# CP violation for electroweak baryogenesis in SMEFT

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2202.11753

In collaboration with

EF, 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


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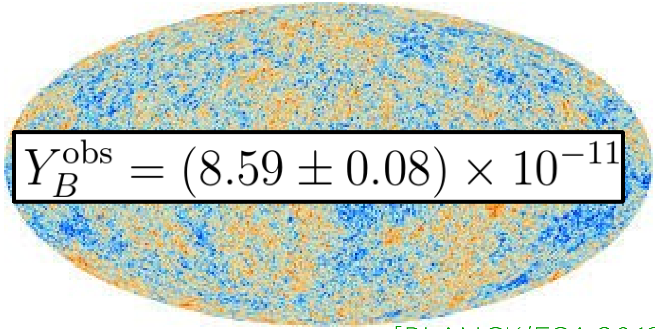
# BSM CP violation for baryon asymmetry

**Sakharov conditions for baryon asymmetry**

I. B number violation
II. CP violation
III. Out of thermal equilibrium




[PLANCK/ESA 2013]

- Observed baryon asymmetry $Y_B^{\rm obs} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$
- SM: $\delta_{\rm CKM}$ and $\bar{\theta}_{\rm QCD} < 10^{-10}$ by far **insufficient**

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

**Electroweak baryogenesis:**
during e.w. phase transition
→ connected to the Higgs
→ potentially testable at colliders

## Need CP violation beyond the SM

# Constraints on CP violation – schematic

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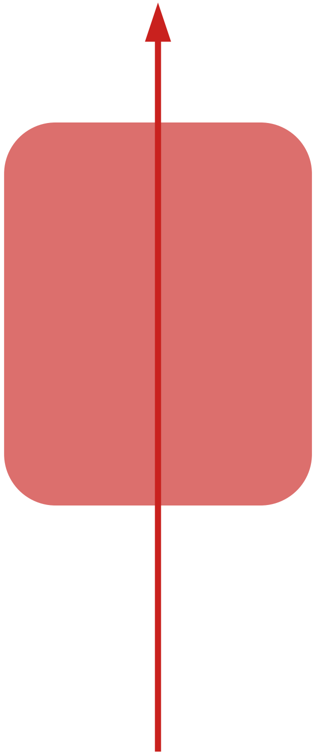

PLANCK: observed baryon asymmetry

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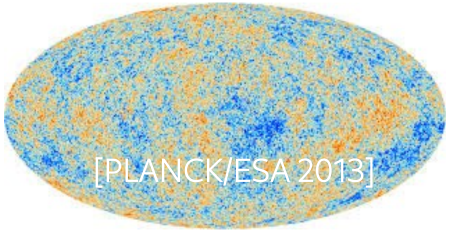
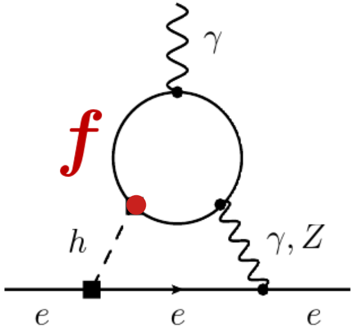


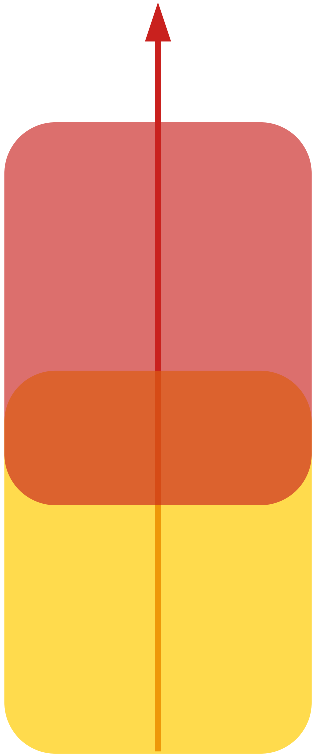
# Constraints on CP violation - schematic

ACME [Nature '18]: upper bound

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

Electric dipole moments restrict CPV



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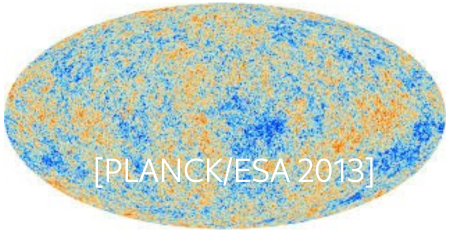

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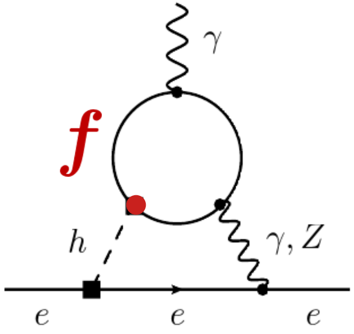


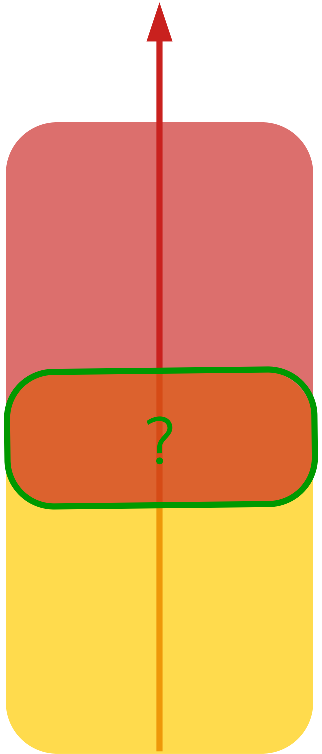


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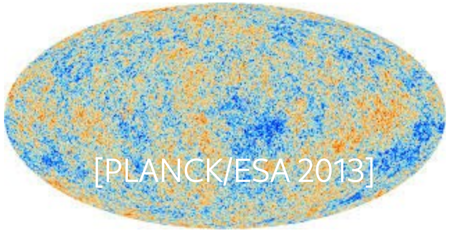

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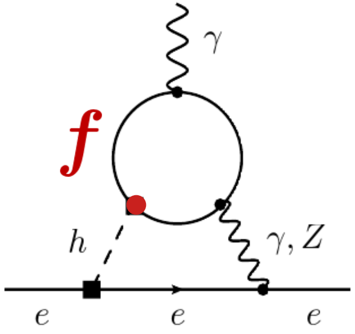


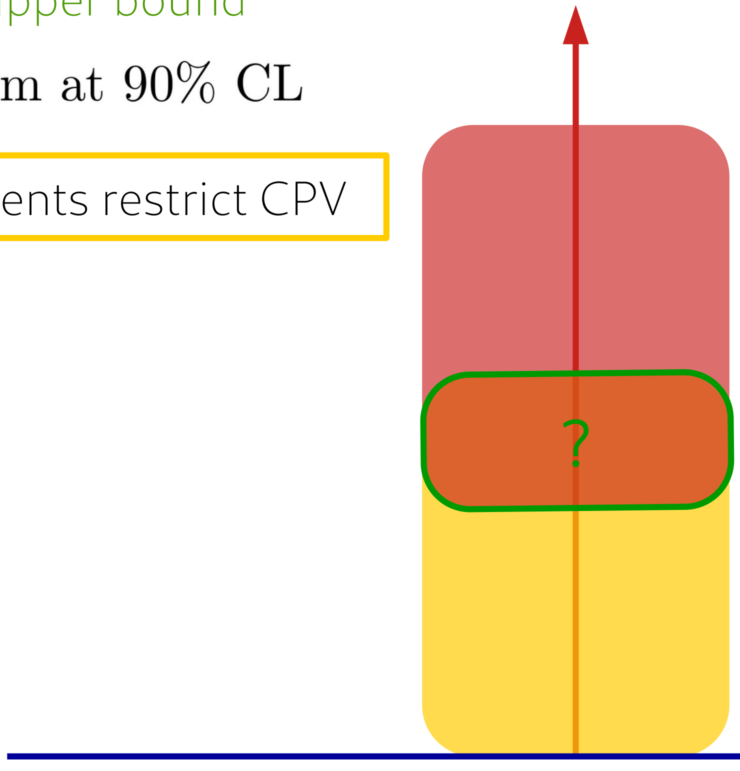


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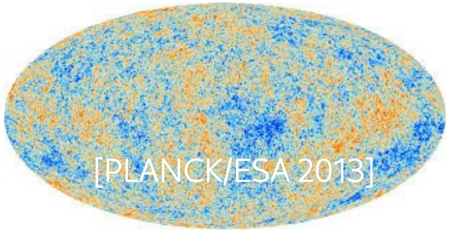

