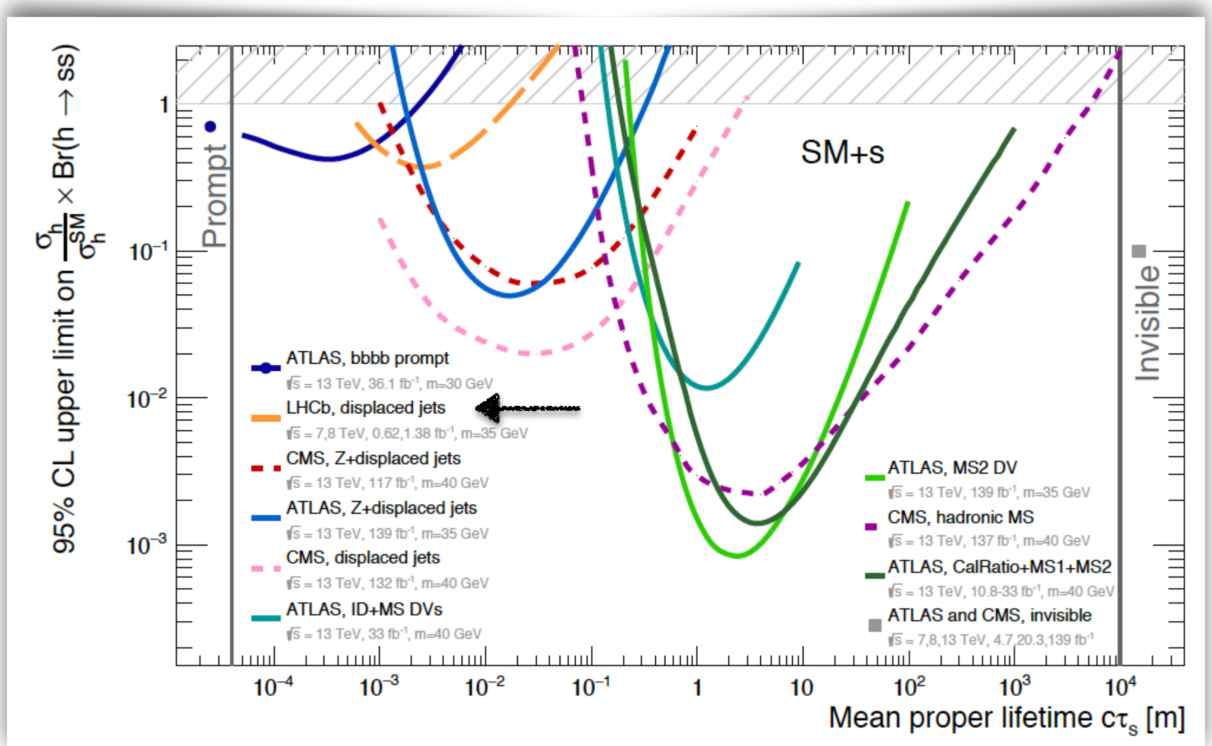
1. Higgs decaying to **long-lived particles**

- Some searches will greatly benefit from the increase in luminosity (low/negligible backgrounds)



Cepeda, SG, Martinez-Outschoorn, Shelton, 2111.12751

- Significant improvements in sensitivity of many searches could be possible in future LHC runs with potential improvements in
  - timing (Liu, Liu, Wang, 1805.05957);
  - triggers (Gershtein, 1705.04321);
  - analysis strategies (e.g. Csaki et al, 1508.01522).

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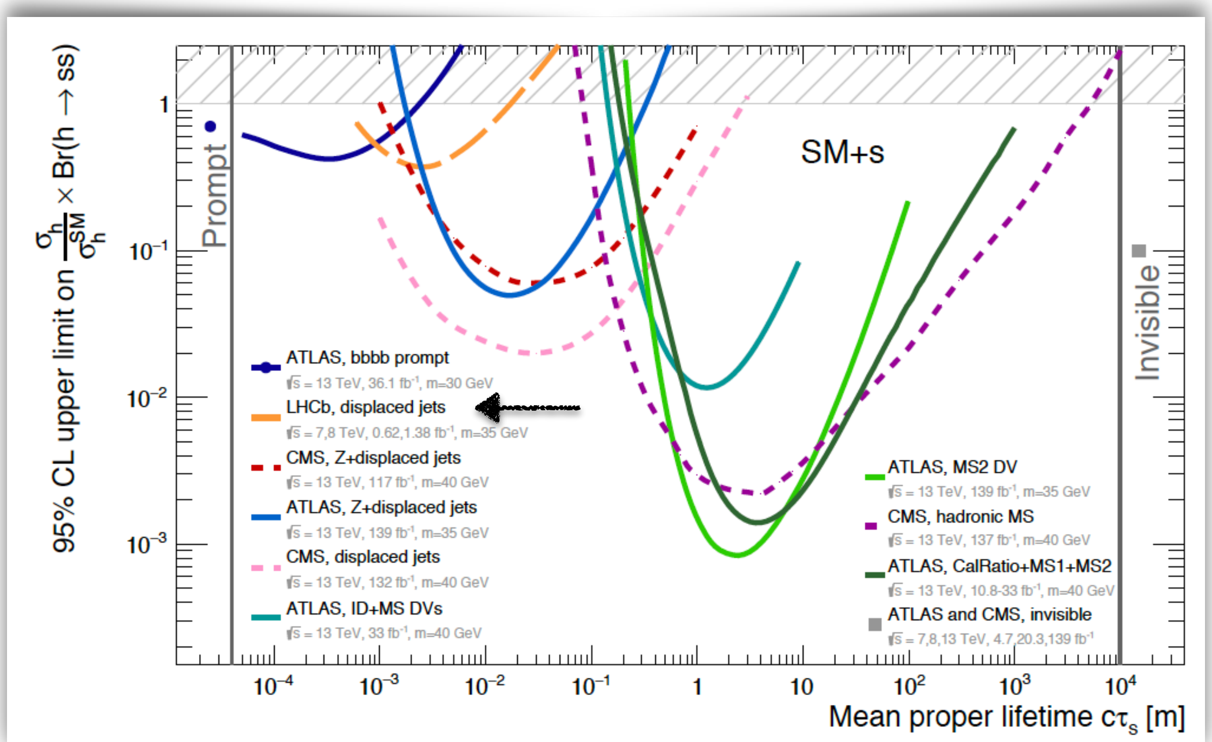

