Constraining the Higgs Yukawa CP structure with a global LHC fit, EDM and baryogenesis

Henning Bahl, Philip Bechtle, Sven Heinemeyer, Judith Katzy, Marco Menen, Krisztian Peters, Matthias Saimpert and Georg Weiglein
[in preparation]

In collaboration with

Marta Losada, Yehonatan Viernik, Yossi Nir
1911.08495 (μ) [PRL]
2002.00099 (τ, t, b) [JHEP]
2006.06940 (EWBG) [JHEP]

Elina Fuchs
CERN & LU Hannover & PTB

14th Annual Meeting of the Helmholtz Alliance "Physics at the Terascale"
November 23, 2021
Parallel session: Higgs physics

Outline

1.) Baryogenesis

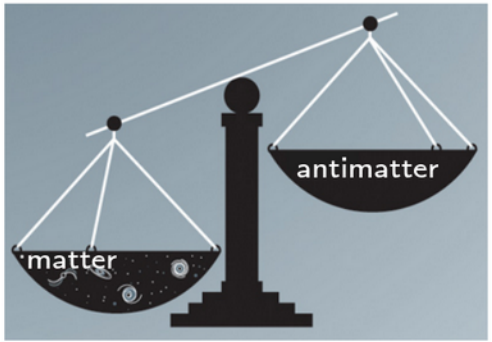
2.) Electric dipole moments

3.) Higgs signal strengths and angular observables at the LHC

4.) Complementarity

CP violation for baryon asymmetry

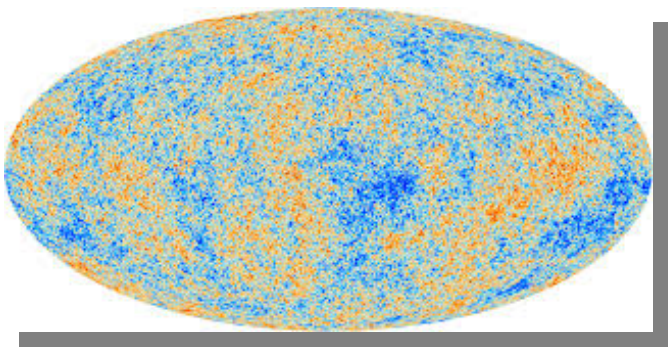
Sakharov conditions for Baryogenesis
I. B number violation
II. CP violation
III. Out of thermal equilibrium



[adapted from quantumdiaries]

- Observed baryon asymmetry $\eta = \dfrac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$
- SM: δ_{CKM} and $\bar{\theta}_{\mathrm{QCD}} < 10^{-10}$ insufficient

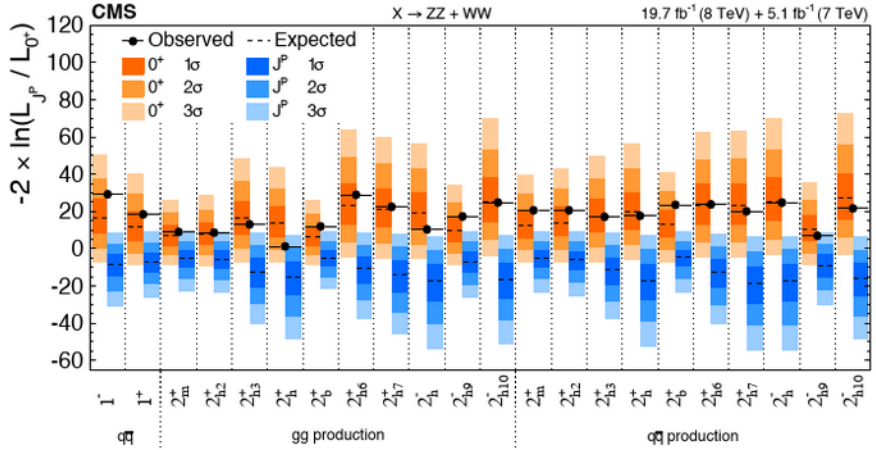
Gavela, Hernandez, Orloff, Pene '93
Huet, Sather '94

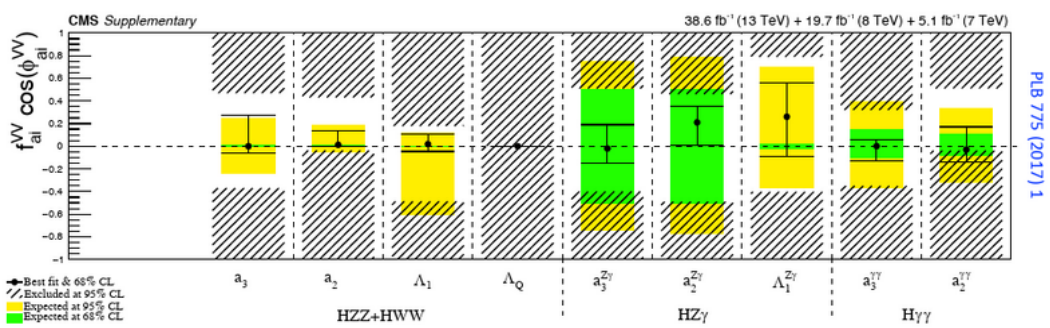

[PLANCK/ESA 2013]

Need CP violation beyond the SM

CP violation in the Higgs sector

- Discovered Higgs compatible with $J^{PC}=0^{++}$
- Non-vanishing CP-odd component possible



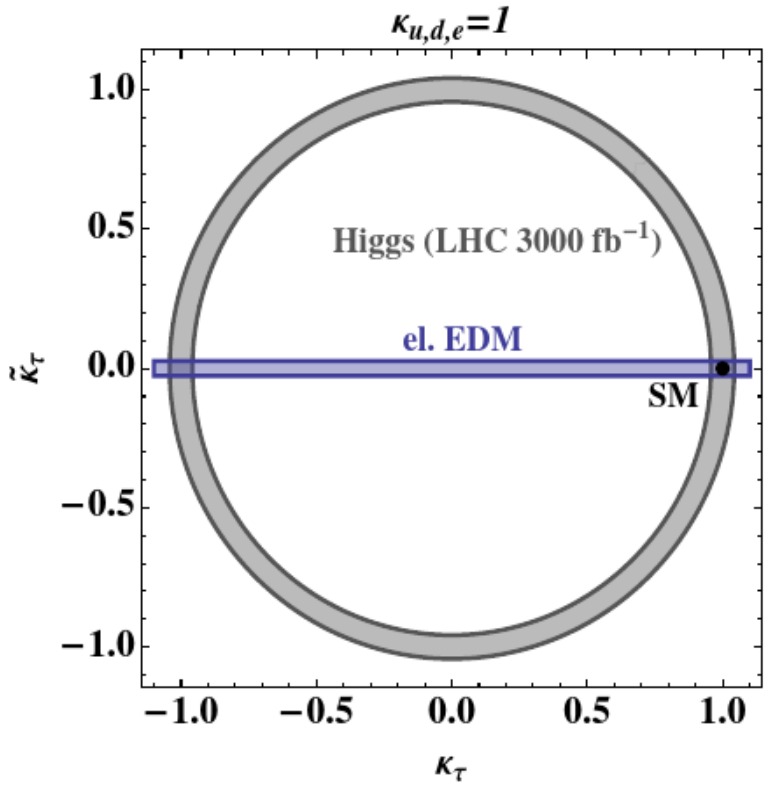


Earlier LHC searches for CPV in hVV

EDM & LHC limits CPV Yukawas

tau

Brod, Haisch, Zupan '13 (also for t, b)



projection ~O(10^{-30})

d_e [e cm]:

EDM & LHC limits CPV Yukawas

tau

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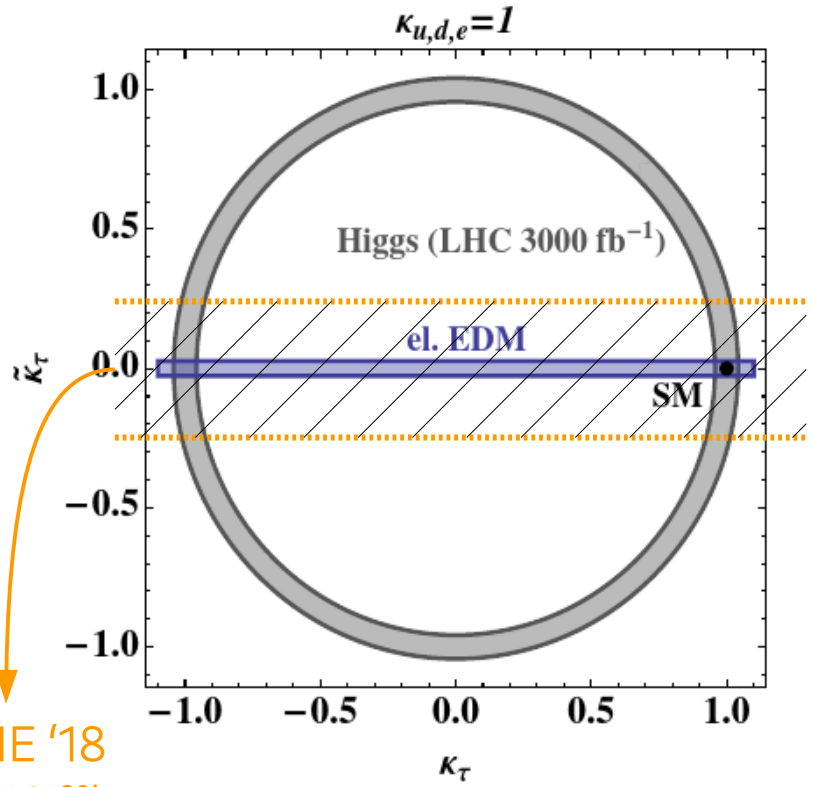

ACME '18
~O(10^{-29})

projection
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d_e [e cm]:

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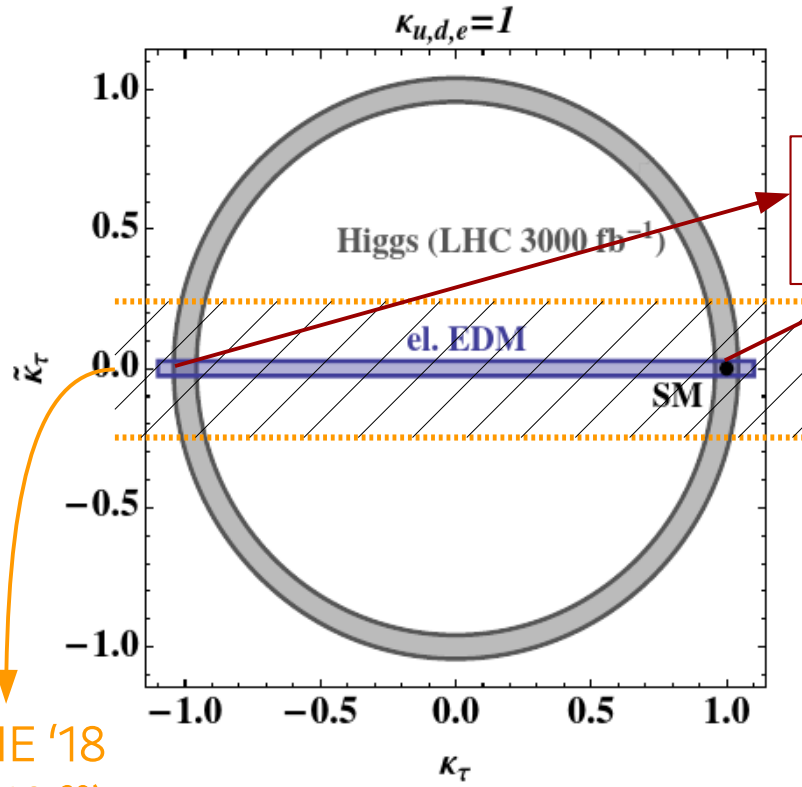


What is Y_B in these remaining areas?

ACME '18
~O(10^{-29})

projection
~O(10^{-30})

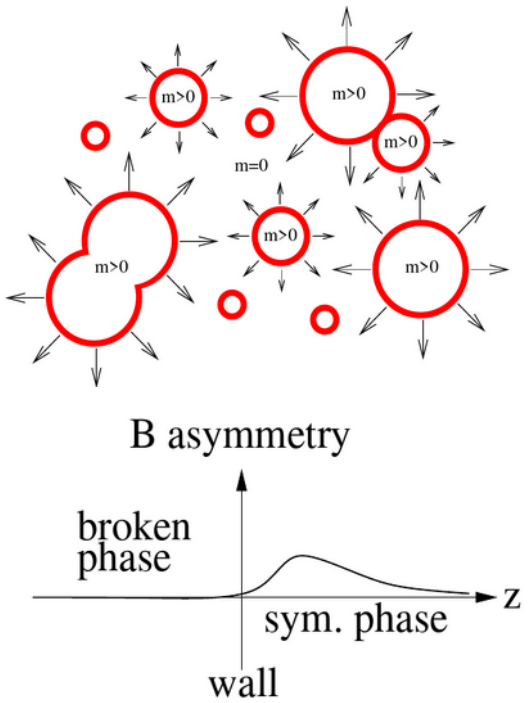
d_e [e cm]:

Our Goals

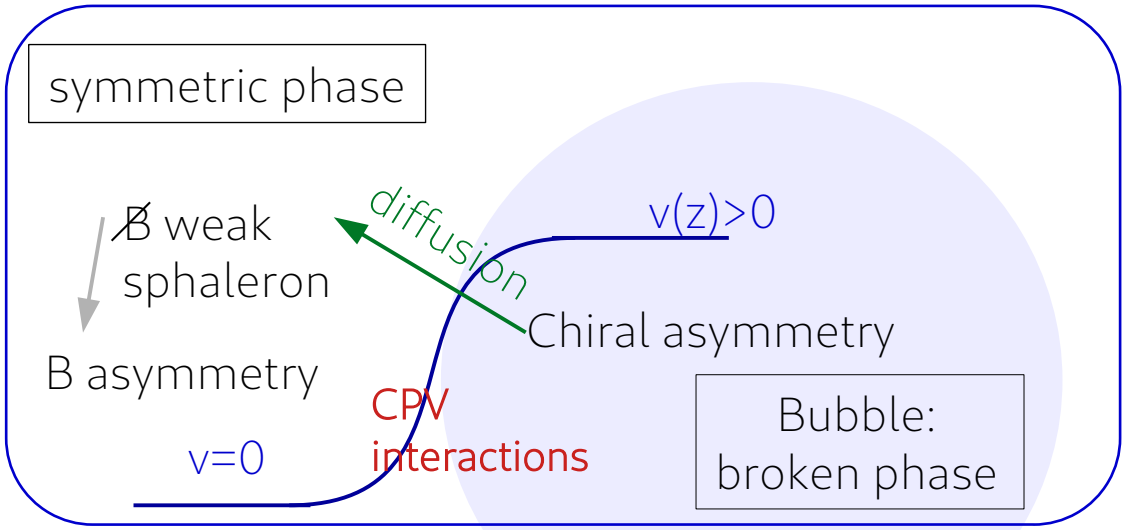
- Calculate baryon asymmetry Y_B from several complex Yukawas in EFT
- Confront CP violation required by BG with
  - inclusive and differential Higgs rates, angular analysis of H→ ττ
  - EDM constraints
- Consider combination of phases
- Focus on CPV, *assume* ew phase transition can be enhanced separatelyt

Find/exclude viable region in agreement with these 3 complementary observables

Electroweak baryogenesis



PLANCK: $Y_B^{\rm obs} = (8.59 \pm 0.08) \times 10^{-11}$



Lots of literature, e.g.
Joyce, Prokopec, Turok '95; Morissey, Ramsey-Musolf '12; White '16; de Vries, Postma, van de Vis, White '16; de Vries, Postma, van de Vis '18; ...