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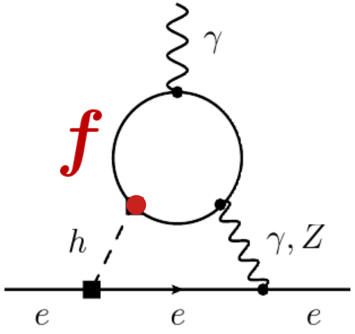


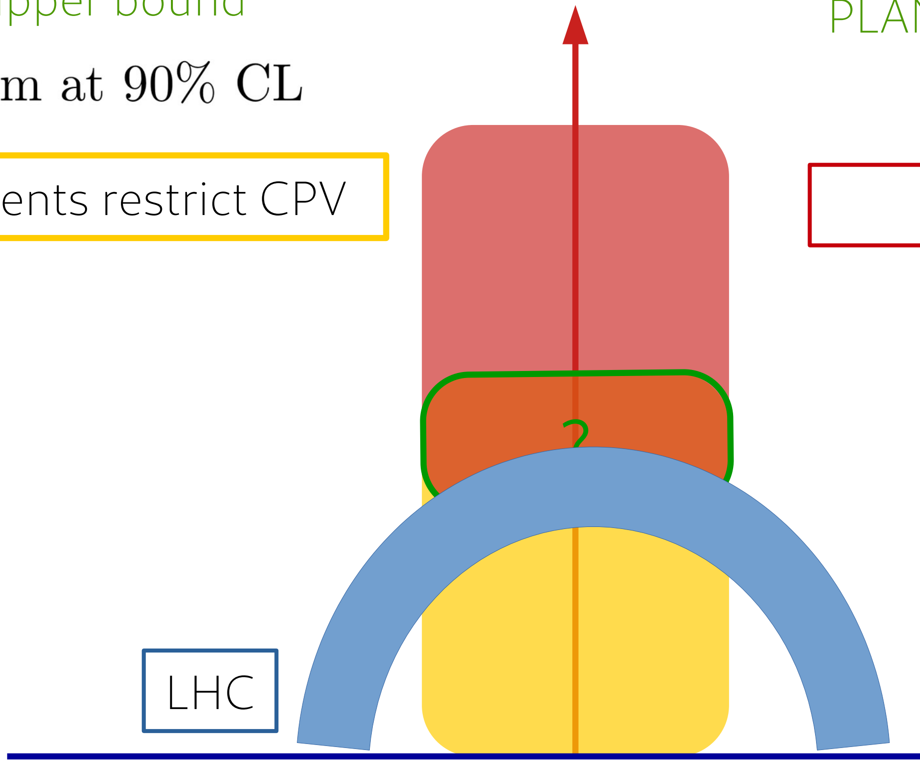


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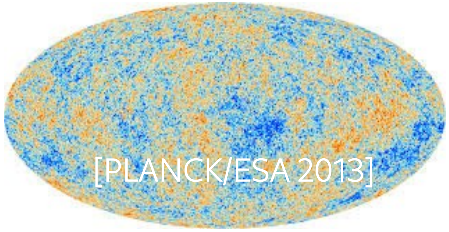
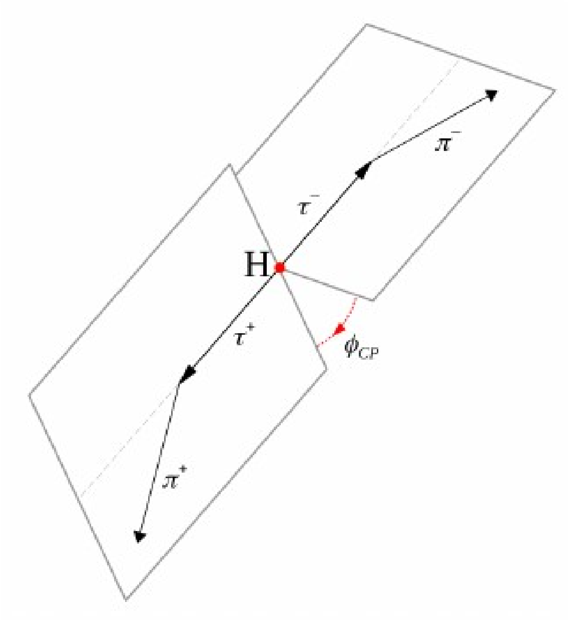
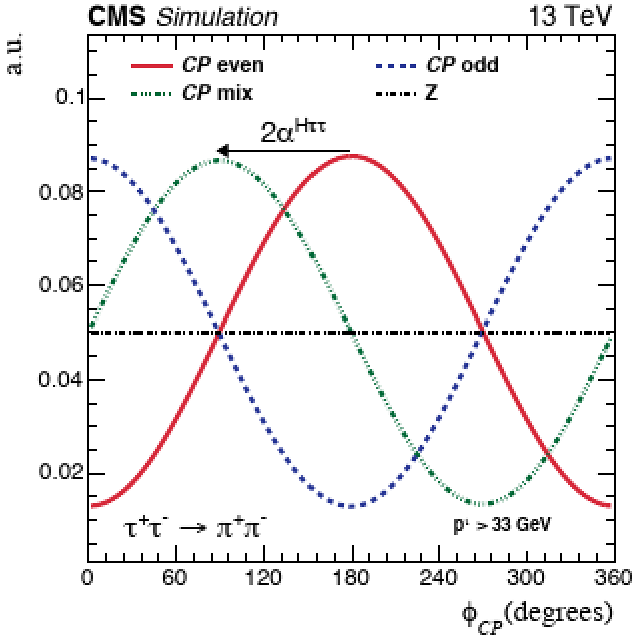


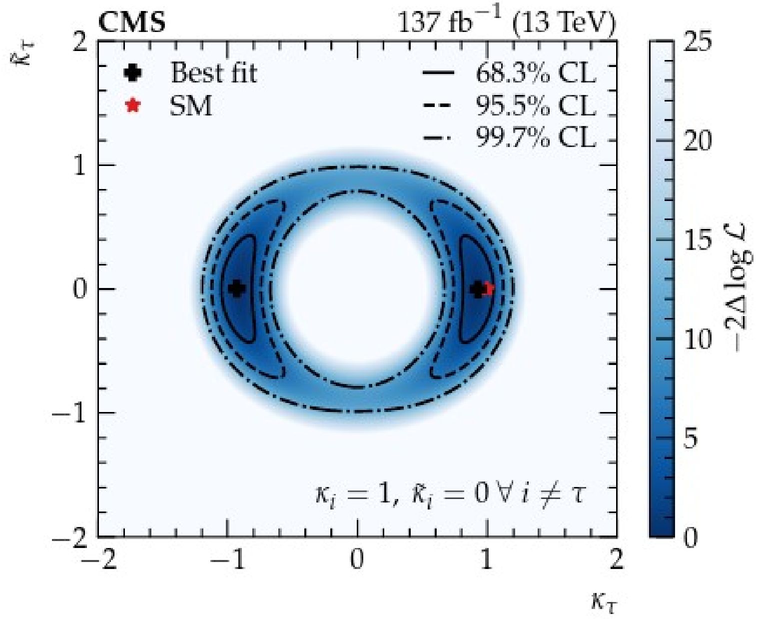
# Timely: CP-odd observables at LHC

CMS 2110.04836, CMS-HIG-20-006

CMS H→ ττ analysis



# Outline

1.) Framework

2.) Baryogenesis

3.) Electric dipole moments

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

5.) Complementarity

# Complex Yukawa in SMEFT dim-6

- 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 $X \equiv \pm i Y_f$

- Relative size of dim-6 normalized to dim-4 $T = m_f^{(6)} / m_f^{(4)}$

Our coordinates →

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$$\mathcal{L}_f = \frac{y_f v}{\sqrt{2}} \left[1 + \frac{v^2}{2\Lambda^2} \frac{X_R^f + iX_I^f}{y_f}\right] \overline{f_L} f_R + \frac{y_f}{\sqrt{2}} \left[1 + \frac{3v^2}{2\Lambda^2} \frac{X_R^f + iX_I^f}{y_f}\right] \overline{f_L} f_R h + \frac{3v}{2\sqrt{2}\Lambda^2}(X_R^f + iX_I^f)\overline{f_L} f_R hh + \frac{1}{2\sqrt{2}\Lambda^2}(X_R^f + iX_I^f)\overline{f_L} f_R hhh.$$