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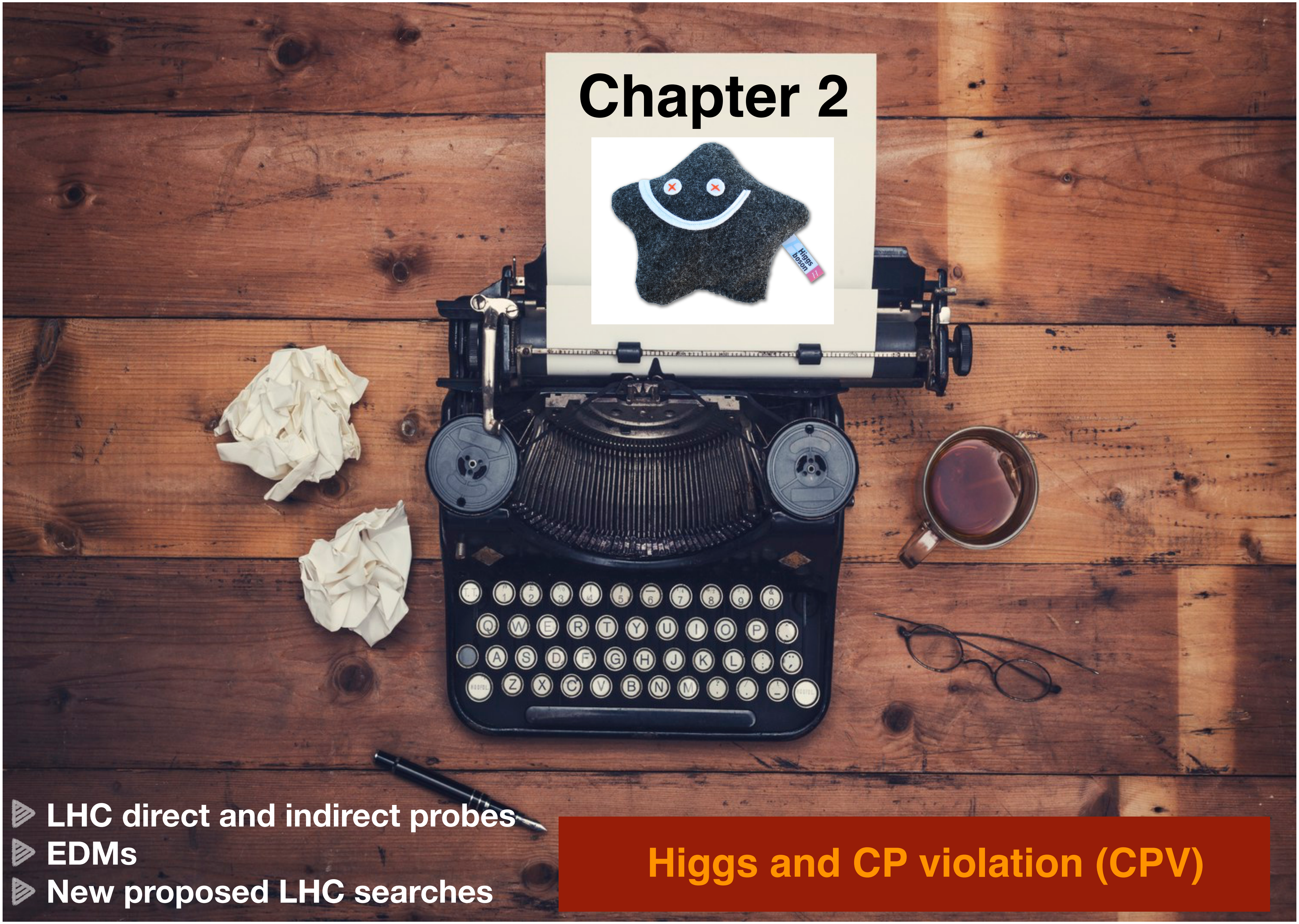
2. Higgs decaying to **visible + invisible particles** (example: $h \to X_1 X_2$, $X_2 \to (ff)$ + MET and X_1 invisible)

Chapter 2



- LHC direct and indirect probes
- EDMs
- New proposed LHC searches

Higgs and CP violation (CPV)

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	$< 1.1 \times 10^{-29}\, e\,\text{cm}$	$\sim 10^{-30}\, e\,\text{cm}$
d_μ	$< 10^{-42}$ e cm	$< 1.9 \times 10^{-19}\, e\,\text{cm}$	$\sim 10^{-23}\, e\,\text{cm}$
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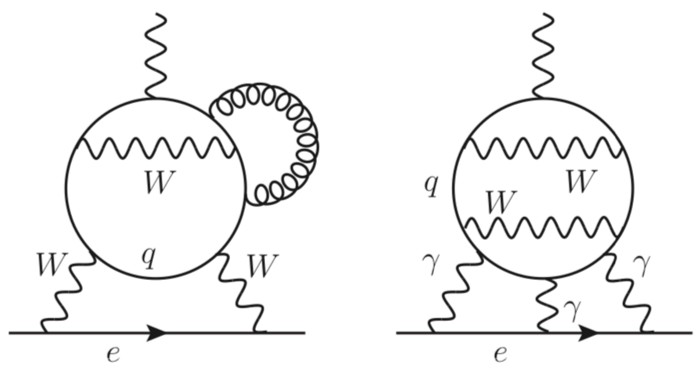
example diagrams
in the Standard Model:



d_e: ACME collaboration — ACME collaboration

d_μ: g-2 collaboration — EDM experiment @ PSI

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

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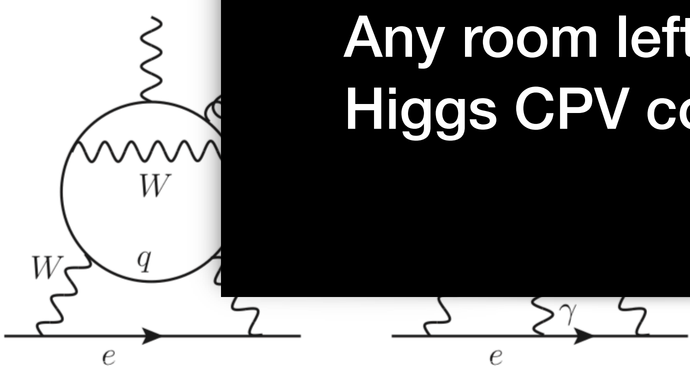
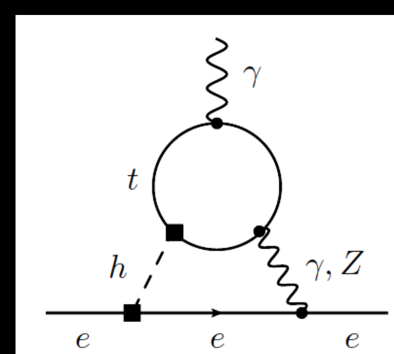
exa
in the



Any room left for
Higgs CPV couplings?



CME
llaboration

M experiment
PSI

elle II &
e^+e^- experiments

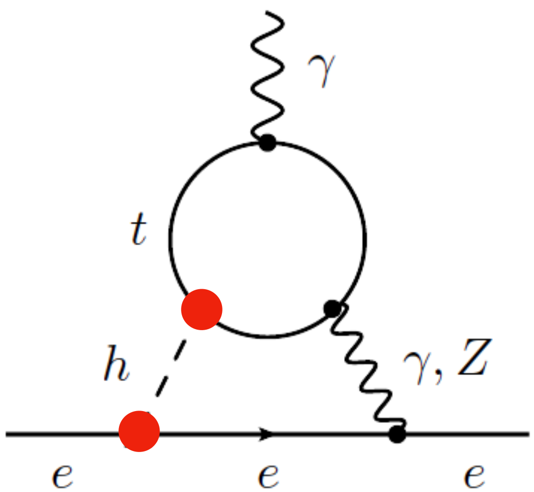
EDMs, naive bounds on Higgs CPV couplings (EFT approach)

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

$$|\tilde{\kappa}_e| \lesssim 1.7\times10^{-3}$$
$$|\tilde{\kappa}_t| \lesssim 1.0\times10^{-3}$$

