CP violation in Higgs and in gauge boson couplings

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Open symposium-update of the European strategy for particle physics
Granada conference center

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Plan of the talk

1. Anomalous Higgs couplings

1.1 Flavor violating couplings

CP violating couplings 1.2

Higgs production

Higgs decays

2. Anomalous gauge couplings & CP violation

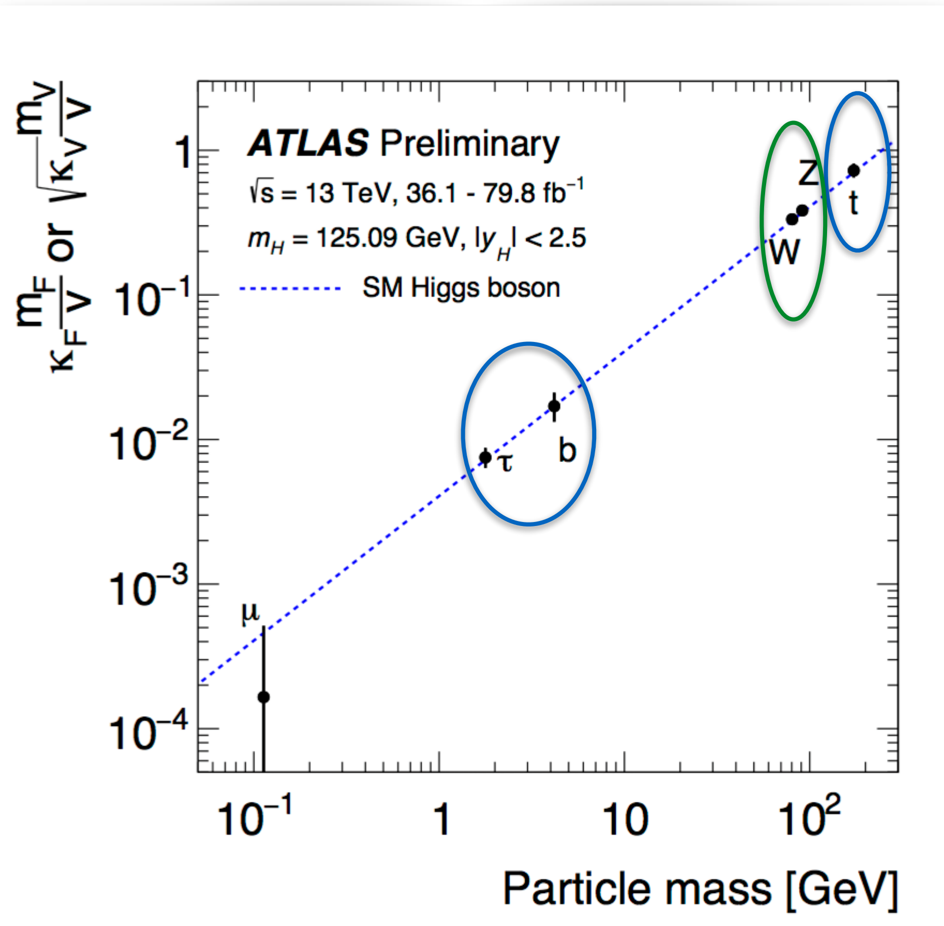
Opportunities at present and future experiments

High energy

Low energy

Higgs: what we know & what we do not

The Higgs we have discovered has SM-like properties



ATLAS-CONF-2018-031

We know:

We have evidence that the Higgs gives mass to the 3rd generation fermions and gauge bosons.

We do not know:

- Many additional couplings!

light generations,
self-coupling,
flavor violating couplings

- Are (some of the) couplings CP violating?
- Higgs rare/exotic decays?
- Higgs width
- Are there new Higgs bosons?

Higgs: what we know & what we do not

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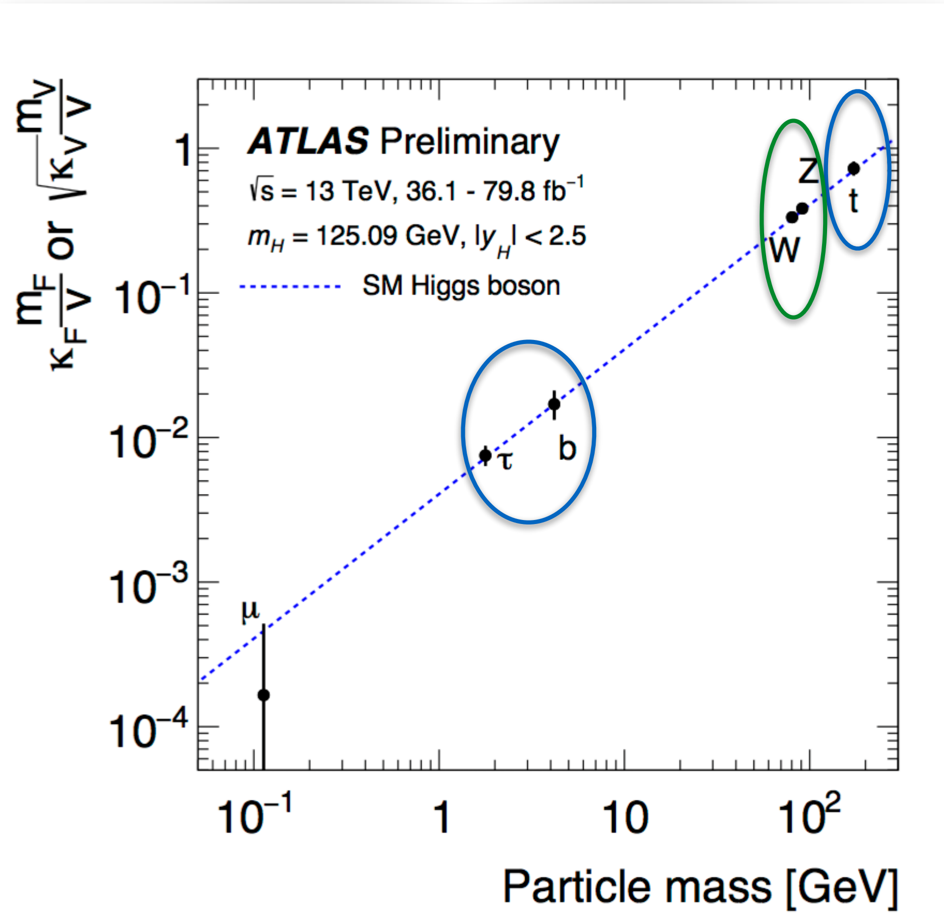