Full Lagrangian
→ focus on Yukawa & mass terms

# Impact on fermion mass & Yukawa

$$m_f = \frac{Y_f v}{\sqrt{2}}\left(1 + T_R^f + iT_I^f\right), \quad \lambda_f = \frac{Y_f}{\sqrt{2}}\left(1 + 3T_R^f + 3iT_I^f\right)$$

**rotate** into basis where mass is **real**

$$m_f \overline{f_L} f_R$$

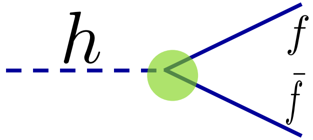
$$\tan\theta_f = \frac{T_I^f}{1 + T_R^f}$$

$$\frac{Y_f v}{\sqrt{2}}\left[1 + T_R^f + \mathcal{O}(T^{f2})\right] \qquad \frac{Y_f}{\sqrt{2}}\left[1 + 3T_R^f + 2iT_I^f + \mathcal{O}(T^{f2})\right].$$

# Higgs characterization model

Consider also simpler description of effective Higgs coupling modifiers (kappa framework)

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




Translate kappa SMEFT: $g_f = c_f + i\tilde{c}_f = 3 - \frac{2}{1 + T_f^R + iT_f^I}$ with $T_f^{R,I} \equiv \frac{v^2}{2\Lambda^2}\frac{X_f^{R,I}}{y_f}$

Allow also modifications of real parts of HVV couplings $\mathcal{L}_V = c_V H \left(\frac{M_Z^2}{v} Z_\mu Z^\mu + 2\frac{M_W^2}{v} W_\mu^+ W^{-\mu}\right)$

Capture BSM effects in effective Hgg and Hγγ couplings: $c_g, \tilde{c}_g, c_\gamma, \tilde{c}_\gamma$

# Limits on CPV in Higgs couplings

SMEFT of dim. 6 $\mathcal{L}_{\text{Yuk}} = -\sum_f y_f \overline{F_L} F_R H + \frac{1}{\Lambda^2}(X_R^f + iX_I^f)|H|^2 \overline{F_L} F_R H + \text{h.c.}$

used in EF, Losada, Nir, Viernik '19, '20, '20
see also de Vries, Postma, v. de Vis '19;
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- Inclusive LHC Higgs rates
- Angular Higgs distributions
- Electric dipole moments

Goals: Remaining allowed regions for 1 or several complex Yukawas?

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Calculate baryon asymmetry within experimental limits ⟶ Maximal possible asymmetry?

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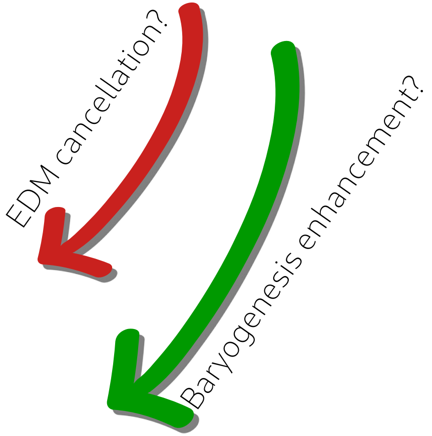


Goals:

Remaining allowed regions for 1 or several complex Yukawas?

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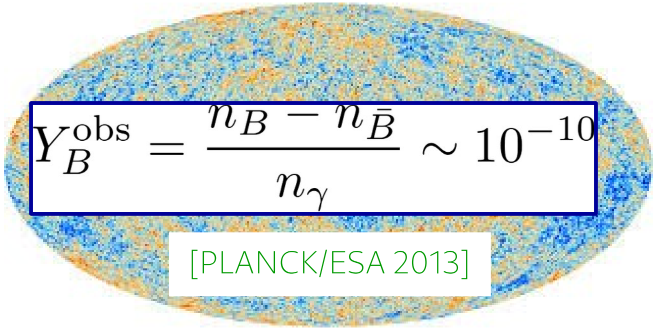
BSM for baryogenesis: focus here on CPV, assume electroweak phase transition can be enhanced separately → later: models

# Electroweak baryogenesis



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[PLANCK/ESA 2013]

Lots of literature, e.g.
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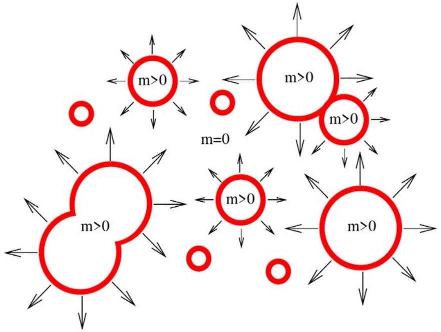


Bubbles of the broken phase expand

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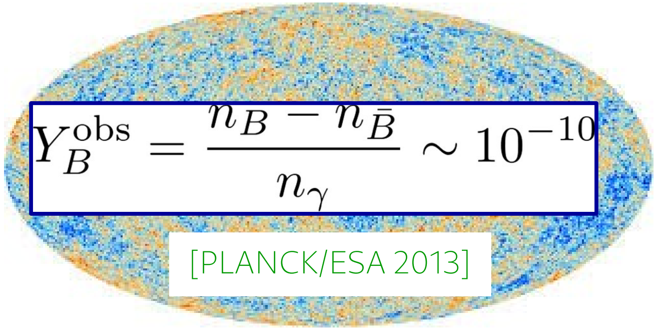

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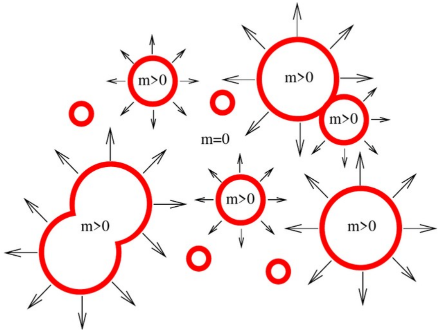


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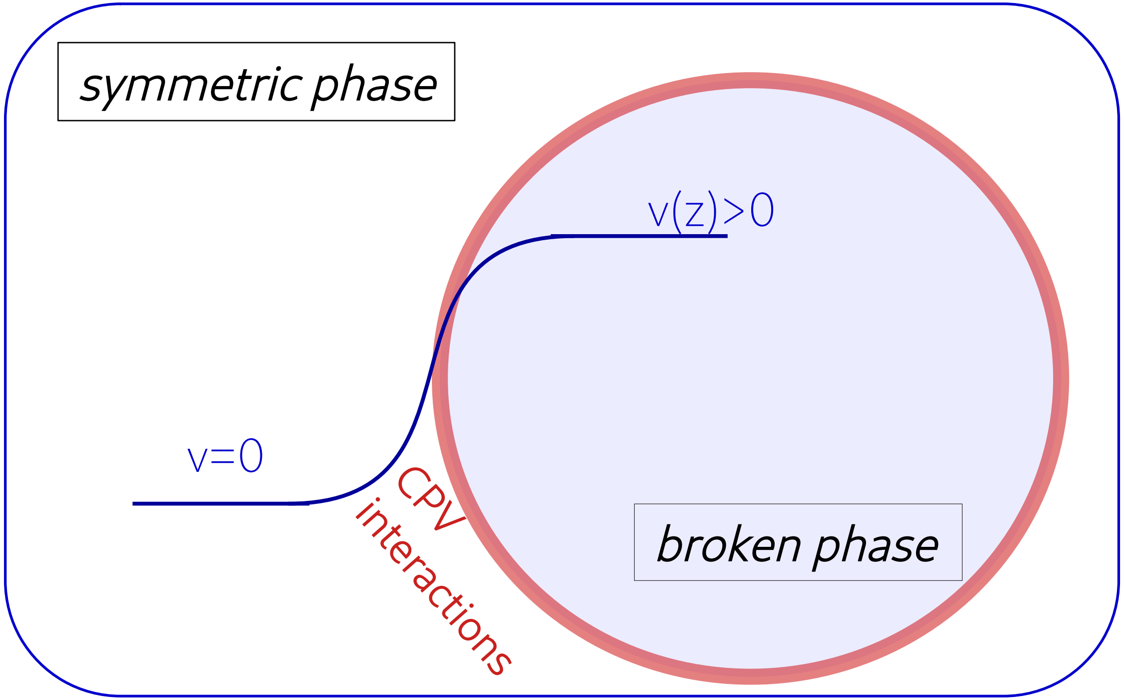