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

CPV couplings & Higgs rate measurements

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

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

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

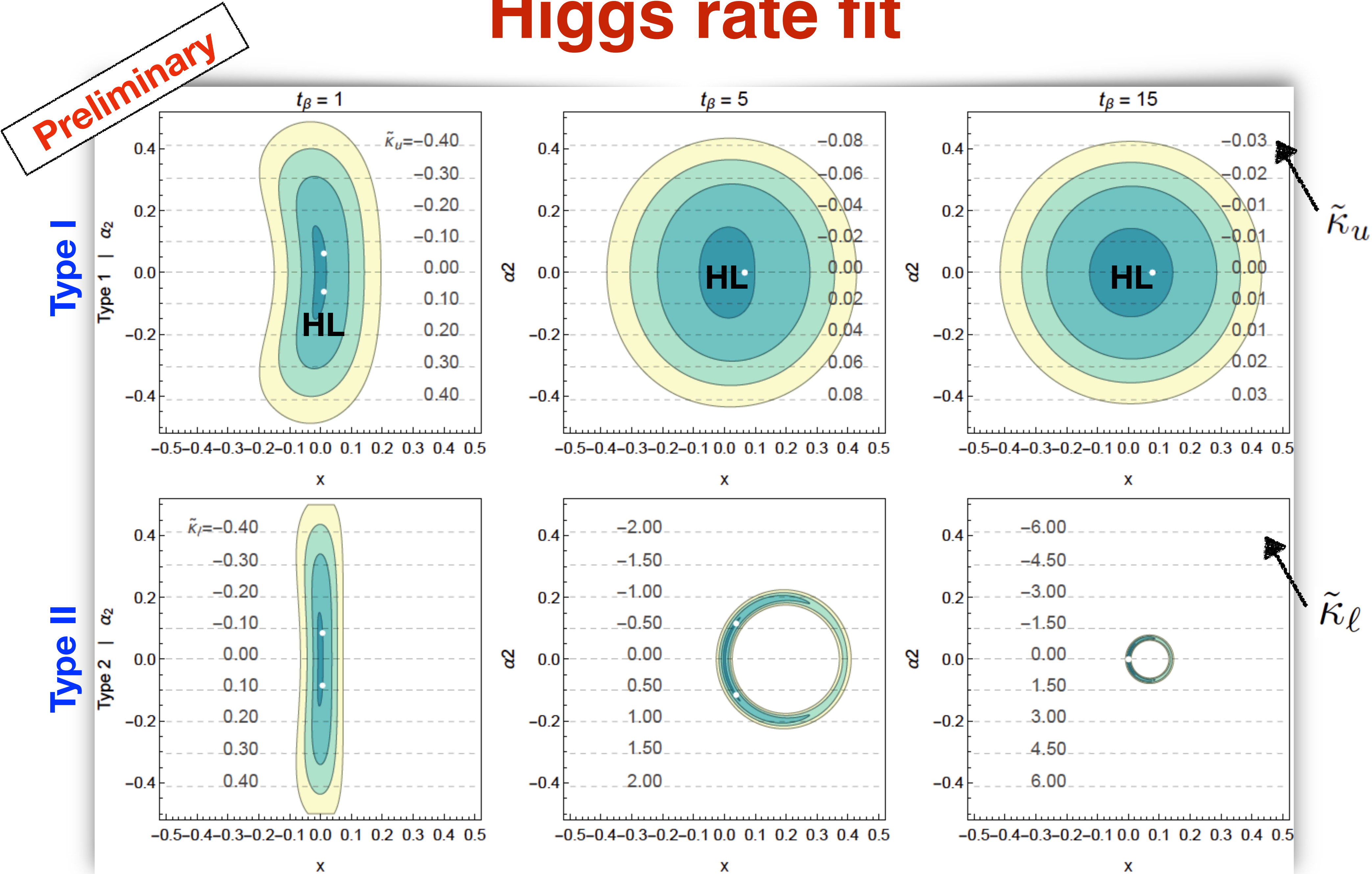
Some rates are easily scaled from the SM predictions:

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.

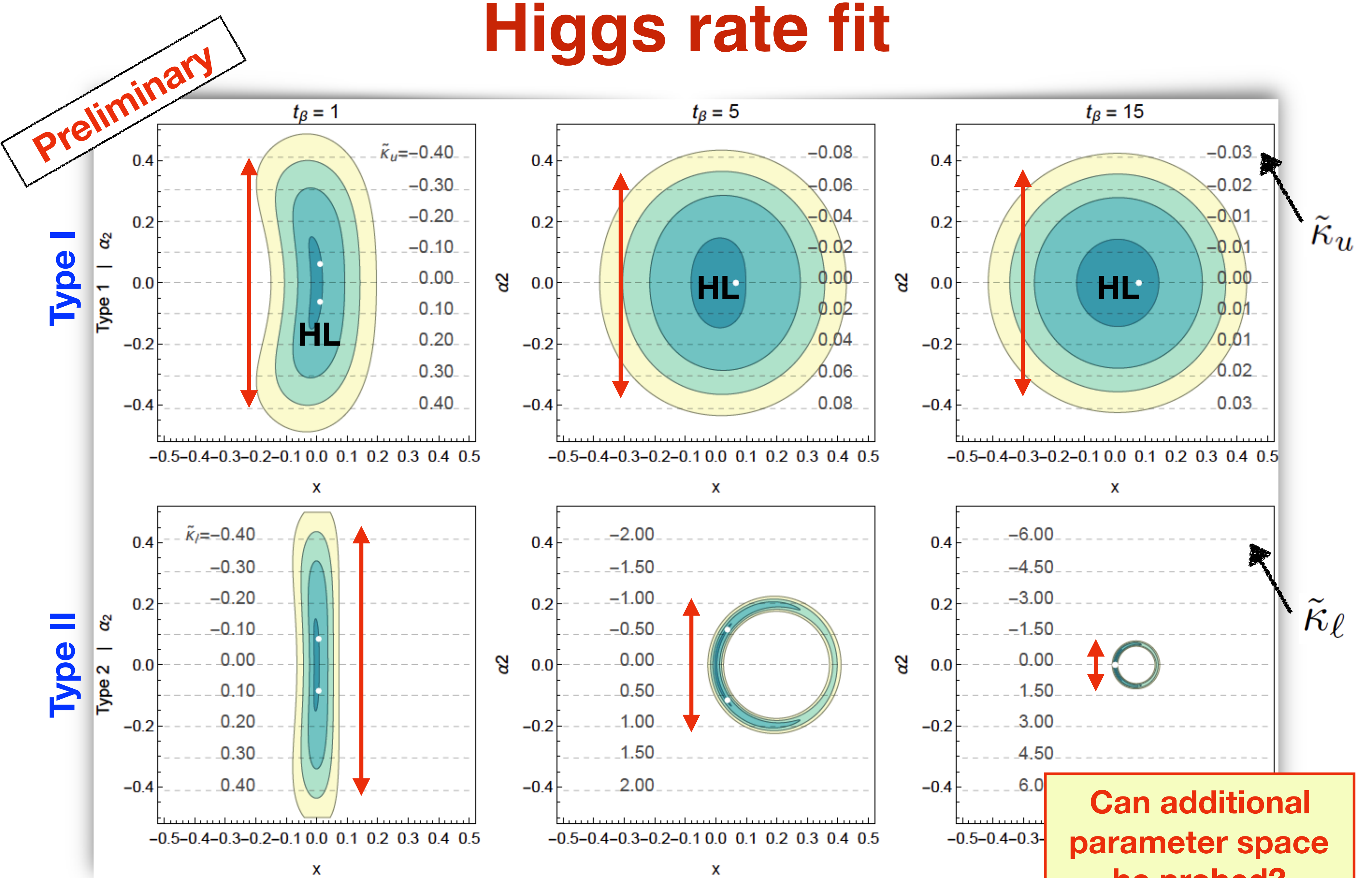
$$\sigma(gg \to h) \simeq \sigma(gg \to h)_{\rm SM} \times$$
$$\times\, (1.1\kappa_u^2 + 3.6\times 10^{-3}\kappa_d^2 - 0.12\kappa_u\kappa_d + 2.5(\tilde{\kappa}_u^{(1)})^2 + 3.6\times 10^{-3}(\tilde{\kappa}_d^{(1)})^2 + 0.19\tilde{\kappa}_u^{(1)}\tilde{\kappa}_d^{(1)})$$

Higgs rate fit



SG, Hamer, appearing soon

Higgs rate fit



Can additional parameter space be probed?

SG, Hamer, appearing soon

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)

$$\begin{cases} \tilde{g}_{hZZ} \simeq -\dfrac{\sin\alpha_2}{\tan\beta}\dfrac{1}{8\times 10^5\ \mathrm{GeV}} \\ \tilde{g}_{hWW} \simeq \dfrac{\sin\alpha_2}{\tan\beta}\dfrac{1}{7\times 10^5\ \mathrm{GeV}} \end{cases}$$ (*)

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

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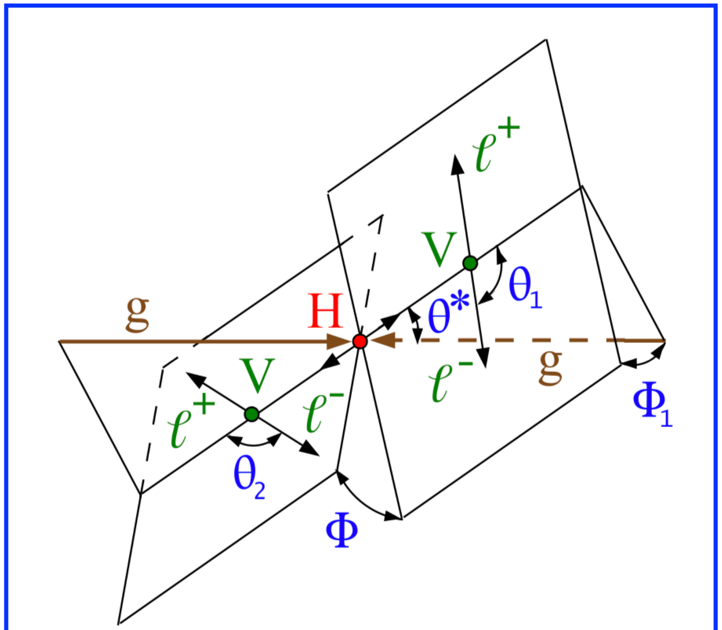
CP-even coupling: $hZ_{\mu\nu}Z^{\mu\nu}$