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Many open questions are in the realm of flavor and CPV physics

Higgs flavor and CPV questions

Does the Higgs give mass to the first and second generation fermions?
Connection to the SM flavor puzzle
we will (relatively soon) get to know about the muons, but what about the others?
(interesting strategies for charm coupling, inclusive vs. exclusive determinations)

Does the Higgs have anomalous flavor violating couplings ⟵ **For this talk**
that show up at high energy experiments as Higgs flavor violating decays or Higgs flavor violating production modes?

Is the Higgs a CP admixture? ⟵ **For this talk**
(we know that the 100% pseudo-scalar hypothesis is experimentally ruled out)

Is there still room for new sources of flavor or CP violation not constrained by low energy measurements? **Where do we expect future progress?**

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In the Standard Model, the picture is quite simple:
Higgs couples $\propto$ mass → tiny couplings for 1st and 2nd generation
No Higgs flavor violating couplings at tree level
NO CPV in Higgs couplings

Why is this important?

Many models generically **allow** new sources of flavor + CPV in the Higgs sector (SUSY, composite Higgs, twin Higgs, …)

Some models **do require** new sources of CPV in the Higgs sector:
Electroweak baryogenesis models
Establishing targets for CPV searches?

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Establishing targets for CPV searches?

Classic example: Two-Higgs-Doublet-model:

All 3 Higgses will have a CP odd and a CP even component

$$\begin{aligned} V(H_1,H_2) &= \mu_1^2|H_1|^2+\mu_2^2|H_2|^2+(bH_1H_2+\mathrm{h.c}) \\ &+ \frac{\lambda_1}{2}|H_1|^4+\frac{\lambda_2}{2}|H_2|^4+\lambda_3|H_1|^2|H_2|^2+\lambda_4|H_1H_2|^2 \\ &+ \left[\frac{\lambda_5}{2}(H_1H_2)^2+\lambda_6|H_1|^2H_1H_2+\lambda_7|H_2|^2H_1H_2+\mathrm{h.c}\right] \end{aligned}$$

New sources of CPV

CPV in hVV couplings

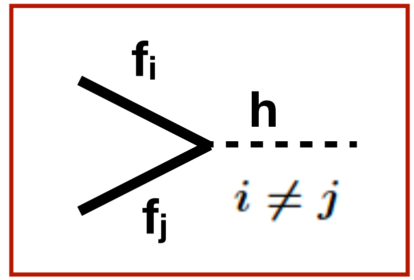
$$\mathcal{H}_Y^{\mathrm{gen}} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \mathrm{h.c.}$$

New sources of CPV and flavor violation, for generic 3*3 Yukawas

CPV in hff couplings

Constraints on flavor violating couplings

Low energy



- <u>Generic very stringent bounds:</u>

meson mixing, EDM (if CPV), $\mu \to e\gamma$, ...

For example:

Eff. couplings	95% C.L. Bound $\lvert c_{\text{eff}}\rvert$	95% C.L. Bound $\lvert\text{Im}(c_{\text{eff}})\rvert$	Observables
$c_{sd}\ c_{ds}^*$	1.1×10^{-10}	4.1×10^{-13}	$\Delta m_K;\ \epsilon_K$
$c_{ds}^2,\ \ c_{sd}^2$	2.2×10^{-10}	0.8×10^{-12}	
$c_{cu}\ c_{uc}^*$	0.9×10^{-9}	1.7×10^{-10}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$c_{uc}^2,\ \ c_{cu}^2$	1.4×10^{-9}	2.5×10^{-10}	
$c_{bd}\ c_{db}^*$	0.9×10^{-8}	2.7×10^{-9}	$\Delta m_{B_d};\ S_{B_d \to \psi K}$
$c_{db}^2,\ \ c_{bd}^2$	1.0×10^{-8}	3.0×10^{-9}	
$c_{bs}\ c_{sb}^*$	2.0×10^{-7}	2.0×10^{-7}	Δm_{B_s}
$c_{sb}^2,\ \ c_{bs}^2$	2.2×10^{-7}	2.2×10^{-7}	
$\lvert c_{e\tau} c_{\tau\mu}\rvert,\ \ \lvert c_{\tau e} c_{\mu\tau}\rvert$	1.7×10^{-7}		$\mathcal{B}(\mu \to e\gamma)$

from Blankenburg, Ellis, Isidori, 1202.5704
see also Harnik, Kopp, Zupan, 1209.1397

- <u>Not all couplings are well probed:</u>

t → c, t → u

τ → μ, τ → e

Low energy constraints at the level of ~O(few 10^{-2})

Opportunity for high energy experiments!