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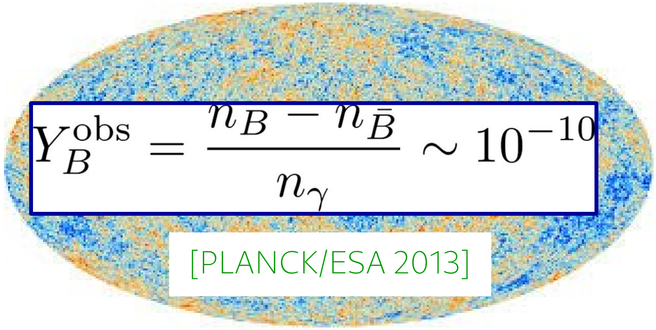

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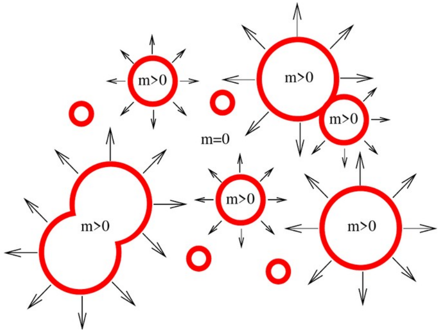


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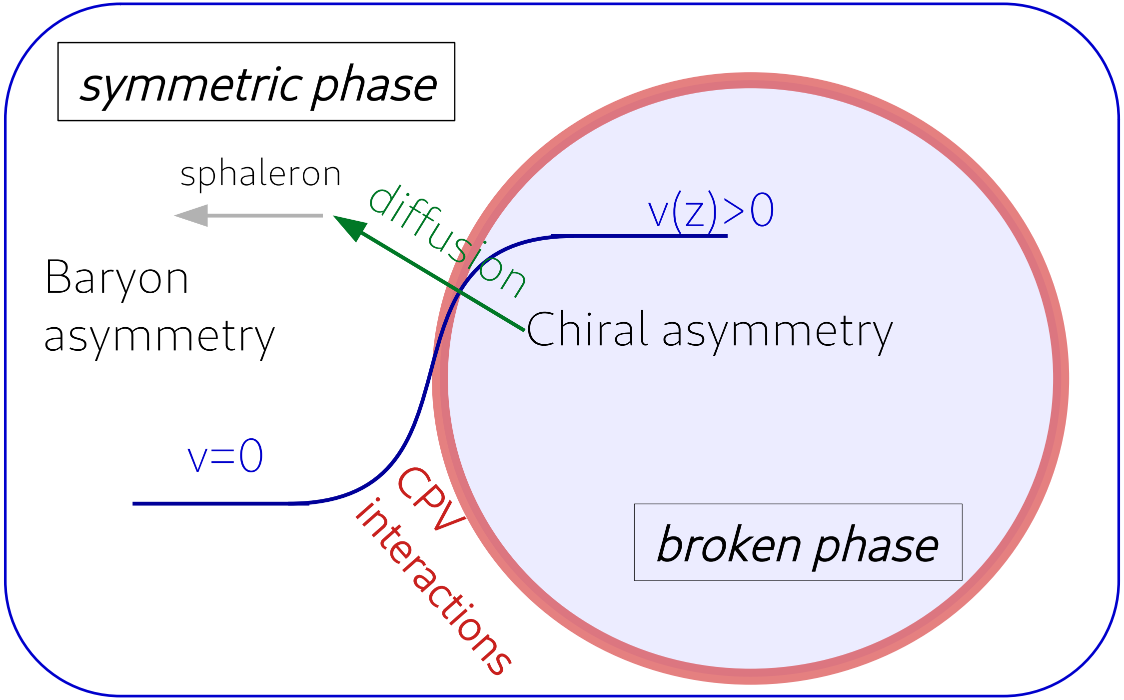

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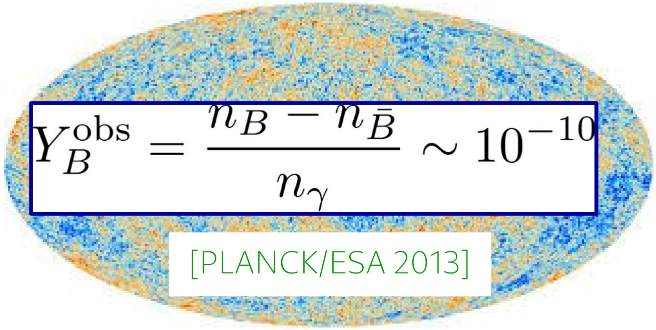

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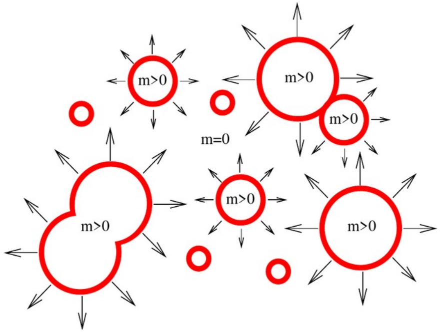


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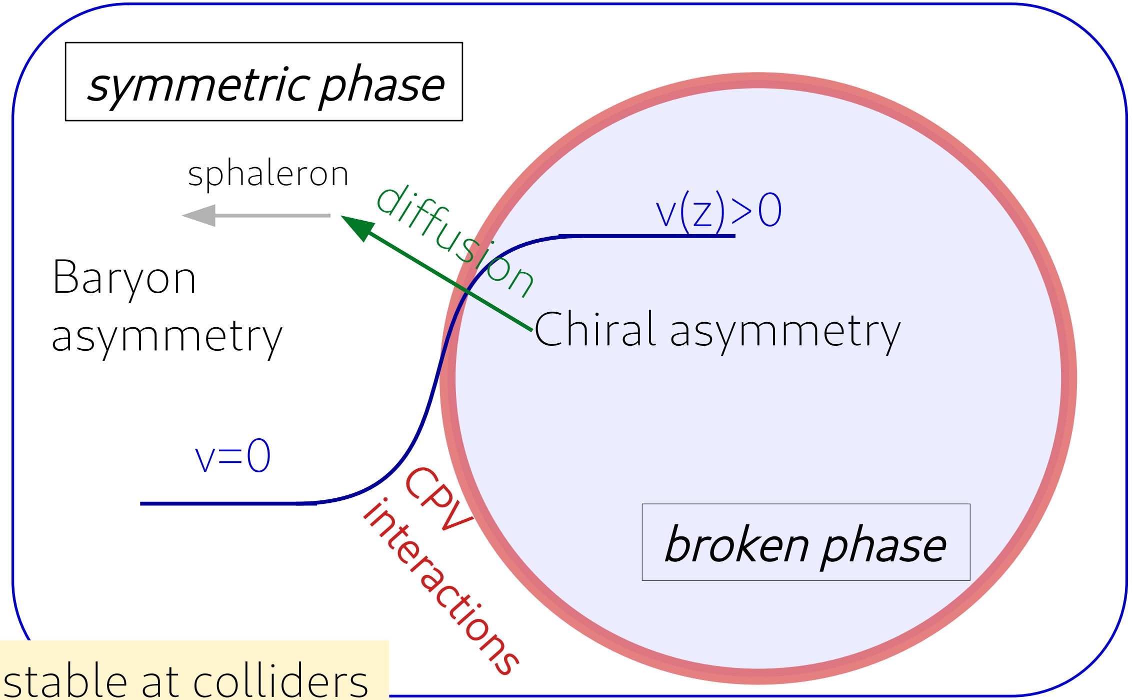


Higgs physics → testable at colliders

# 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 sphaleron — CPV source

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- thin wall
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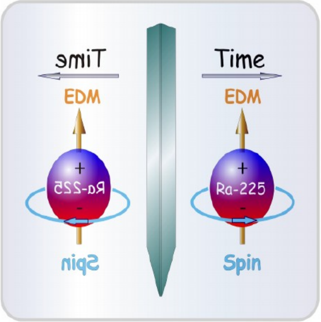
Same scaling as EDM

Benchmark of wall properties:

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

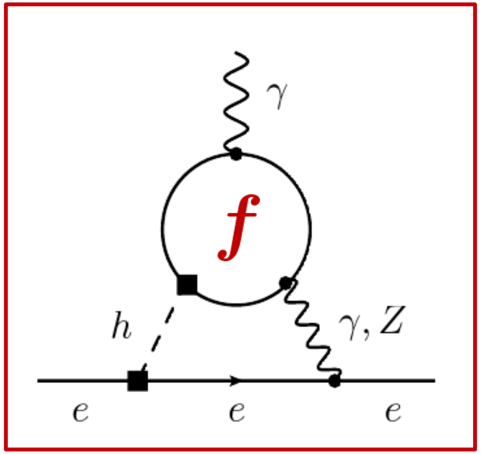
EF, Losada, Nir, Viernik '19, '20, '20
Aharony-Shapira '21

# Electron's Electric Dipole Moment




[Hewett, Weerts et al '12]

EDM violates $\mathcal{T}$ and $\mathcal{P}$
$\Rightarrow \not{CP}$




ACME [Nature '18]:

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

for t, b, c, τ, μ: electron EDM most sensitive

Using [Panico, Pomarol, Riembau '18], [Brod, Haisch, Zupan '13], [Brod, Stamou '18],...
See also recent [Brod, Cornell, Skodras, Stamou '22]

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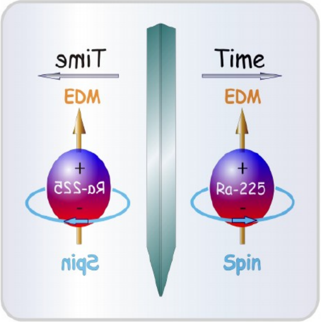


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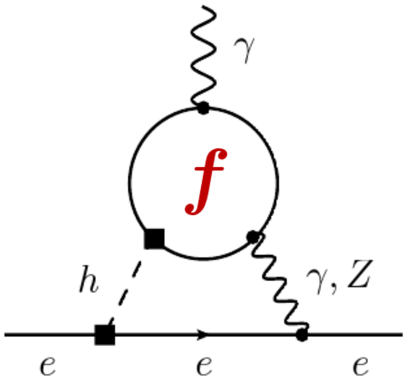


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$$\frac{d_e}{d_e^{\rm ACME}} = c_e\left(870.0\tilde{c}_t + 3.9\tilde{c}_b + 2.8\tilde{c}_c + 0.01\tilde{c}_s + 8\cdot 10^{-5}\tilde{c}_u + 7\cdot 10^{-5}\tilde{c}_d + 3.4\tilde{c}_\tau + 0.03\tilde{c}_\mu\right)$$
$$+\,\tilde{c}_e\left(610.1c_t + 3.1c_b + 2.3c_c + 0.01c_s + 7\cdot 10^{-5}c_u + 6\cdot 10^{-5}c_d + 2.8c_\tau + 0.02c_\mu - 1082.6c_V\right)$$
$$+\,2\cdot 10^{-6}c_e\tilde{c}_e.$$

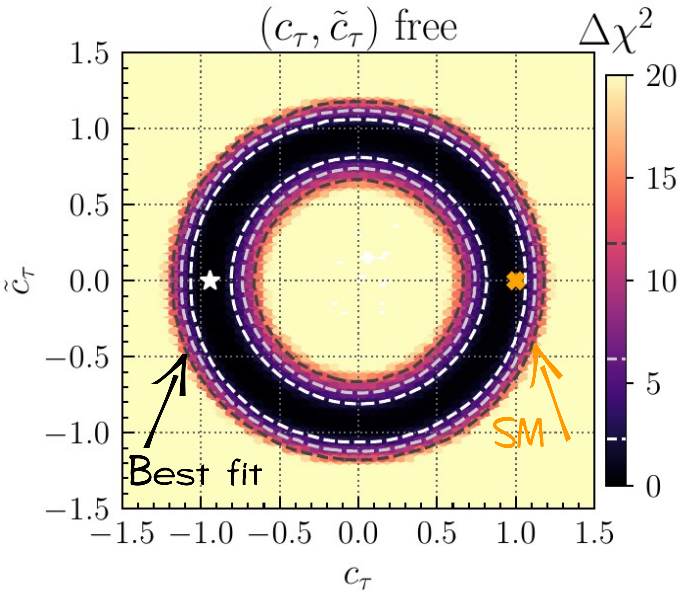
Cancellations possible

# CP structure of Higgs couplings - τ

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

Bahl, EF, Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein '22

Global fit using **HiggsSignals** + recent analyses




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

Ring-structure from upper/lower bound on BR

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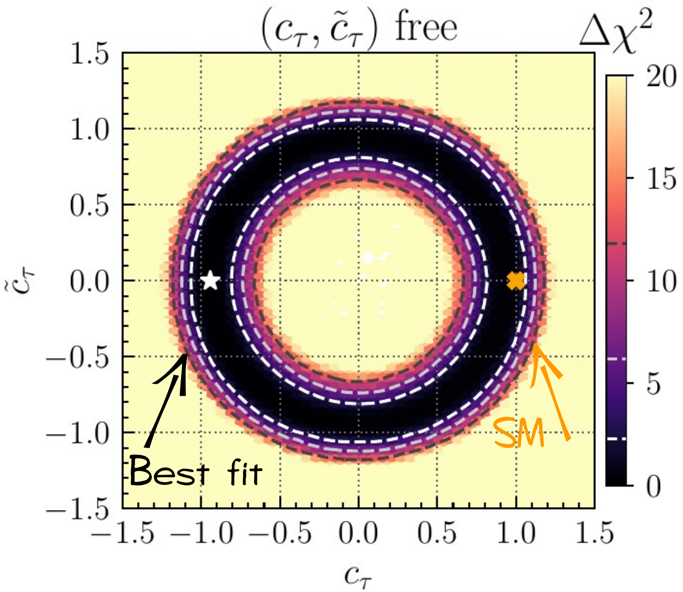
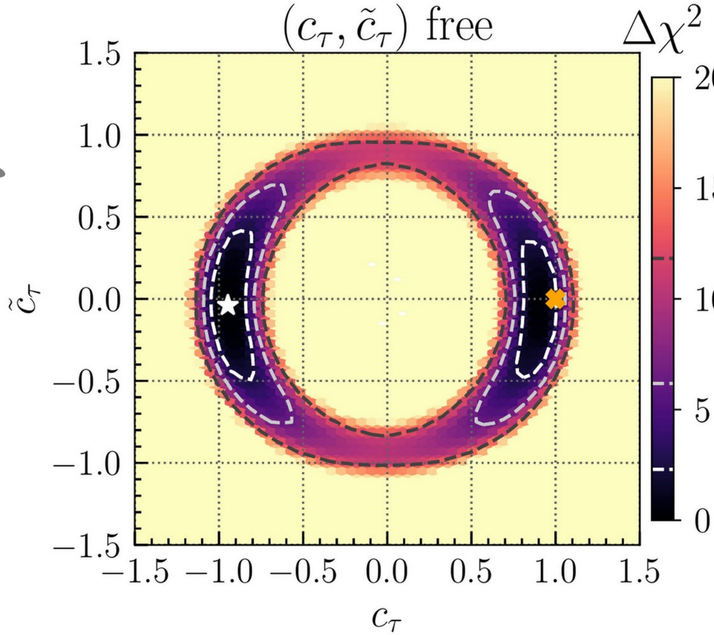