Searches for:

- $h \to ZZ^* \to 4l$, $h \to WW^* \to l\nu l\nu$;
- $h \to \tau\tau$ with the Higgs produced in vector boson fusion;
- $h \to bb$ 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)

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

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

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

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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 $h \to \tau^\pm \tau^\mp$: $\left|\frac{\tilde{\kappa}_\tau}{\kappa_\tau}\right| \lesssim 0.87$ (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

Direct searches for Higgs CPV (fermionic)

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

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$$\begin{cases} \tilde{\kappa}_u & -\frac{s_{\alpha_2}}{t_\beta} & -\frac{s_{\alpha_2}}{t_\beta} \\ \tilde{\kappa}_{d,\ell} & \frac{s_{\alpha_2}}{t_\beta} & -s_{\alpha_2} t_\beta \end{cases}$$

Type I **Type II**

- 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)
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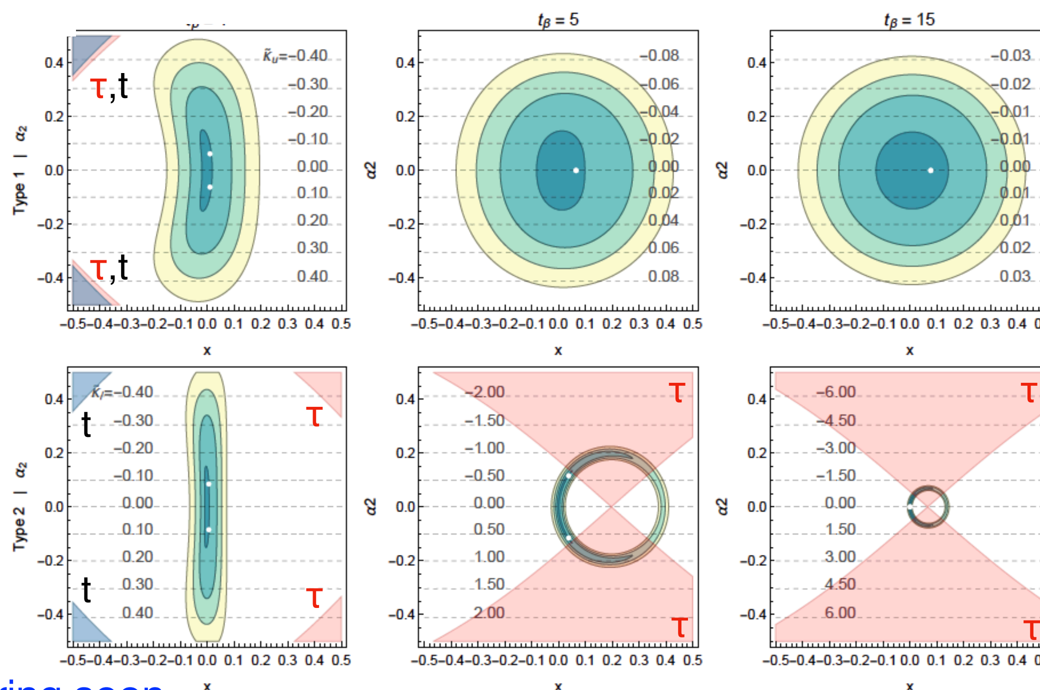
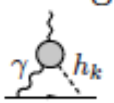
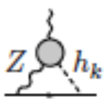
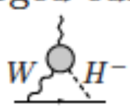
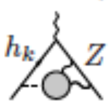
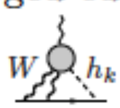


SG, Hamer, appearing soon

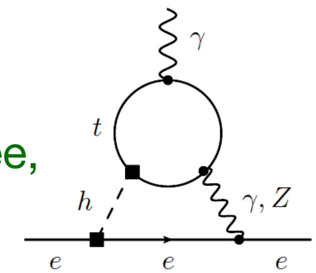
EDMs, a complete 2HDM study

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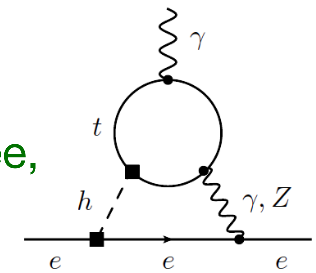
Altmannshofer, SG, Hamer, Patel, 2009.01258

◯ Note the gauge dependence

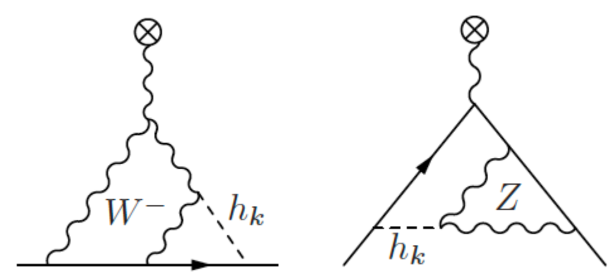


Barr-Zee, 1990

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

Barr-Zee	Fermion loop	Charged Higgs loop	Gauge boson loop
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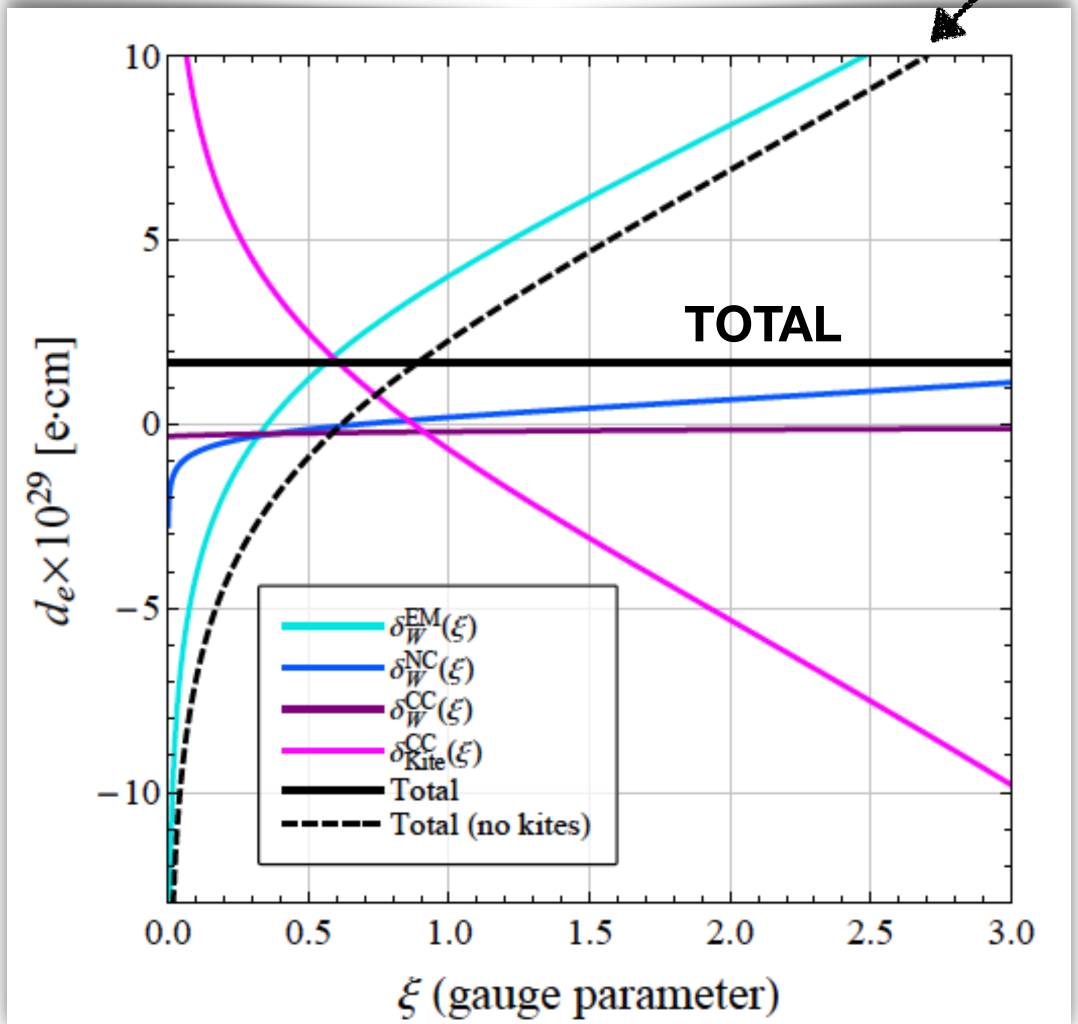
Altmannshofer, SG, Hamer, Patel, 2009.01258