1.1

Constraints on flavor violating couplings

High energy

Decays

LHC searches for Higgs flavor violating decays, **h** → τμ, **h** → τe give the most stringent bounds on the corresponding couplings (present bounds at the level of ~**2*10^{-3}**).

Production

Same message for the LHC searches for t → c**h**, t → u**h** (present bounds on the branching ratio at the level of **10^{-3}**)

Possible targets

	2HDM	MSSM
$t \to cZ$	$\lesssim 10^{-6}$	$\lesssim 10^{-7}$
$t \to c\gamma$	$\lesssim 10^{-7}$	$\lesssim 10^{-8}$
$t \to cg$	$\lesssim 10^{-5}$	$\lesssim 10^{-7}$
$t \to ch$	$\lesssim 10^{-2}$	$\lesssim 10^{-5}$

1.1

Constraints on flavor violating couplings

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Production

Same message for the LHC searches for t → **ch**, t → u**h** (present bounds on the branching ratio at the level of **10^{-3}**)

Discovery opportunity for anomalous (rare) Higgs decays or production modes.

Large improvements are expected at the HL-LHC and higher energy colliders

(t → ch at the level of **few*10^{-6}** obtainable at a 100 TeV collider with 10 ab^{-1} data)

Possible targets

	2HDM	MSSM
$t \to cZ$	$\lesssim 10^{-6}$	$\lesssim 10^{-7}$
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Additional questions:

H → τμ, H → tc (heavy Higgs)? or Htc production? htc production?

These questions can be linked to the origin of light generation fermion masses

Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927

1.2

CPV in Higgs couplings to gauge bosons

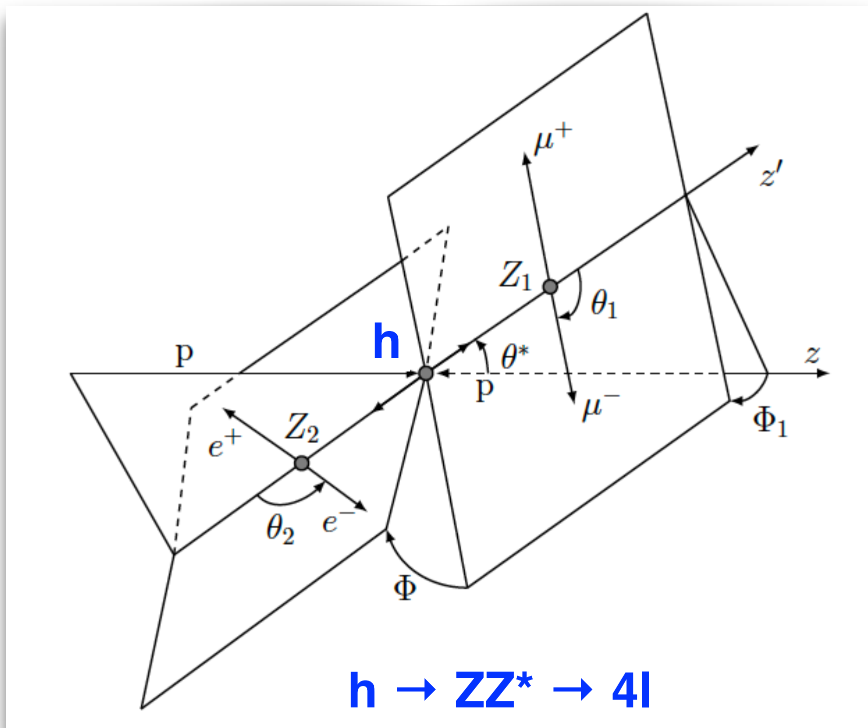
h → 4 leptons (decay)