CMS '21
h→ ττ CPV analysis

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

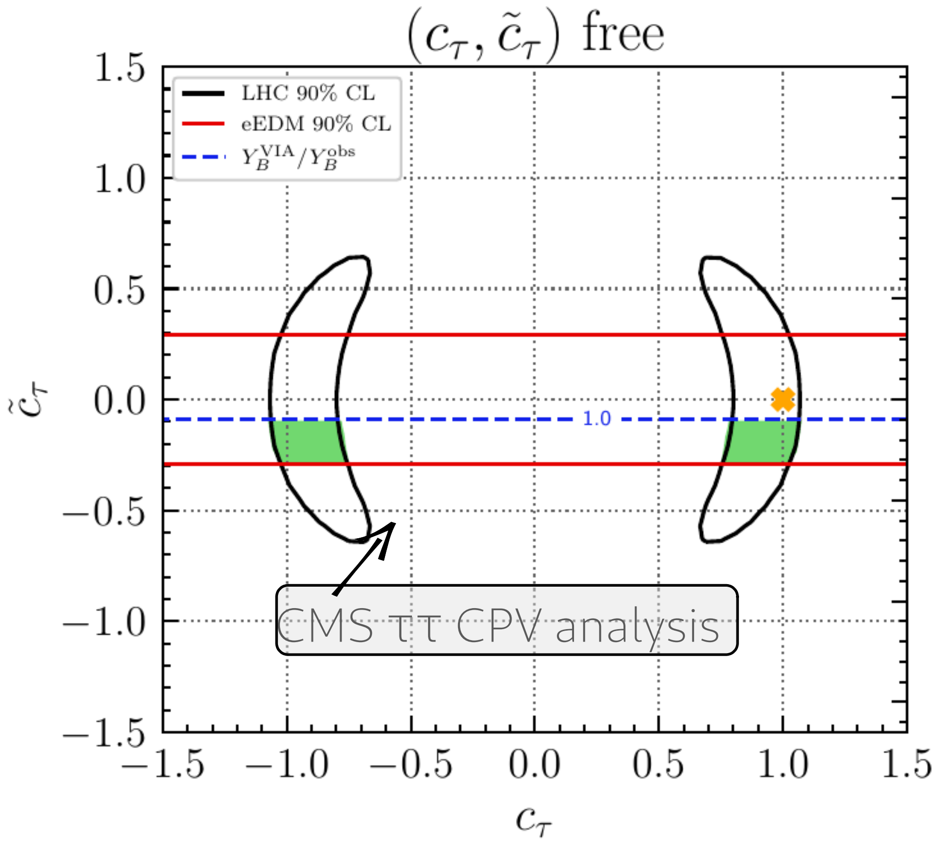



Ring-structure from upper/lower bound on BR

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

# Complementary (τ): LHC, EDM, EWBG

Bahl, **EF,** Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein '22



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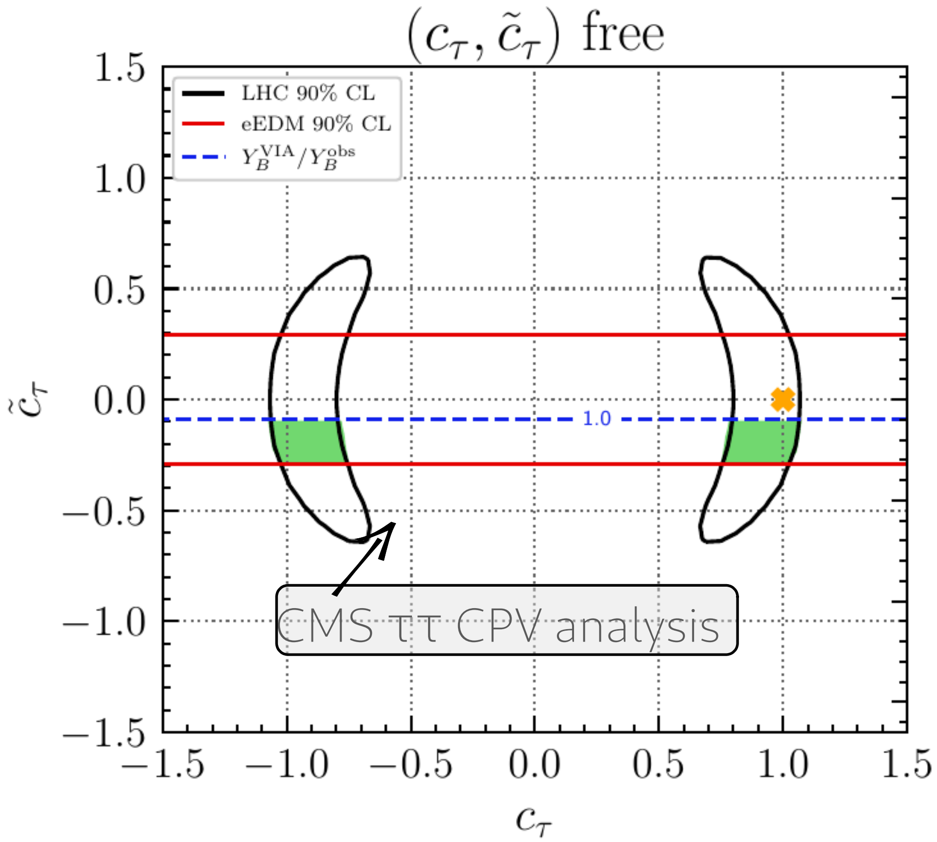
Electron electric dipole moment
$d_e \propto \tilde{c}_f$



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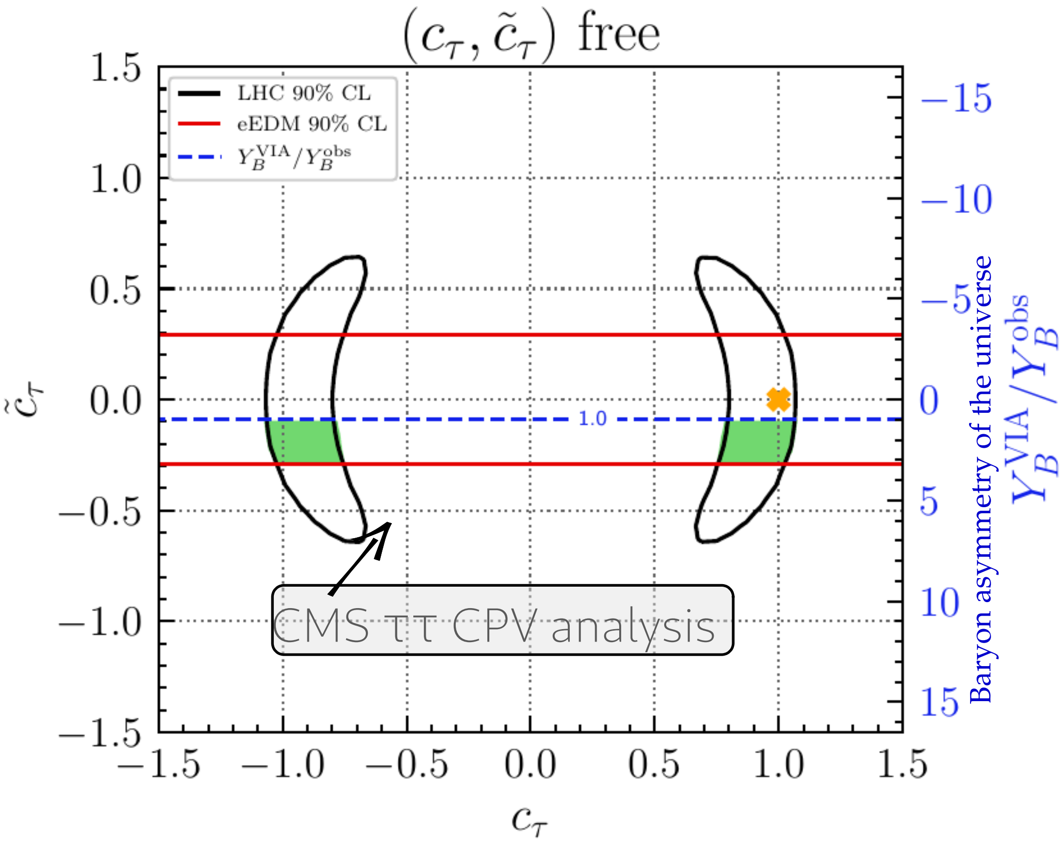