Transport equations for baryogenesis

Transport equations for each fermion and Higgs, set of coupled differential equations

$$\partial_\mu f^\mu = -\Gamma^f_M \mu^f_M - \Gamma^f_Y \mu^f_Y + \Gamma^f_{\rm ss} \mu_{\rm ss} - \Gamma^f_{\rm ws} \mu^f_{\rm ws} + S_f$$

relaxation — Yukawa — Strong sphaleron — weak — CPV source

Approximations
- vev-insertion
- thin wall
- diffusion

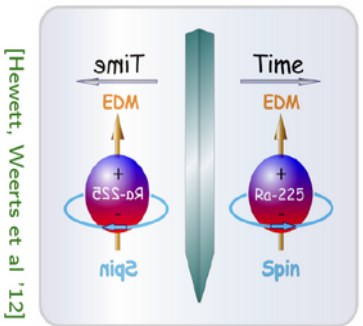
$$Y_B \propto S_f \propto {\rm Im}\left[m_f^* m_f'\right] \tilde{c}_f$$

Same scaling as EDM

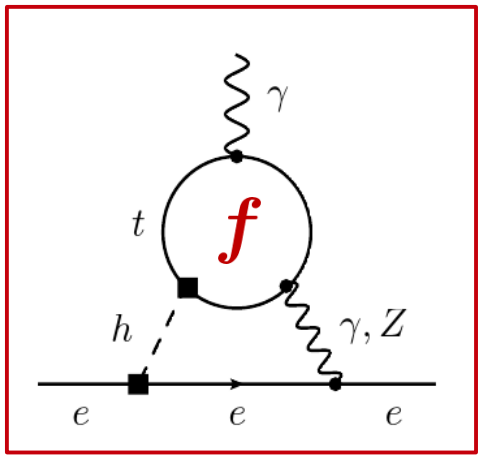
$$\frac{Y_B}{Y_B^{\rm obs}} = 28\tilde{c}_t - 0.2\tilde{c}_b - 0.03\tilde{c}_c - 2\cdot 10^{-4}\tilde{c}_s - 9\cdot 10^{-8}\tilde{c}_u - 4\cdot 10^{-7}\tilde{c}_d$$
$$- 11\tilde{c}_\tau - 0.1\tilde{c}_\mu - 3\cdot 10^{-6}\tilde{c}_e$$

Fuchs, Losada, Nir, Viernik 19'- '20
Aharony-Shapira '21

Electron's Electric Dipole Moment



EDM violates $\mathcal{T}$ and $\mathcal{P}$
$\Rightarrow \mathcal{CP}$



ACME [Nature '18]:

$$d_e \leq 1.1 \times 10^{-29}\, e\,\text{cm at } 90\%\ \text{CL}$$

Using [Panico, Pomarol, Riembau '18], [Brod, Haisch, Zupan '13], [Brod, Stamou '18],...

$$\frac{d_e}{d_e^{\text{ACME}}} = c_e \left(854.2\tilde{c}_t + 4.1\tilde{c}_b + 2.7\tilde{c}_c + 0.01\tilde{c}_s + 8\cdot 10^{-5}\tilde{c}_u + 7\cdot 10^{-5}\tilde{c}_d + 3.4\tilde{c}_\tau + 0.03\tilde{c}_\mu\right)$$
$$+ \tilde{c}_e \left(1082.6 c_V - 610.1 c_t\right).$$

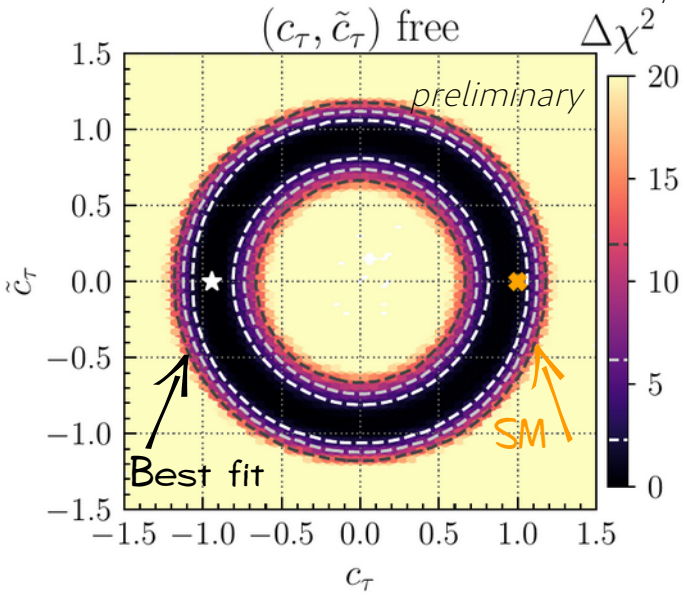
CP structure of Higgs couplings - τ

$$\mathcal{L}_{\text{Yuk}} = -\sum_f \frac{y_f}{\sqrt{2}} \bar{f} \left(c_f + i\gamma_5 \tilde{c}_f \right) f h,$$

Bahl, Bechtle, EF, Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein (in preparation)

Global fit using **HiggsSignals** + recent analyses

can also be analyzed in EFT



$c_\tau \simeq \pm 1$ almost degenerate minima of $\Delta\chi^2$

Ring-structure from upper/lower bound on BR

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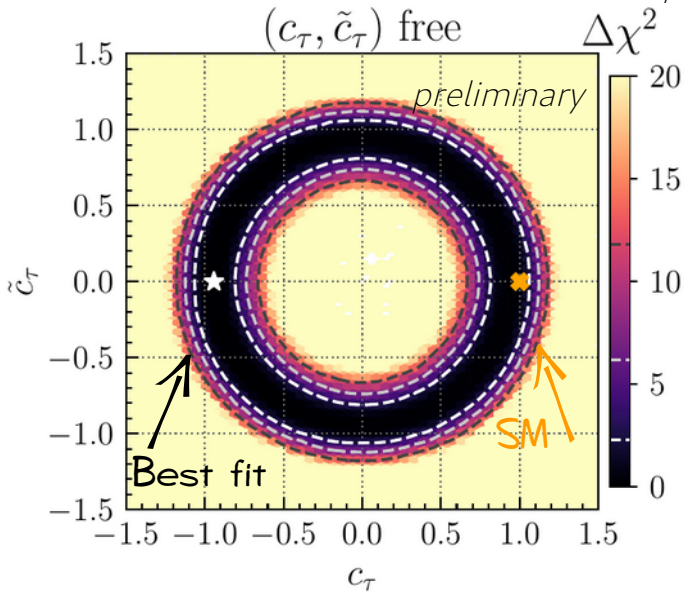