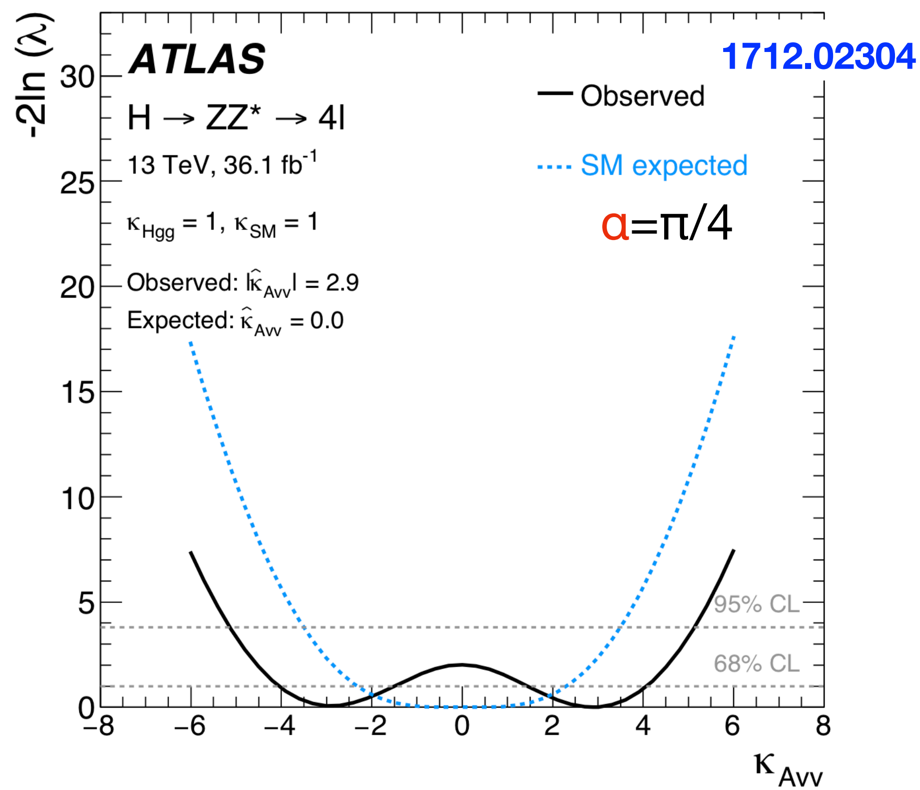
Using an effective Lagrangian approach…

α is the mixing between the CP-odd and CP-even states

$$\mathcal{L}_V = \left[\cos(\alpha)\kappa_{\rm SM}\left(\frac{1}{2}g_{hZZ}Z_\mu Z^\mu\right) - \frac{1}{4}\frac{1}{\Lambda}\left(\cos(\alpha)\kappa_{hZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right)\right] h$$

(In the SM: $\alpha=0$, $k_{SM}=1$, $g_{hZZ}=2m_Z^2/v$)





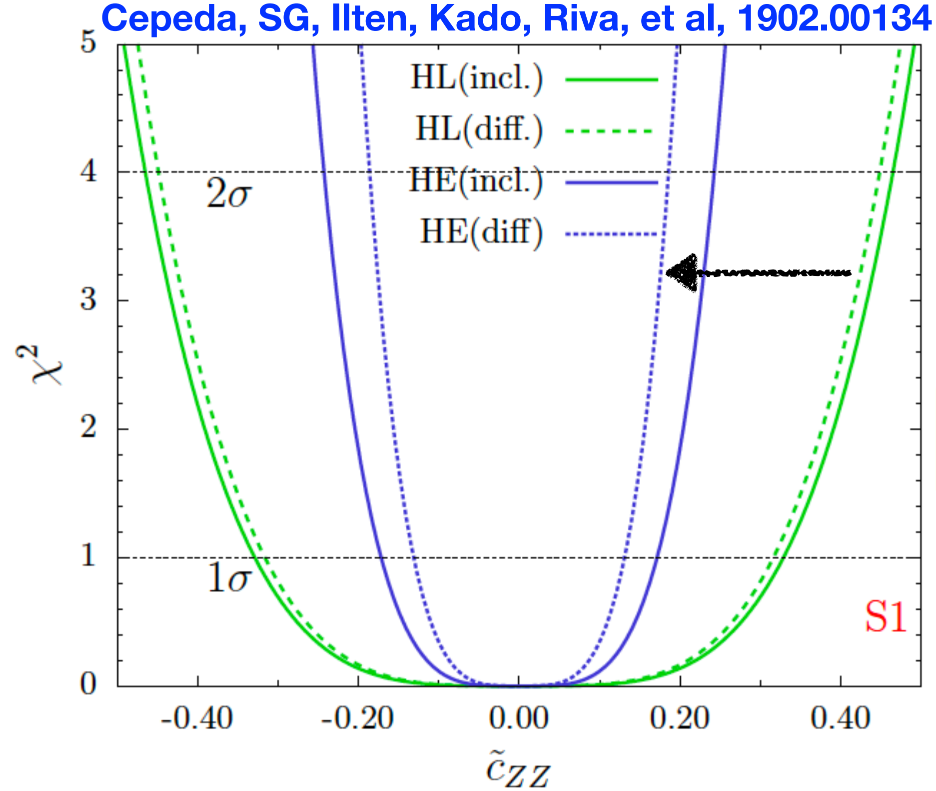
Fits also include differential measurements of h → WW* →2l 2nu (weaker)

CPV in Higgs couplings to gauge bosons
$h \to$ 4 leptons (decay), future

With more LHC data (HL), it will be more and more important the interplay between

- Inclusive measurements (Higgs rate) ← Higgs precision program
- Exclusive measurements (differential)

HL/HE Higgs Yellow Report,
Cepeda, SG, Ilten, Kado, Riva, et al, 1902.00134



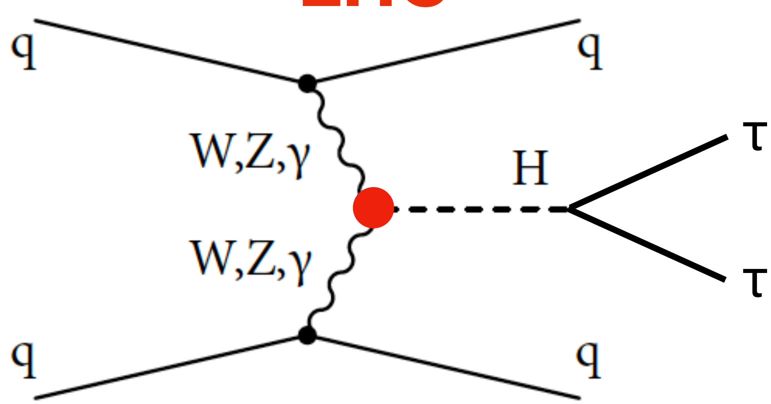
$$\left[\tilde{c}_{ZZ}\frac{g_1^2+g_2^2}{4v}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] h$$