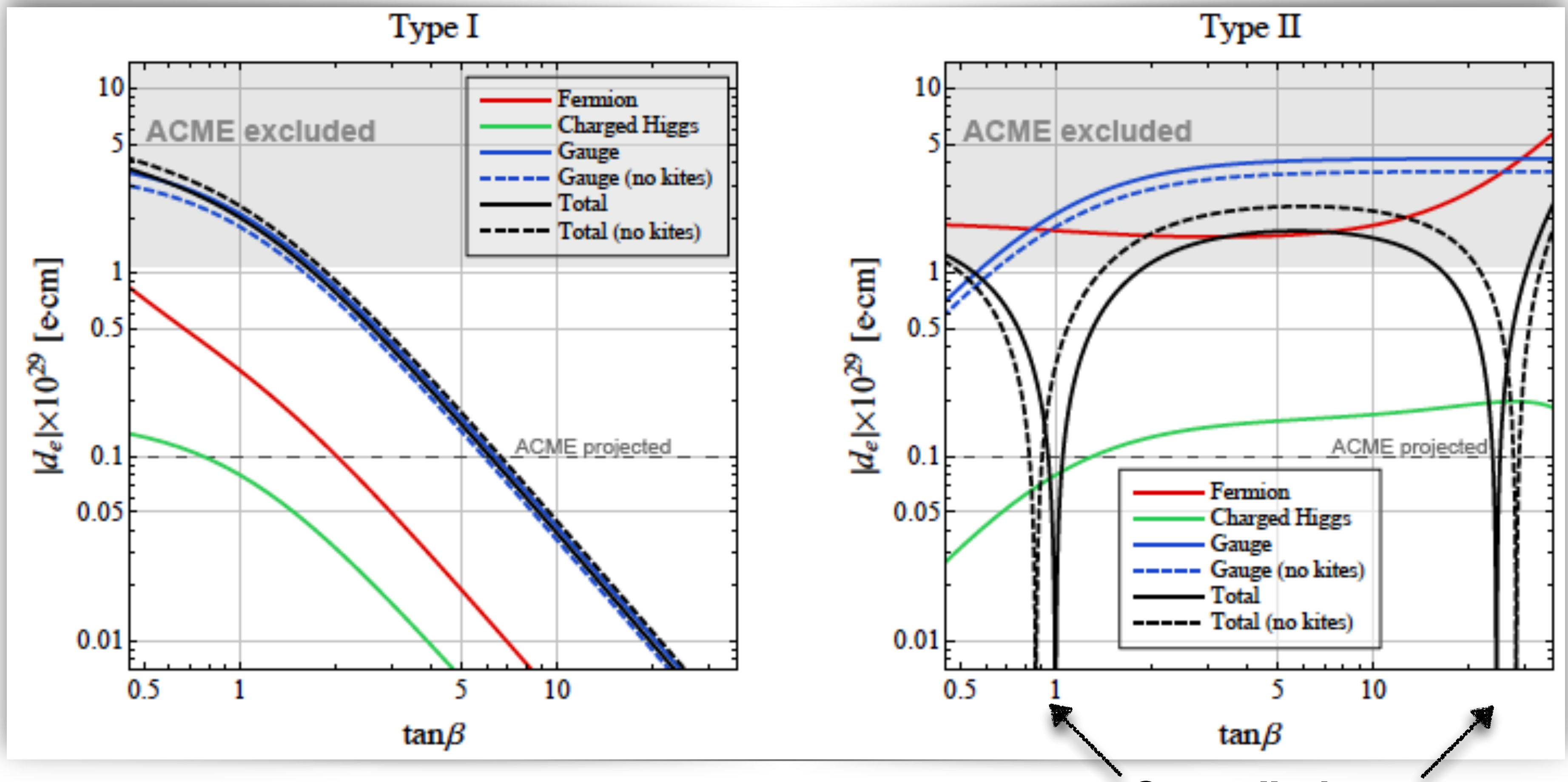
Notice the **gauge dependence** if we do not include the Kite diagrams



EDMs, 2HDM results

Example benchmark:

Altmannshofer, SG, Hamer, Patel, 2009.01258



Cancellations

In the decoupling limit:

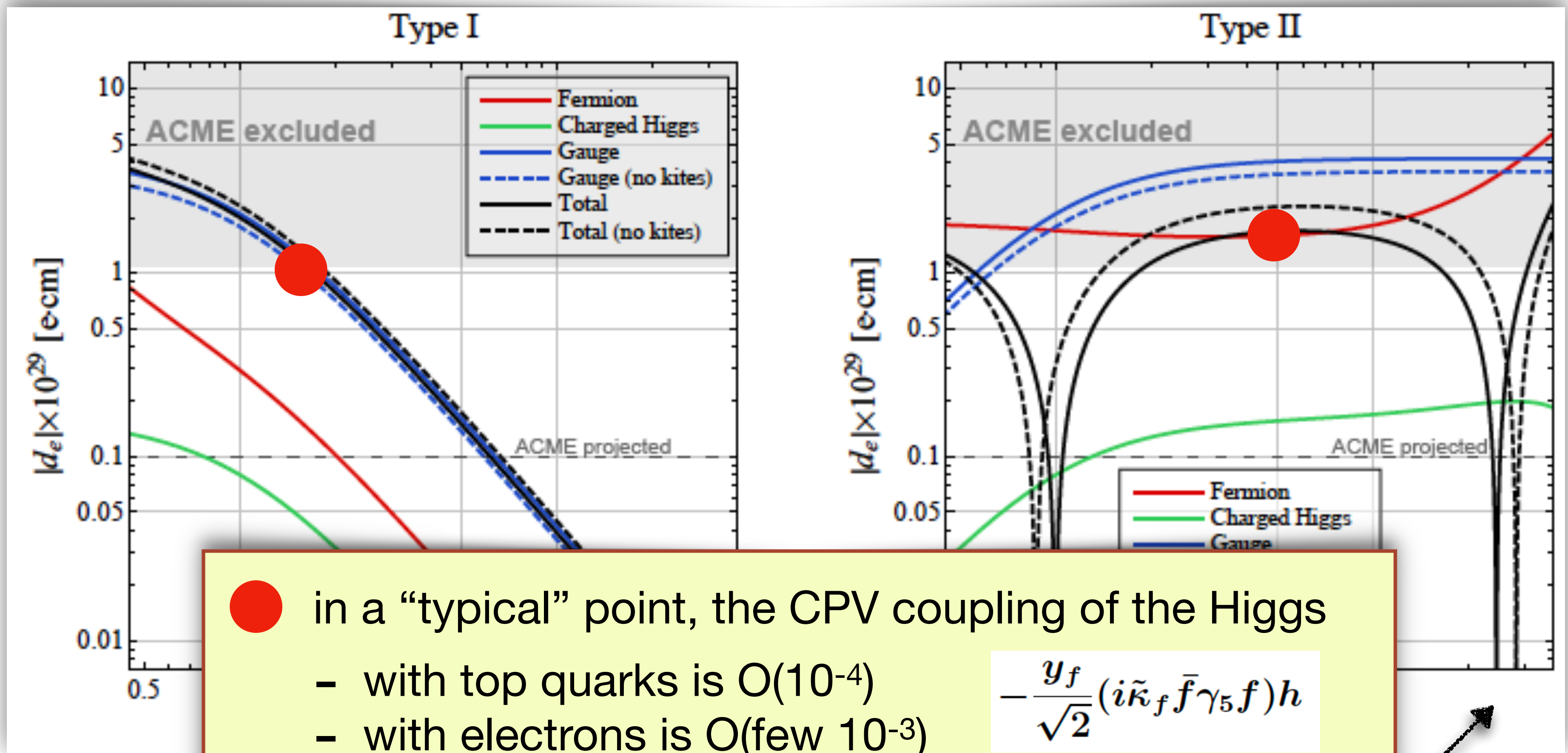
$$\text{Type I:} \quad d_e = -1.06 \times 10^{-27} e\,\text{cm} \times \left(\frac{1\,\text{TeV}}{M}\right)^2 \text{Im}(\lambda_5) \quad \cos^2\beta \left[1 + 0.07 \ln\left(\frac{M}{1\,\text{TeV}}\right)\right],$$