CMS 2110.04836
h→ ττ CPV analysis

See talk tomorrow by Andrea Cardini

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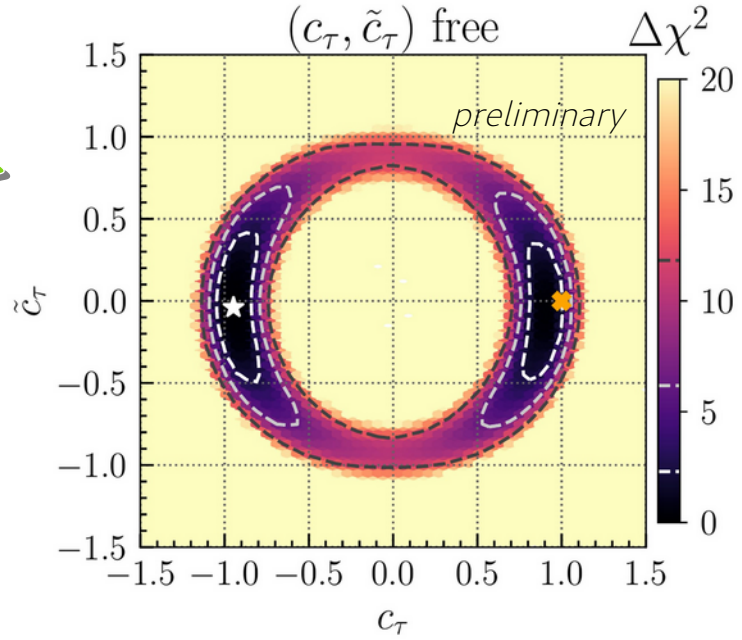


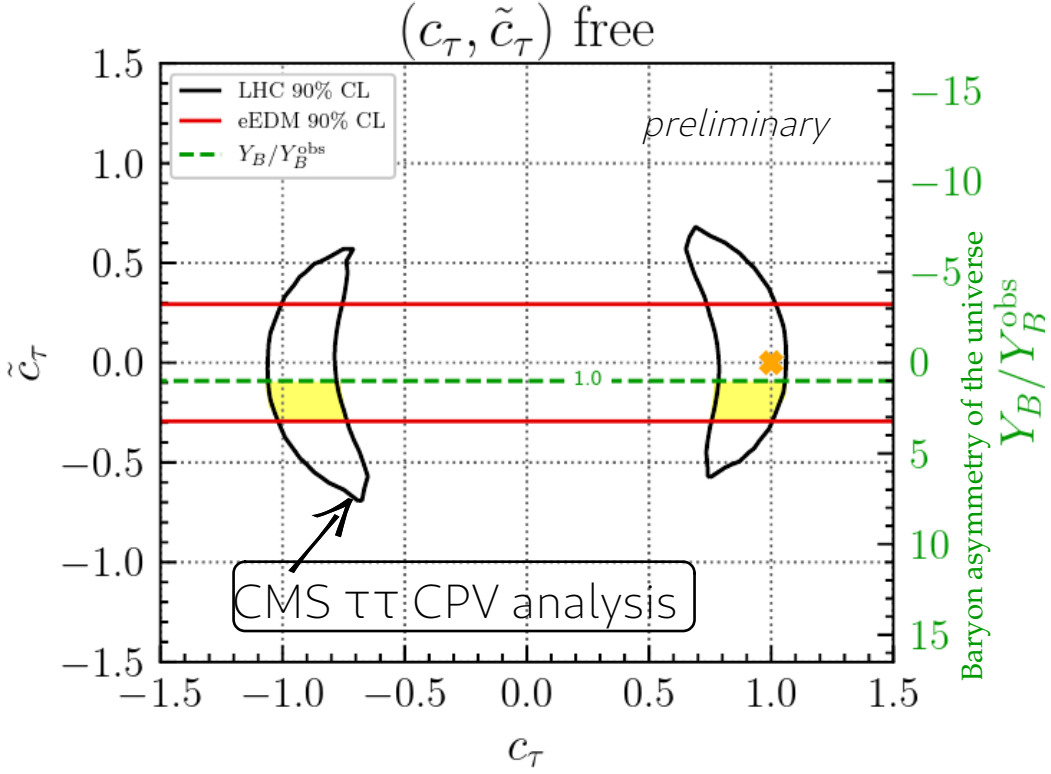
Ring-structure from upper/lower bound on BR

CMS analysis excludes large $\tilde{c}_\tau$

Complementary (τ): LHC, EDM, EWBG

Bahl, Bechtle, EF, Heinemeyer, Katzy, Menen, Peters, Weiglein (in preparation)

Electron electric dipole moment
$d_e \propto \tilde{c}_f$



See also
Brod, Haisch, Zupan '13
De Vries, Postma, van de Vis '18
EF, Losada, Nir, Viernik '19, '20, '20
Aharony-Shapira 2106..05338
Brod et al (in preparation)

Electroweak baryogenesis
$Y_B \propto \tilde{c}_f$

Caveat: "optimistic" scenario, large uncertainty (vev-insertion approximation)
→ almost upper bound

Cline, Kainulainen 2001.00568
Cline, Laurent 2108.04249
Postma 2107.05971
Kainulainen 2108.08336

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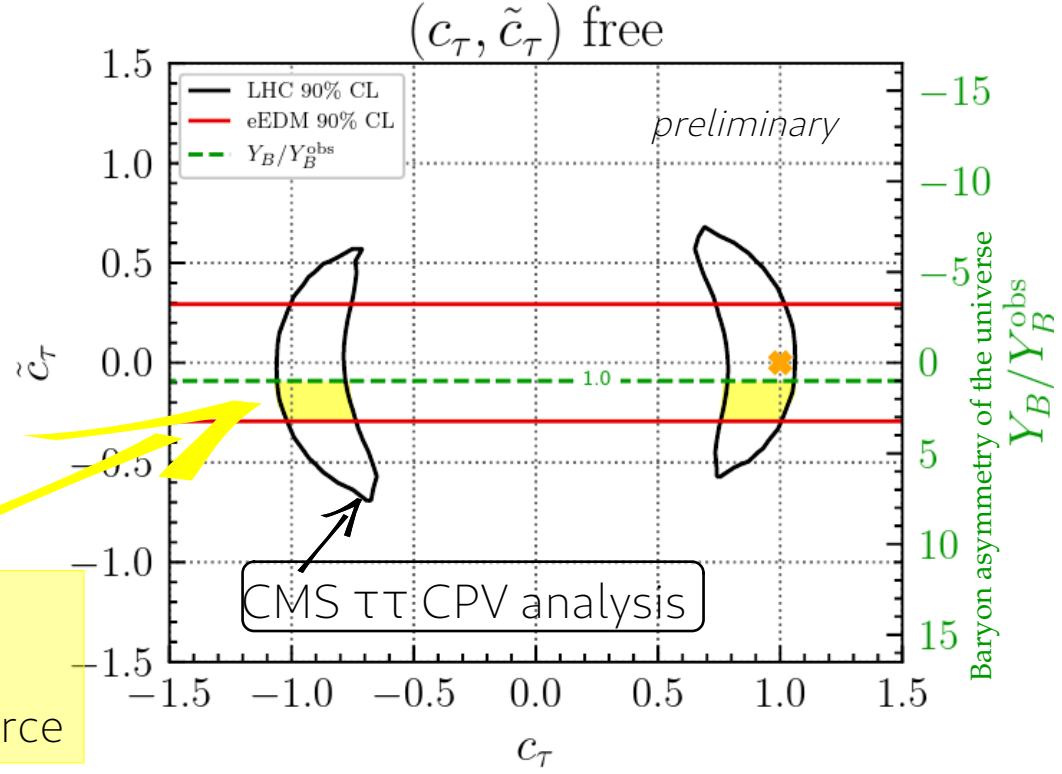