Electroweak baryogenesis
$Y_B \propto \tilde{c}_f$

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

Basler, Mühlleitner, Müller '20
Cline, Kainulainen '20
Cline, Laurent '21, Postma '21
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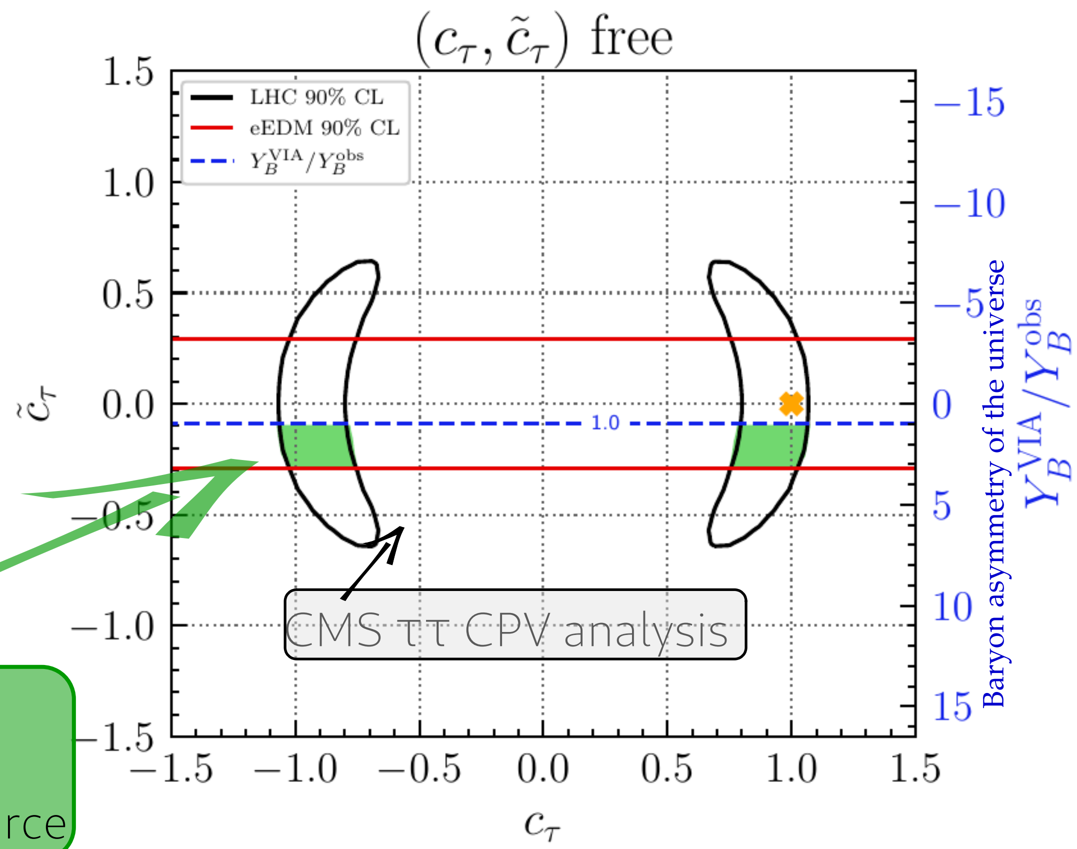


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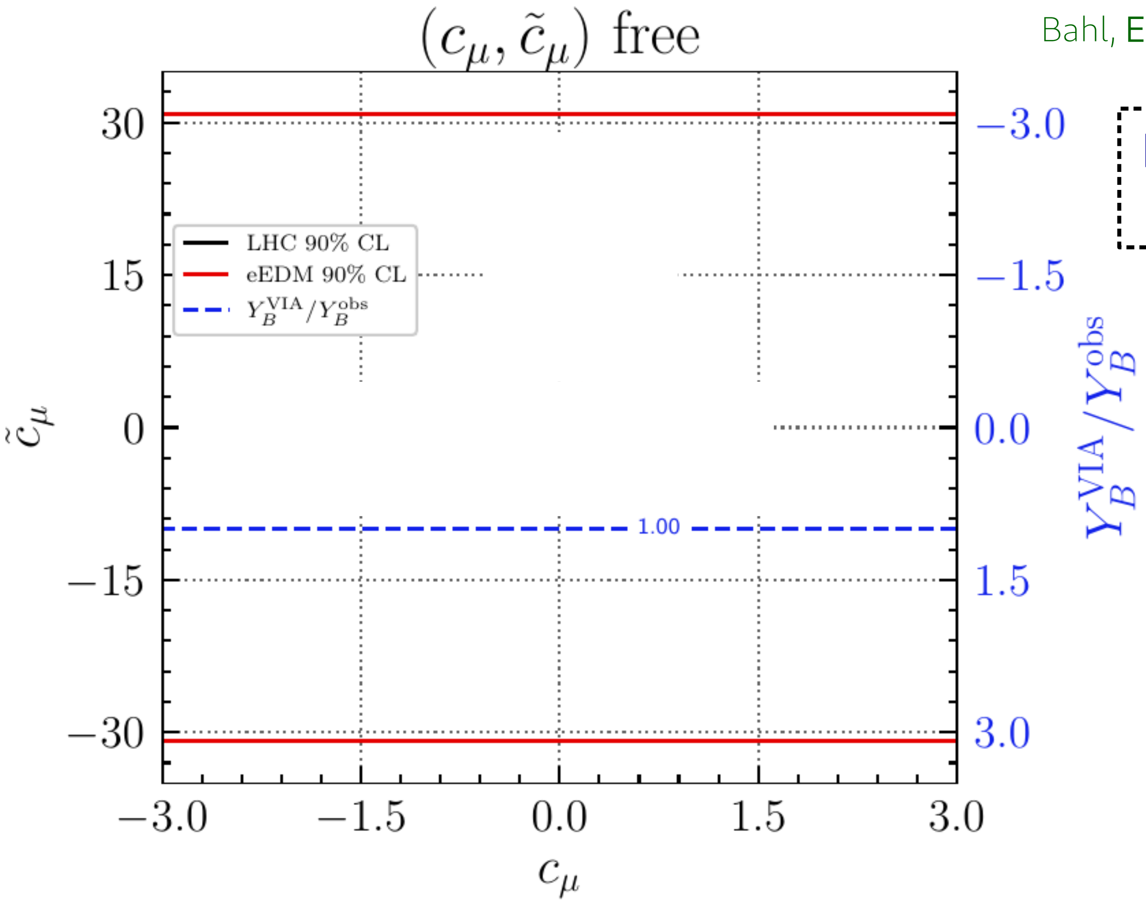
Allowed by LHC, EDM, EWBG → τ may be single source

# Role of muon

Bahl, **EF,** Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein '22




EWBG from μ allowed by EDM

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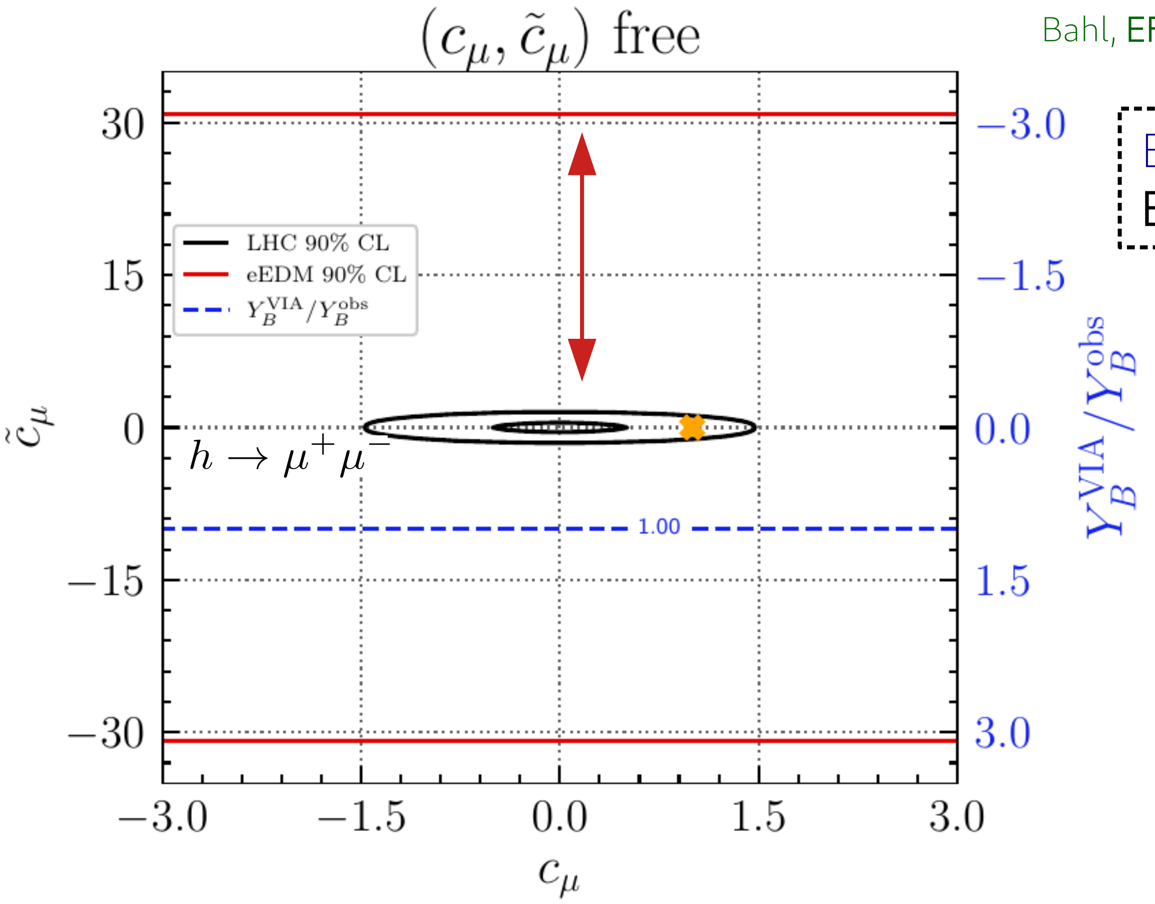