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

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

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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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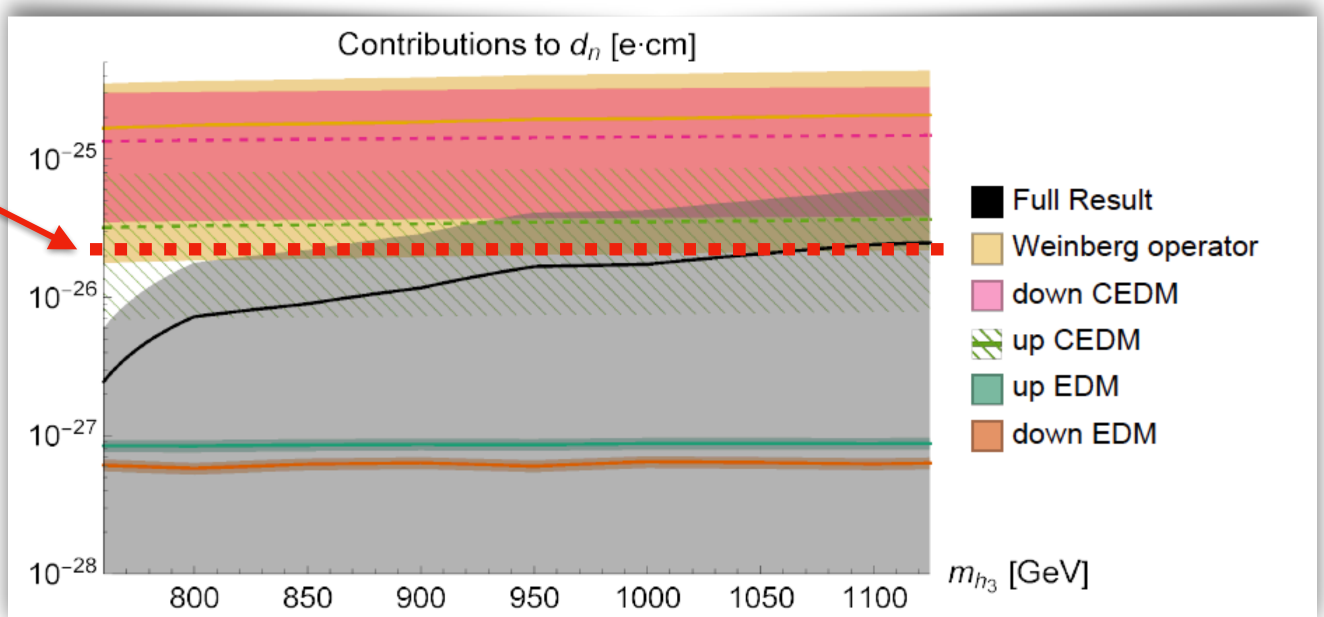
Very large theoretical uncertainties

exp bound



This is for a benchmark scenario with

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

SG, Hamer, appearing soon

Heavy Higgs pheno. CPV signatures

H_3 and H_2 can lead to striking CPV signatures

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
- $H_3 \to H_2 Z$, $H_2 \to H_1 Z$
- $H_3 \to H_1 H_2$
- ...

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

Heavy Higgs pheno. CPV signatures

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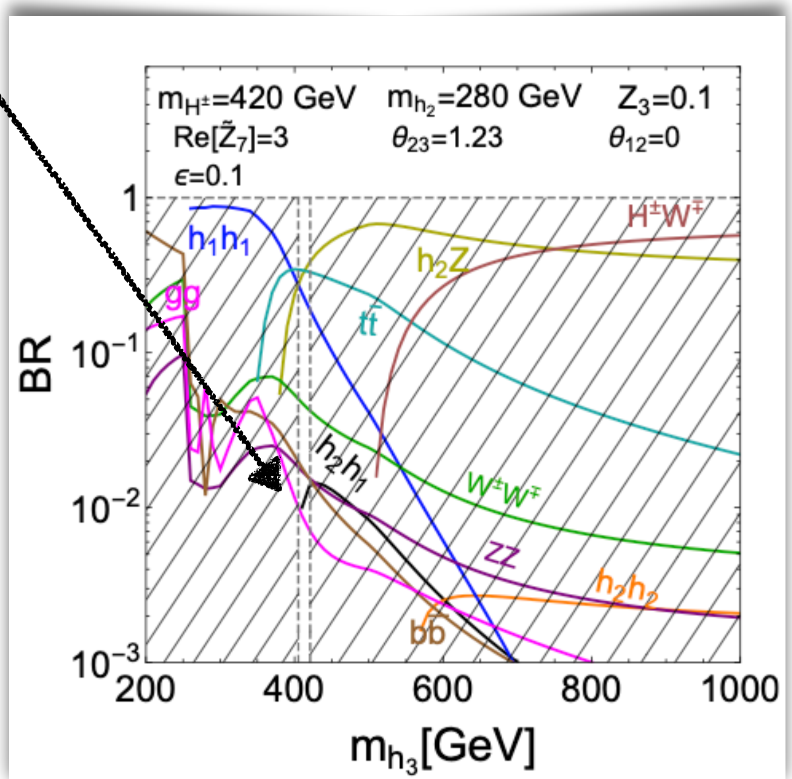

Low, Shah, Wang, 2012.00773.

Theory & pheno constraints on large mass splittings

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

Constraints from

- perturbativity
- vacuum stability

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

Possible constraints from **electroweak precision tests**: **m_W!**

However, no New Physics effect on m_W if

$$m_{H^\pm} = m_{h_2} \text{ or}$$
$$m_{H^\pm} = m_{h_3}$$

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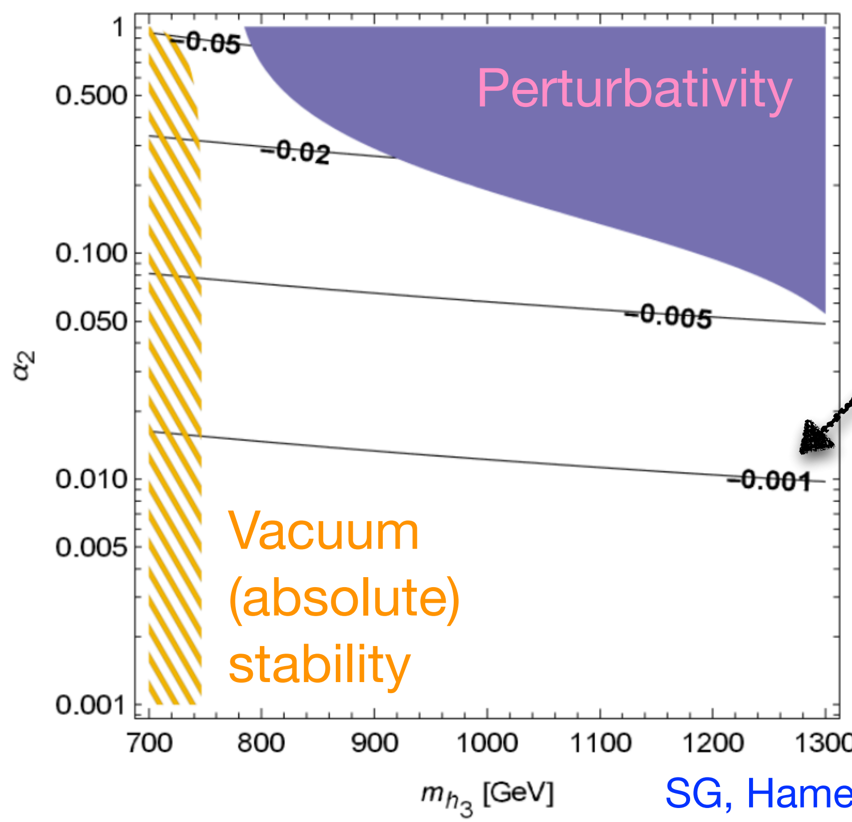