Allowed by
LHC, EDM, EWBG
→ τ can be single source

See also
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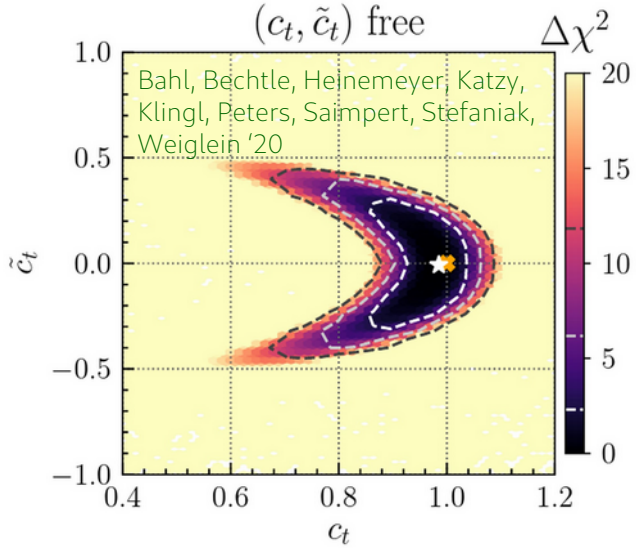
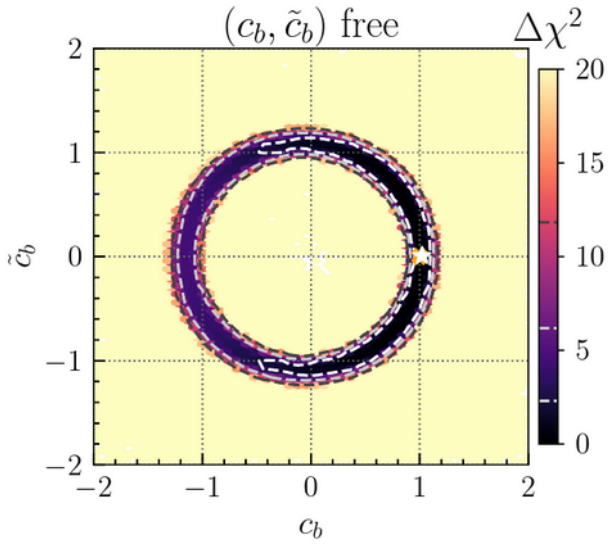
Top, bottom, and their combination

Bahl, Bechtle, EF, Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein (in preparation)



Top: ellipse (ggF) cut off by $h \to \gamma\gamma$

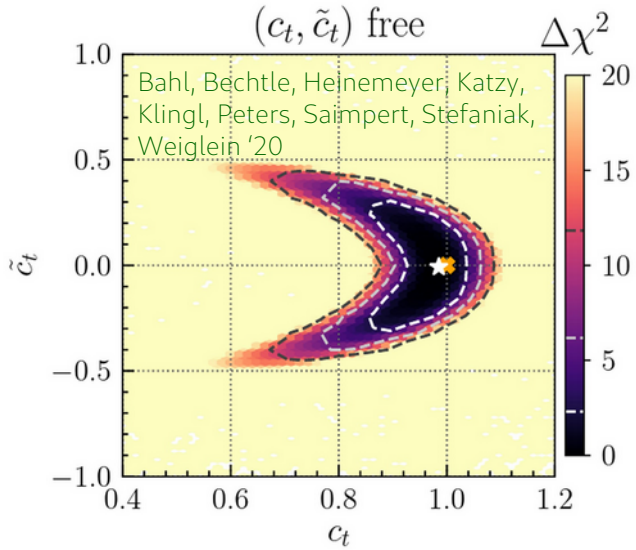


Bottom: ring (h→ bb) reduced by ggF (positive interference with t)

Top, bottom, and their combination

Bahl, Bechtle, EF, Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein (in preparation)

Floating several coupling modifiers simultaneously



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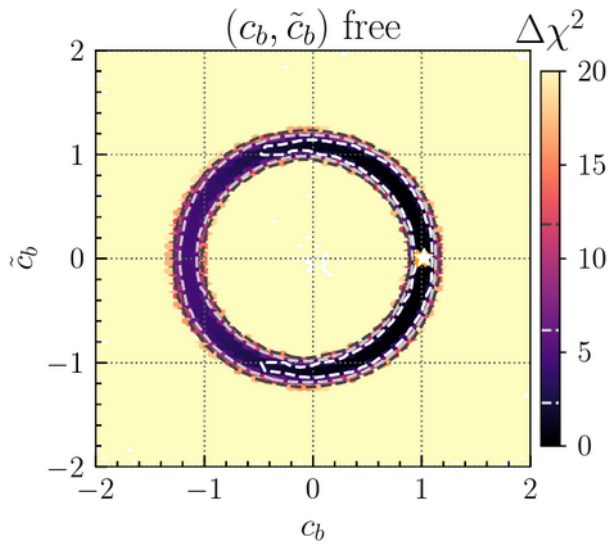