1.2

CPV in Higgs couplings to gauge bosons
Higgs production

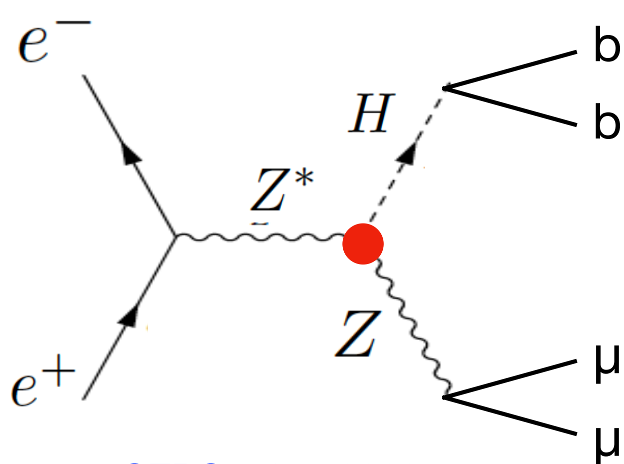
An alternative way to probe the CPV phase in the h-gauge boson couplings is through Zh, Wh or VBF production (Higgs decays that are fully reconstructable)

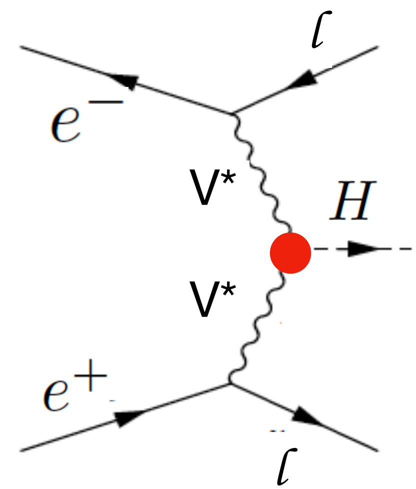
LHC



CMS: 1903.06973
ATLAS: 1602.04516

e+e- colliders





CEPC: 1810.09037
ILC: 1712.09772

CP odd coupling bound ~3 more stringent than the HL-LHC projections

1.2

CPV in Higgs-fermion couplings
Higgs-tau-tau

CPV in fermion couplings can be completely independent on the CPV in the Higgs-gauge boson couplings

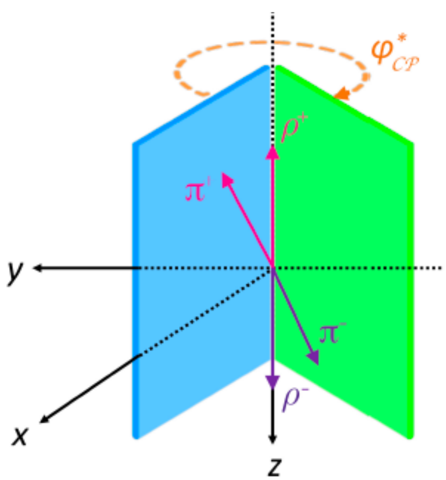
(Reminder of 2HDM: $\bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2$)

Pheno idea:

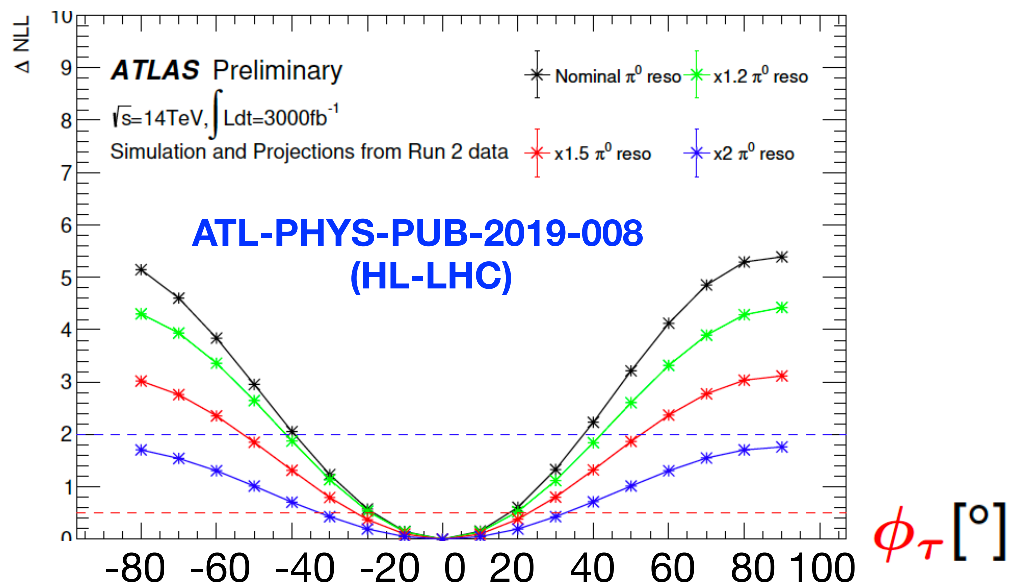
Berge et al., 1108.0670
Harnik et al., 1308.1094

$$h \to \tau^+\tau^-,$$
$$\tau^\pm \to (\rho^\pm \to \pi^\pm\pi^0)\nu$$

measurement of tau polarization



$$g_{\tau\tau}\left(\cos(\phi_\tau)\bar{\tau}\tau + \sin(\phi_\tau)\bar{\tau}i\gamma_5\tau\right)h$$