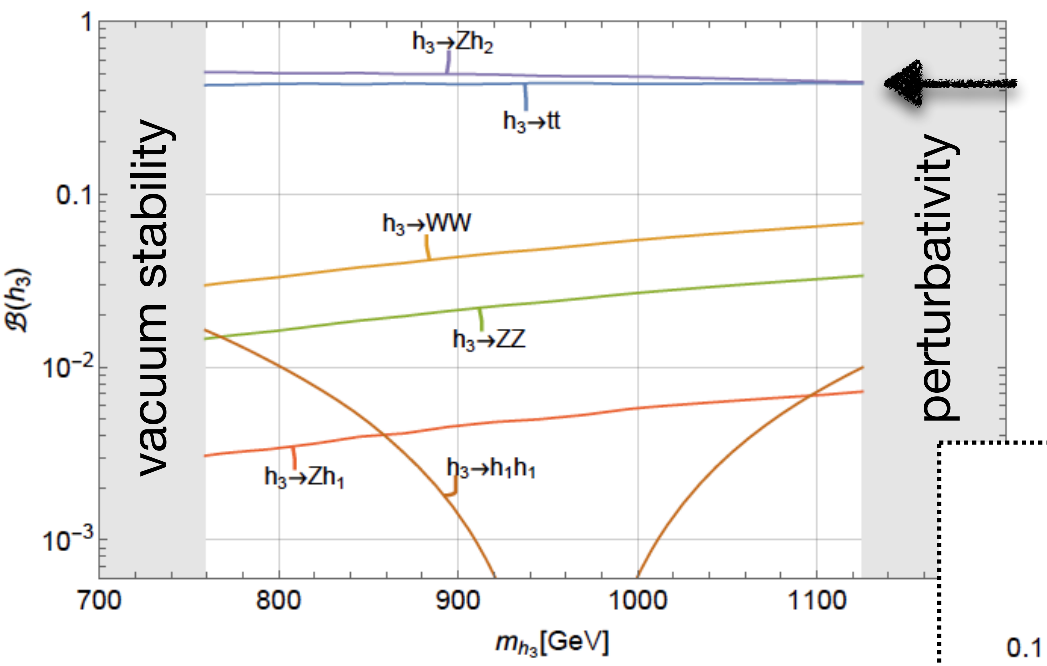
α_3 contours

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

SG, Hamer, appearing soon

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

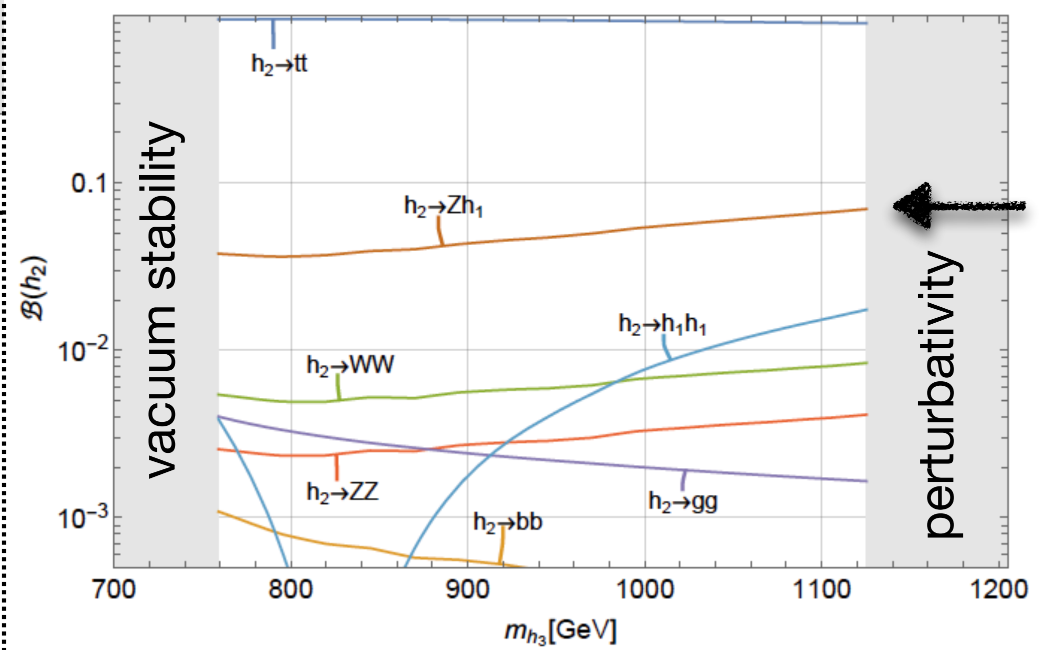
h_3 mainly CP odd



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

(benchmark allowed by EDMs)

h_2 mainly CP even



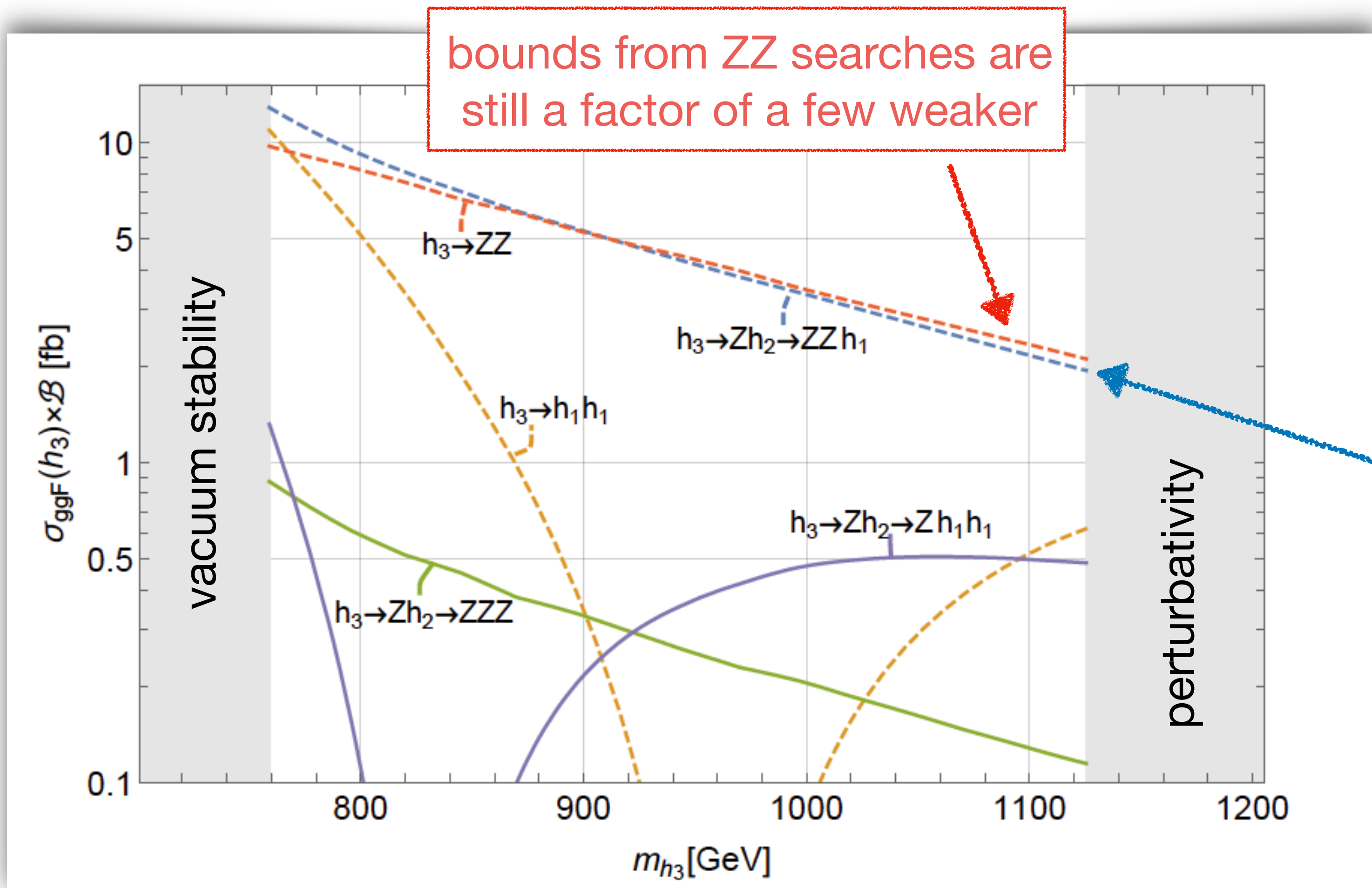
$$\mathcal{L}_{\text{gauge}} = \frac{g^2 v}{4} \sum_k g_{h_k VV} \left[2W_\mu^+ W^{\mu -} + \frac{1}{\cos^2\theta} Z_\mu Z^\mu \right] h_k + \frac{g}{2\cos\theta} Z_\mu \sum_{i<j} g_{Z h_i h_j} \left[h_i \partial^\mu h_j \right]$$