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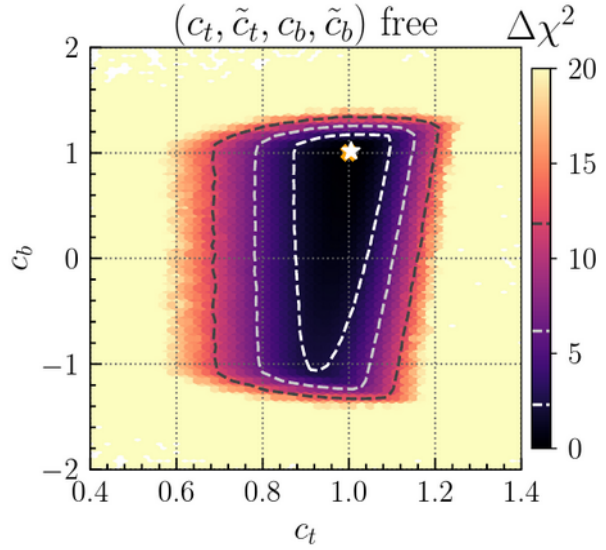
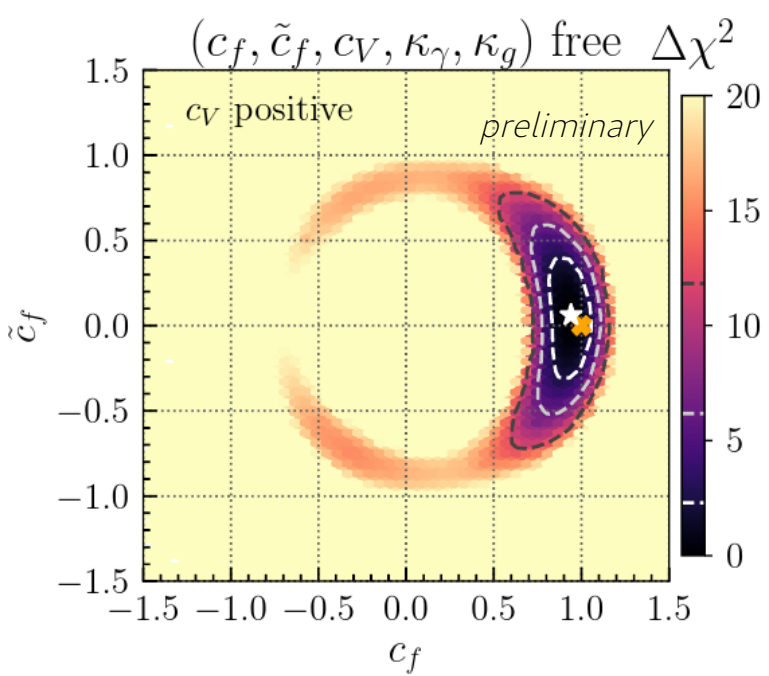
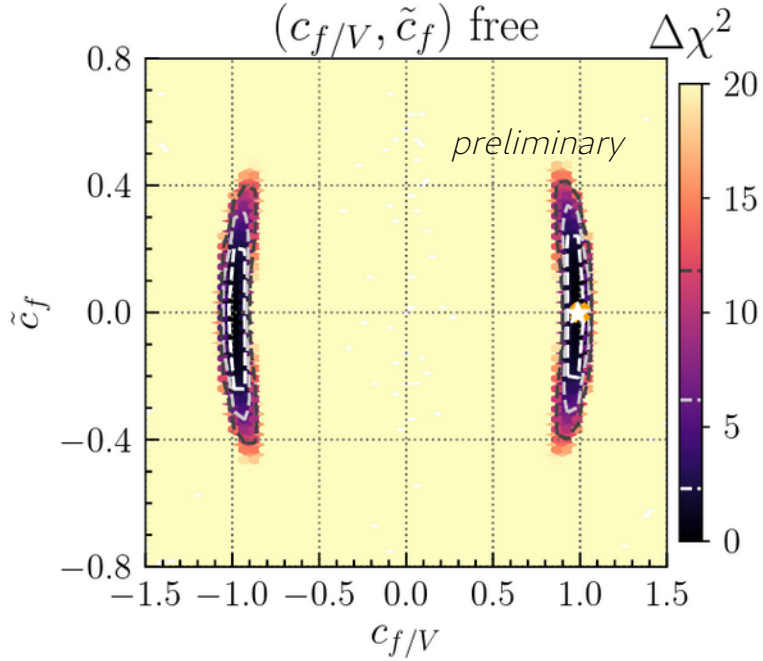


t+b: small c_b can be compensated by $\tilde{c}_b$

Varying vector couplings



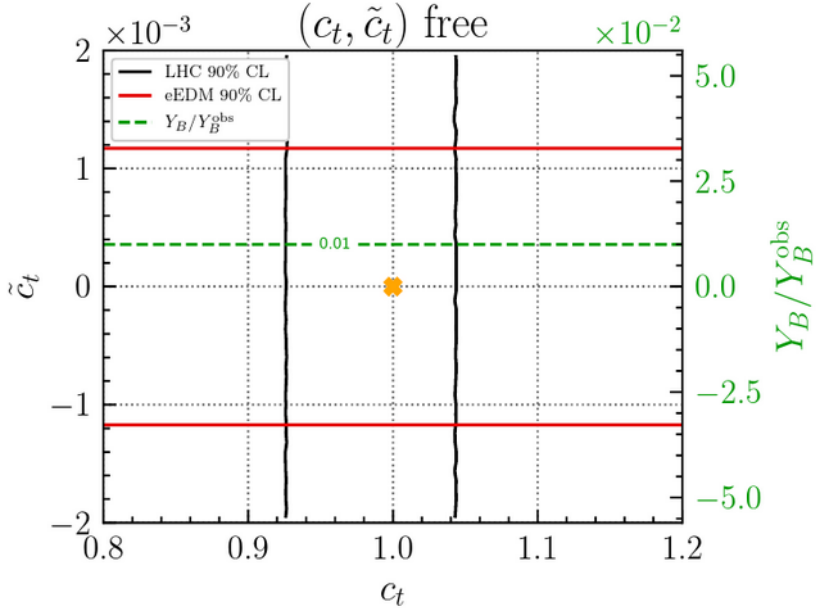
Universal fermion coupling modifier: Dominated by top