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

S.Gori

1.2

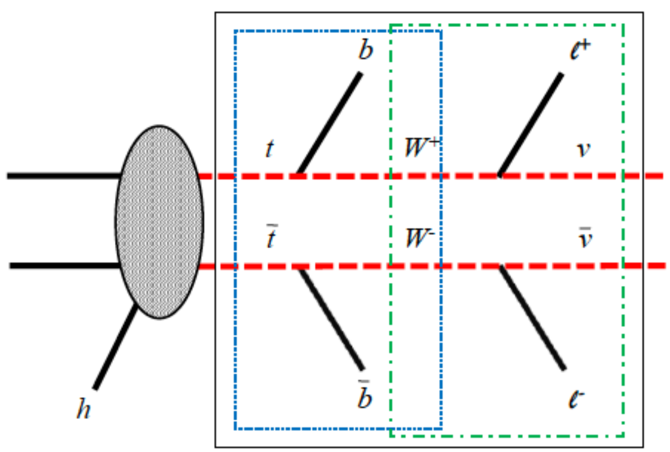
CPV in Higgs-fermion couplings
Higgs-top-top

$$\frac{y_t}{\sqrt{2}}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) h$$

LHC, tt h → bb tt

Exploring the spin correlations in the top decays

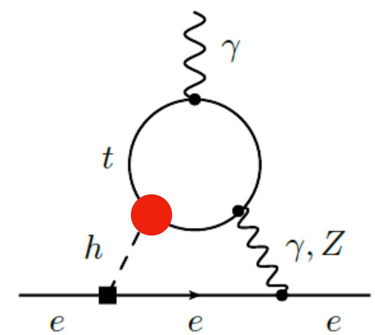
Goncalves, Kong, Kim, 1804.05874

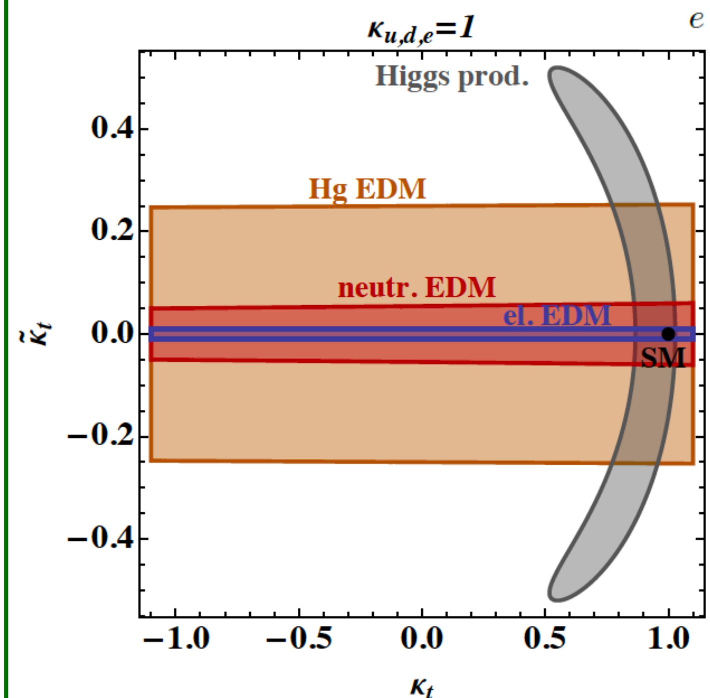


At the HL-LHC, the bound is rather weak (even if ~model independent).
Possible exclusion of the maximal phase

EDM measurements

give complementary information





Brod, Haisch, Zupan, 1310.1385

1.2

Additional CPV Higgs coupling probes

An (incomplete) list…

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 → $\tau\,\tau$. Uses associated jets for angular analysis

$\gamma\gamma$ (important constraints from EDMs)

- Requires converted photons and angular resolution on leptonic opening angles Bishara, Grossman, Harnik, Robinson, Shu, Zupan [1312.2955]
- Measurement of the angle between the beam axis and the photon pair in the Collins–Soper frame ATLAS, 1802.04146

bb, cc (important constraints from EDMs)

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

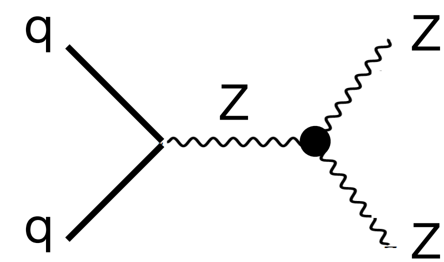
Can possible overcome QCD wash-out of quark polarization