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

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

SG, Hamer, appearing soon

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



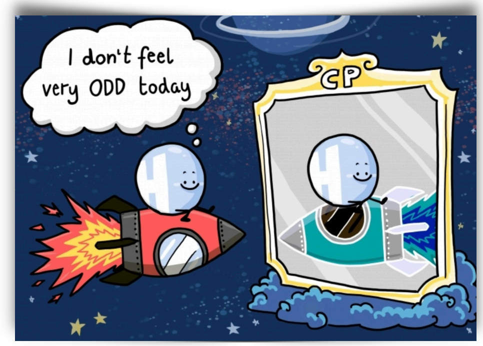
SG, Hamer, appearing soon

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

However, 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

$\left(\begin{array}{l} H_3 \to H_2\, Z,\ H_2 \to H_1\, Z \\ H_3 \to H_1\, H_2 \end{array} \right)$

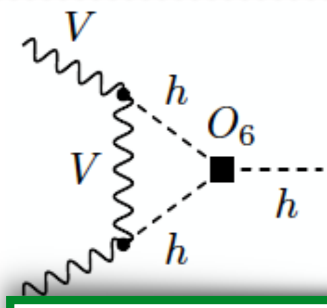
Complementarity

2. Higgs self-couplings and single Higgs

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

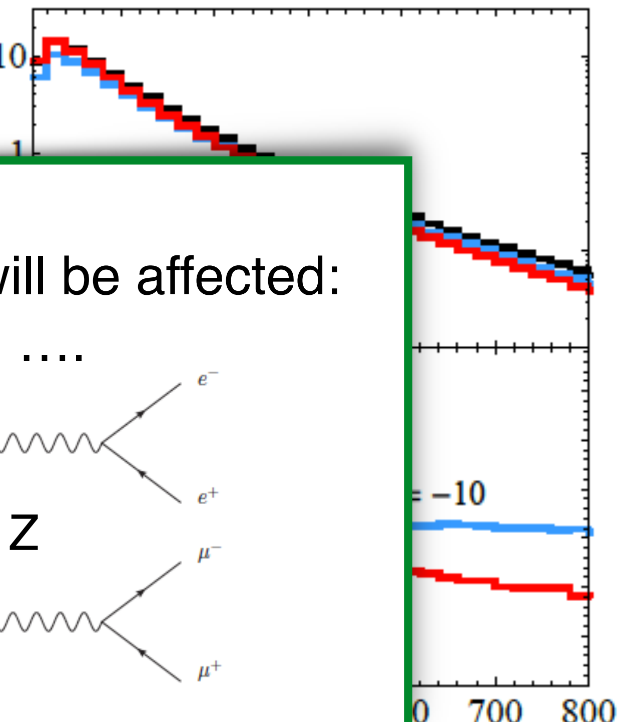
For example, the coupling to W and Z bosons:

example diagram:



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

2. NP effects in differential distributions, as well

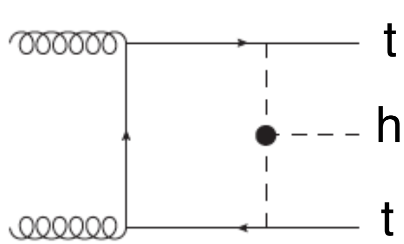


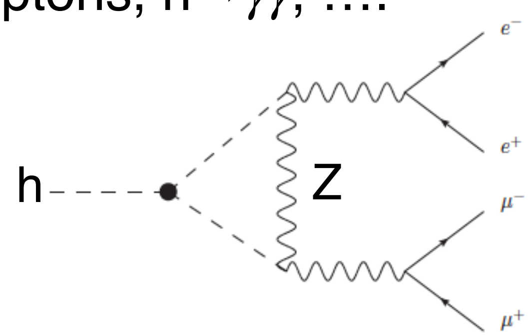
Bizon et al., 1610.05771

Maltoni et al., 1709.08649

Many additional single Higgs measurements will be affected:

tth production, h → 4leptons, h→$\gamma\gamma$, ….





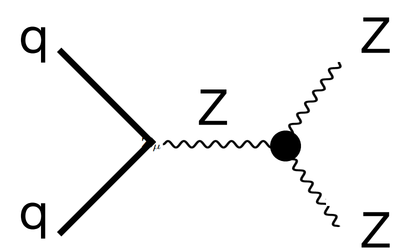
Extracted kλ with the one from di-Higg

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:

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

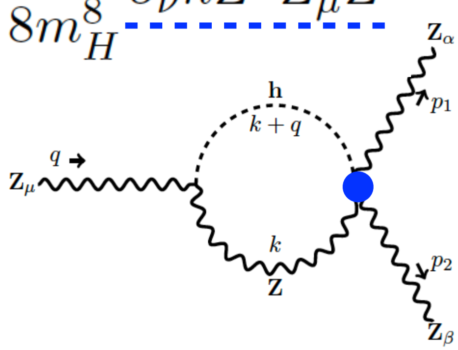


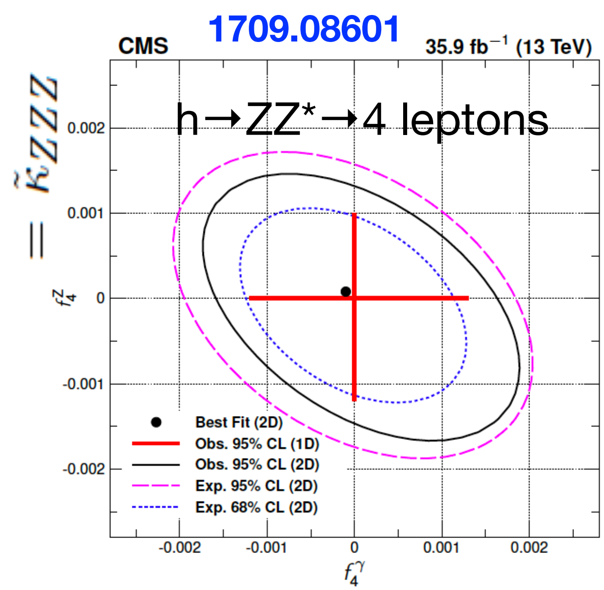
this CPV operator enters eg. the pp → ZZ production (together with CP conserving operators)

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

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

Parameters of the 2HDM potential





S.Gori

Backup

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.