General mixing scenario: $c_f = c_V$
No CPV included in vector couplings

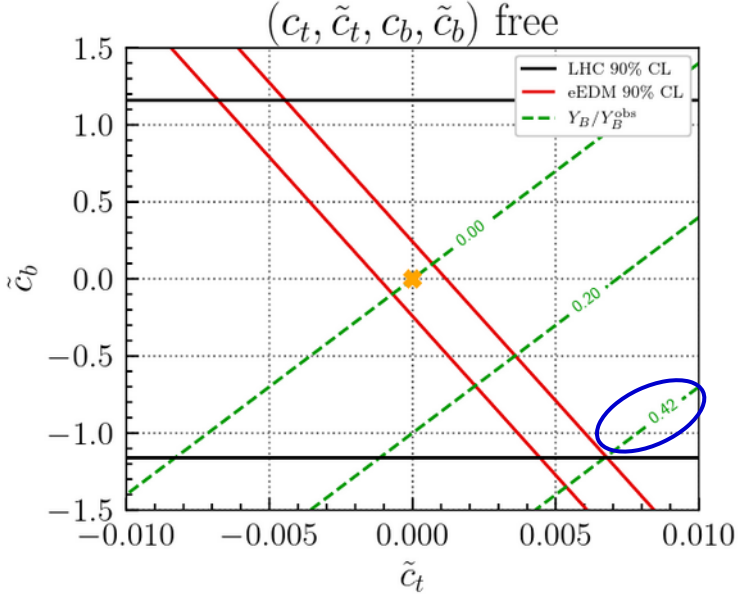
Complementarity

Top: EDM very constraining



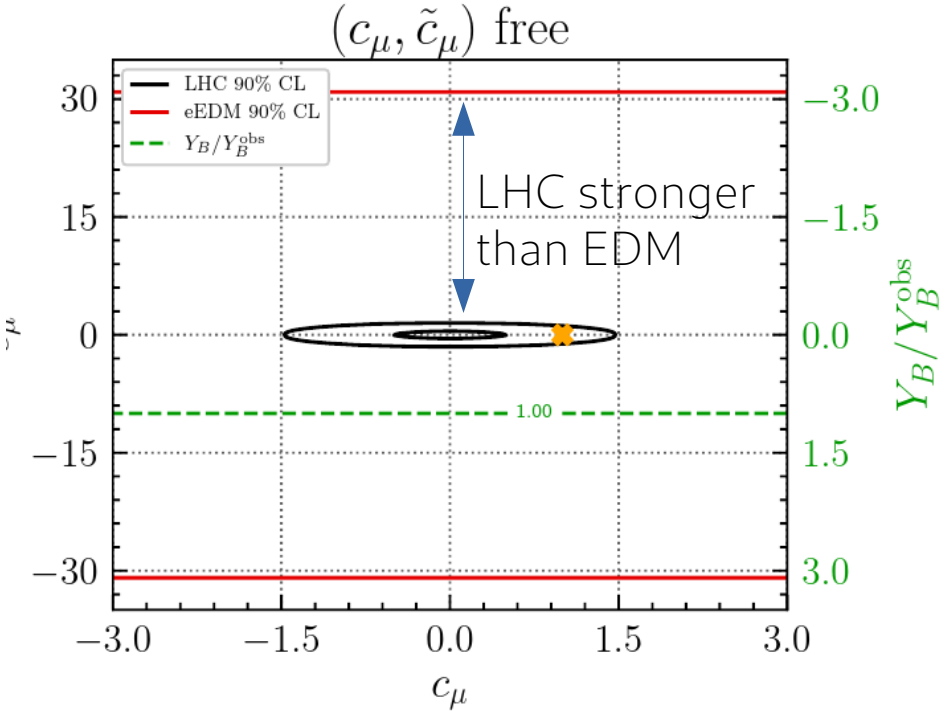
t, b: each only few % of observed BAU

t, b: cancellations of EDM allow larger CPV



Combined: max. 42% of observed BAU

Role of muon and electron



EWBG from μ allowed by EDM
Excluded by LHC, but 17% contribution

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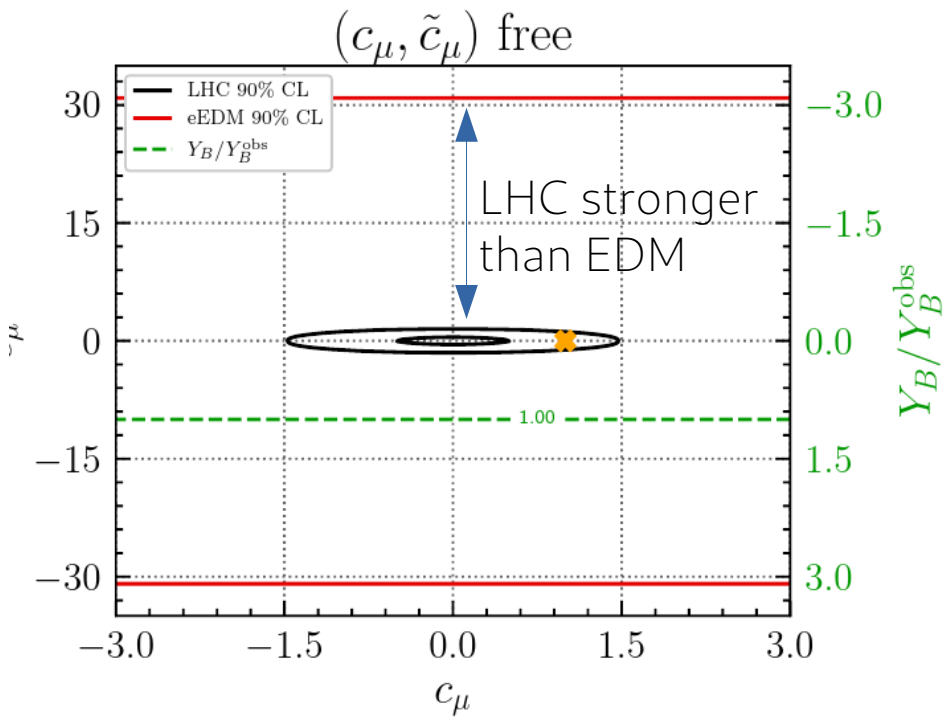

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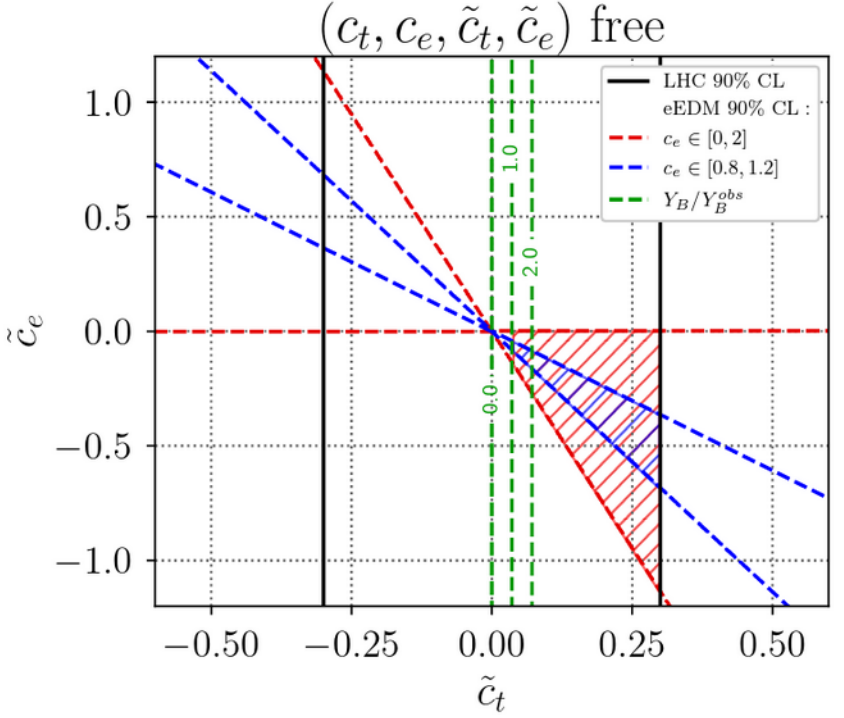


Interpretation of eEDM depends strongly on c_e.
If c_e small → bound on other $\tilde{c}_f$ much weakened

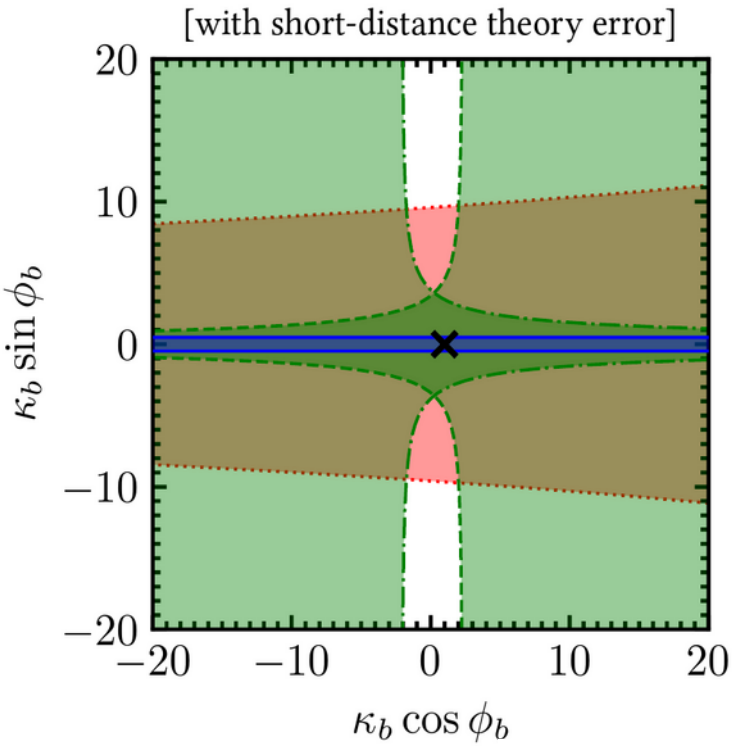
Conclusions

- Complementarity of EDM, EWBG and LHC Higgs physics
- H→ττ CP analysis excludes large $\tilde{c}_\tau$, but τ remains viable EWBG source
- LHC constrains cosmological scenarios, separates flavors; now also 2nd gen.
- Cancellations and enhancements with 2 fermions, e.g. t+b: few → 42% of Y_B
- Electron Yukawa has big impact on interpretation of electron EDM

THANK YOU!