2

CPV in triple gauge couplings

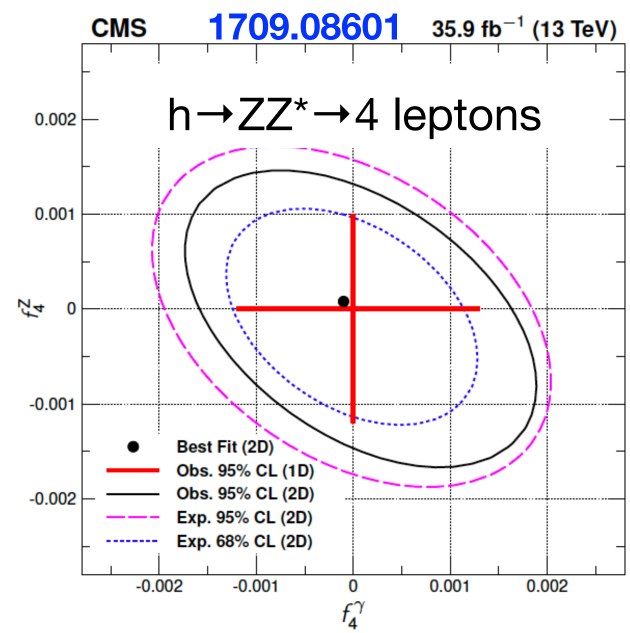
Beyond Higgs measurements, measurements of di-boson production can unveil the existence of new sources of CPV in triple gauge couplings

For example:



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

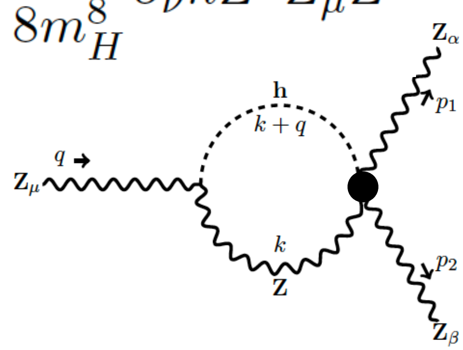
this CPV operator enters eg. the pp → ZZ production (together with CP conserving operators)



For a recent 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



other CPV couplings as WWγ are highly constrained by EDM measurements
see eg. Gavela et al., 1406.6367

Conclusions & outlook

How can we learn more?

First two generations;
down quark 3dr generation

Meson mixing (Bs);
Rare B decays experiments

Higgs flavor violation

up type and lepton
3dr generation

Higgs rare processes

$t \to c$, $t \to u$

$\tau \to \mu$, $\tau \to e$

High energy machines

Higgs & gauge boson CP violation

High energy machines

&

e^+e^- machines

CPV in Higgs-gauge boson couplings

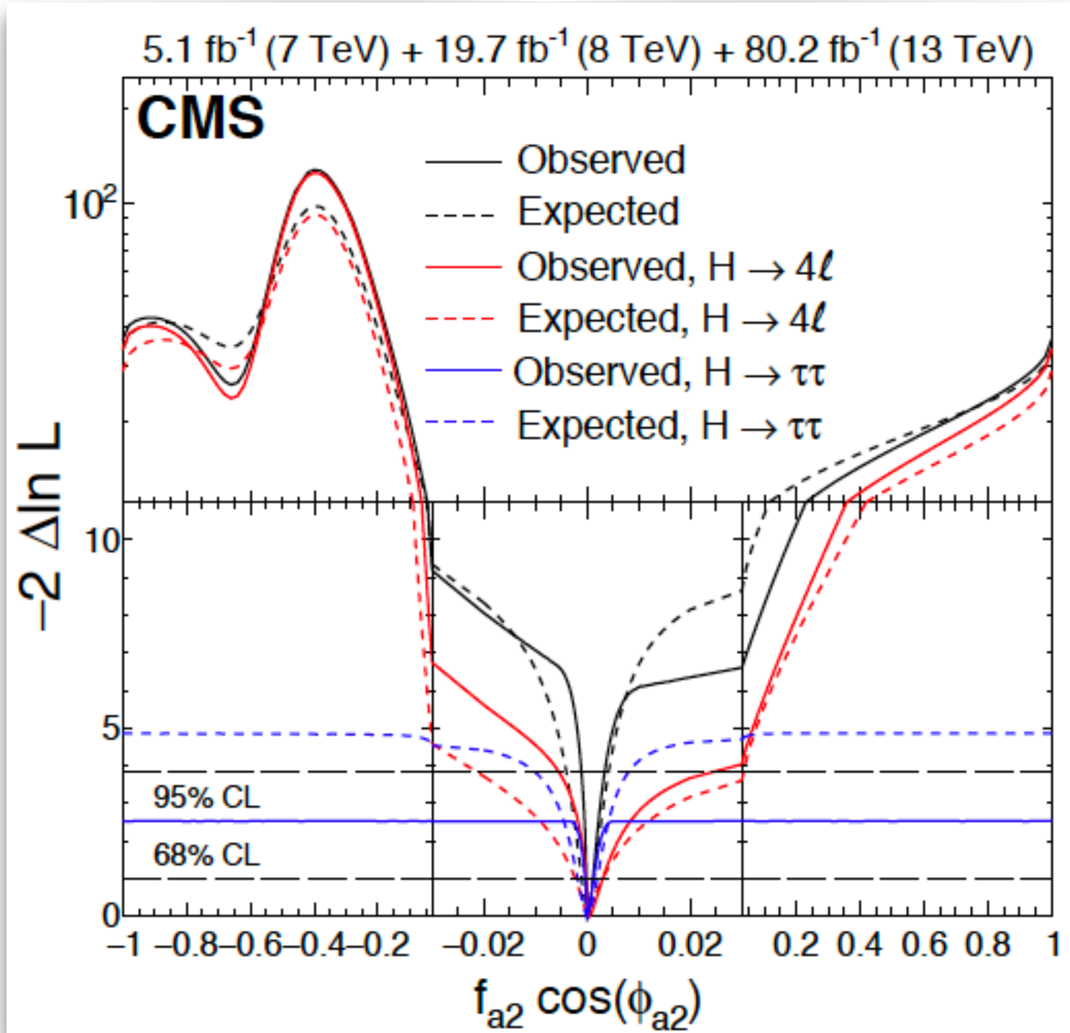
CPV in Higgs-fermion couplings

CPV in triple-gauge boson couplings

Electron EDM experiments

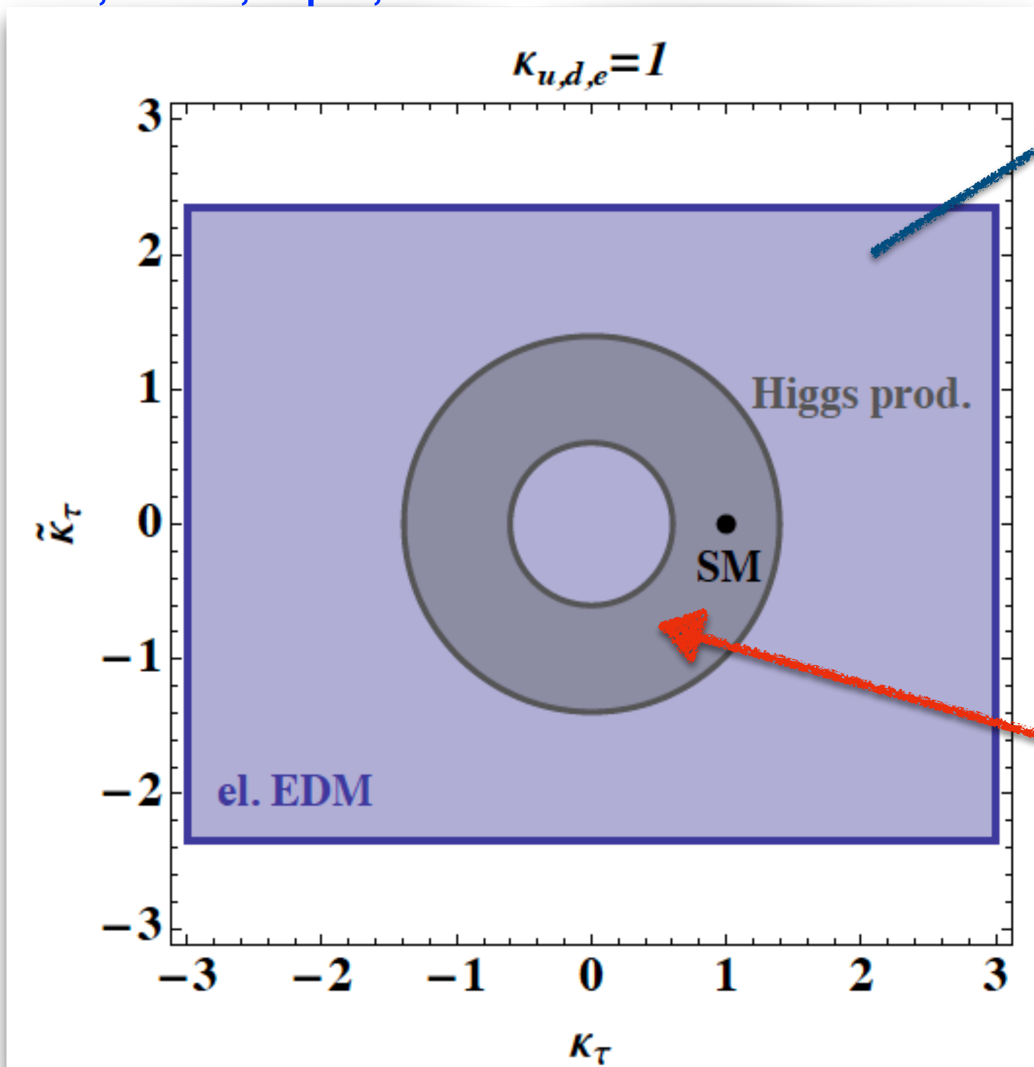
Comparison of analyses, CPV in hVV

1903.06973

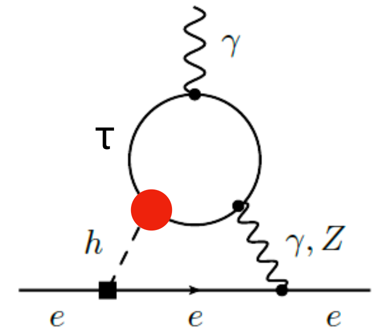


Low energy vs. high energy, CPV Hττ

Brod, Haisch, Zupan, 1310.1385



Electron EDM constraint
is rather weak



Need differential distributions
to break the degeneracy