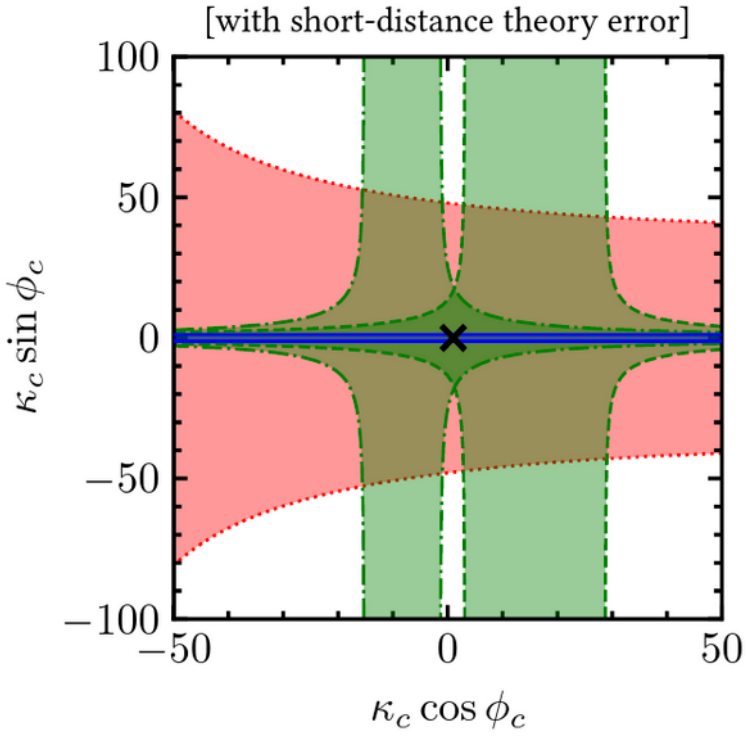
Backup slides

EDMs: e, n, Hg



Brod, Stamou '18

Electron EDM strongest if c_e=1



neutron EDM [$\text{sign}_W = +$]

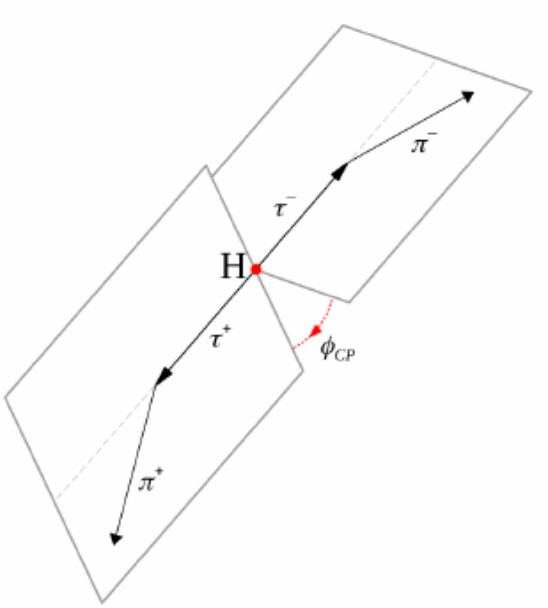
neutron EDM [$\text{sign}_W = -$]

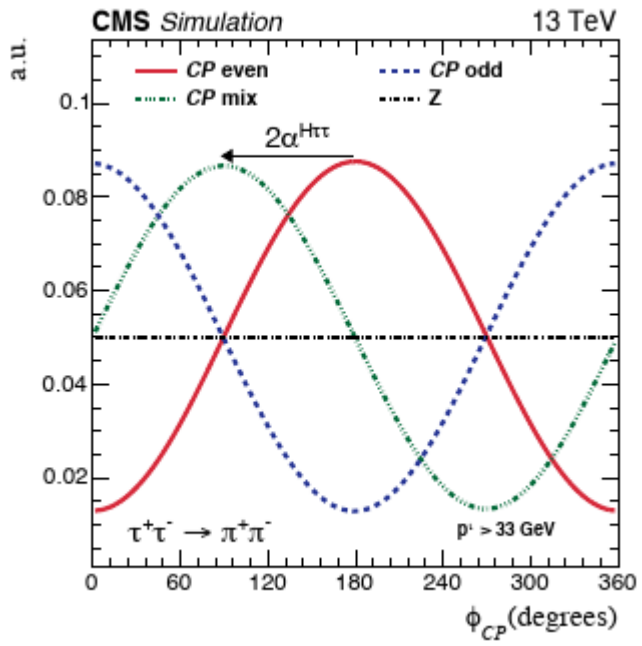
Hg EDM

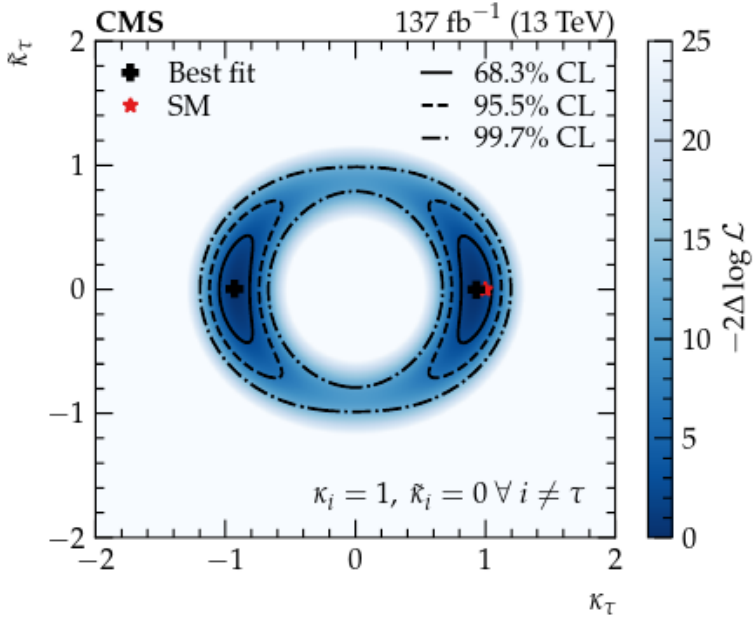
electron EDM

CMS H→ ττ analysis

CMS 2110.04836, CMS-HIG-20-006







SMEFT: dim-6 Yukawa

- Consider dim-6 Yukawa with real and imaginary part

$$\mathcal{L}_{\text{Yuk}} = Y_f \overline{F_L} F_R H + \frac{1}{\Lambda^2}(X_R^f + iX_I^f)|H|^2 \overline{F_L} F_R H. + \text{h.c.}$$

cf [de Vries, Postma, van de Vies '18] where $X_R^f \equiv 0$ $X \equiv \pm iY_f$

- Relative size of dim-6 normalized to dim-4

$$T = m_f^{(6)}/m_f^{(4)}$$

$$T_R^f \equiv \frac{v^2}{2\Lambda^2}\frac{X_R^f}{Y_f}, \qquad T_I^f \equiv \frac{v^2}{2\Lambda^2}\frac{X_I^f}{Y_f}$$

Fuchs, Losada, Nir, Viernik 19'- '20 as coordinates

Cut-off scales $\Lambda/\sqrt{X_{R,I}}$

Minimal scales for maximally **allowed** T (collider, EDM)

- τ: 2.4 TeV, 3.1 TeV
- b: 1.5 TeV, 1.7 TeV
- t: 247 GeV, 318 GeV (only v at T_R=-0.5, but larger at T~0);
  - 8.7 TeV from EDM
- μ: 10 TeV, 12 TeV

Maximal scales for minimally **required** T_I (EWBG)

- τ: $\Lambda/\sqrt{X_I^\tau} \lesssim 18\ \text{TeV}\ (0.01/T_I^\tau)^{1/2}$

Fuchs, Losada, Nir, Viernik 19'- '20