Bahl, **EF,** Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein '22

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

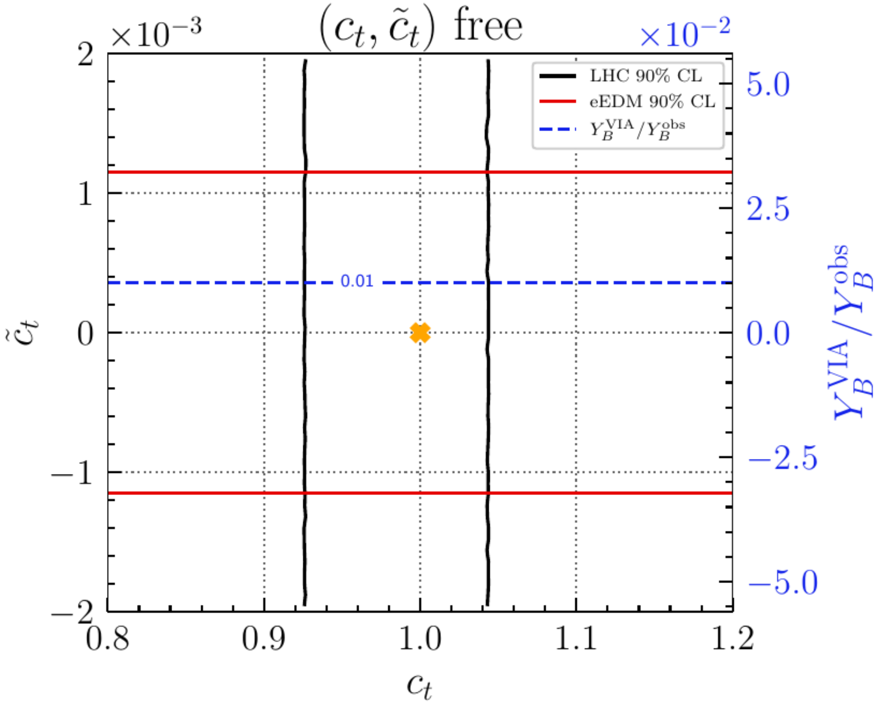
Confirmation of **EF**, Losada, Nir, Viernik [PRL 2020]

LHC stronger than EDM

LHC probes cosmology

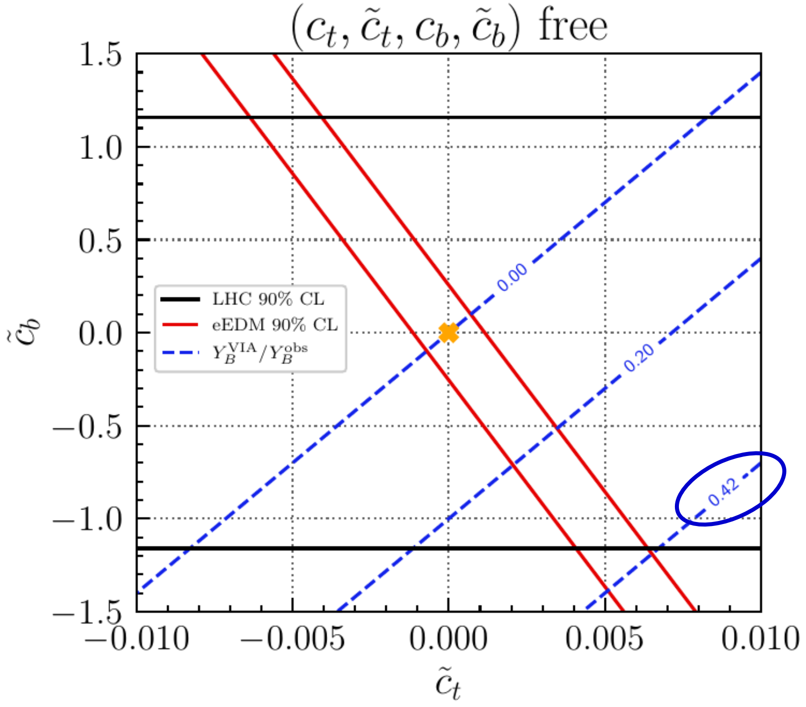
# Complementarity

**Top:** EDM very constraining




t, b: each only 3-5 % of observed BAU

**t, b:** cancellations of EDM allow larger CPV




Combined: max. 42% of observed BAU

# Summary of baryogenesis outcome

Maximal $Y_B/Y_B^{\rm obs}$ within LHC and EDM limits

| | $t$ | $b$ | $c$ | $\tau$ | $\mu$ |
|---|---|---|---|---|---|
| $t$ | 0.03 | | | | |
| $b$ | 0.42 | 0.05 | | | |
| $c$ | 0.37 | 0.19 | 0.01 | | |
| $\tau$ | 6.9 | 6.9 | 6.9 | 3.2 | |
| $\mu$ | 0.18 | 0.19 | 0.16 | 3.2 | 0.16 |

- Calculated in VIA approach
- In near-optimal benchmark scenario

⟶ Robust upper bound

$Y_B/Y_B^{\rm obs} < 1$

⟶ Disfavored by EWBG/ additional CPV needed

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$\longrightarrow$ Robust upper bound

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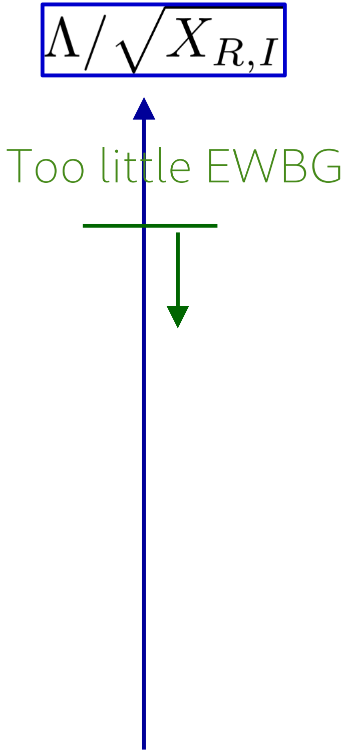
$Y_B/Y_B^{\rm obs} \geq 1$

$\longrightarrow$ EWBG possible in VIA, but WKB might need additional CPV

Also evaluated models with universal fermion coupling modifiers, and with vector coupling modifiers; investigated also complex electron Yukawa

# SMEFT: Cut-off scales




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

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

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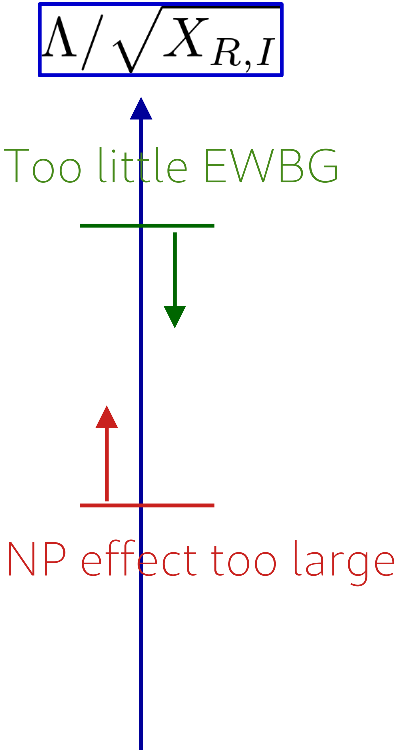


**Maximal** scales for minimally **required** $T_I$ (EWBG)

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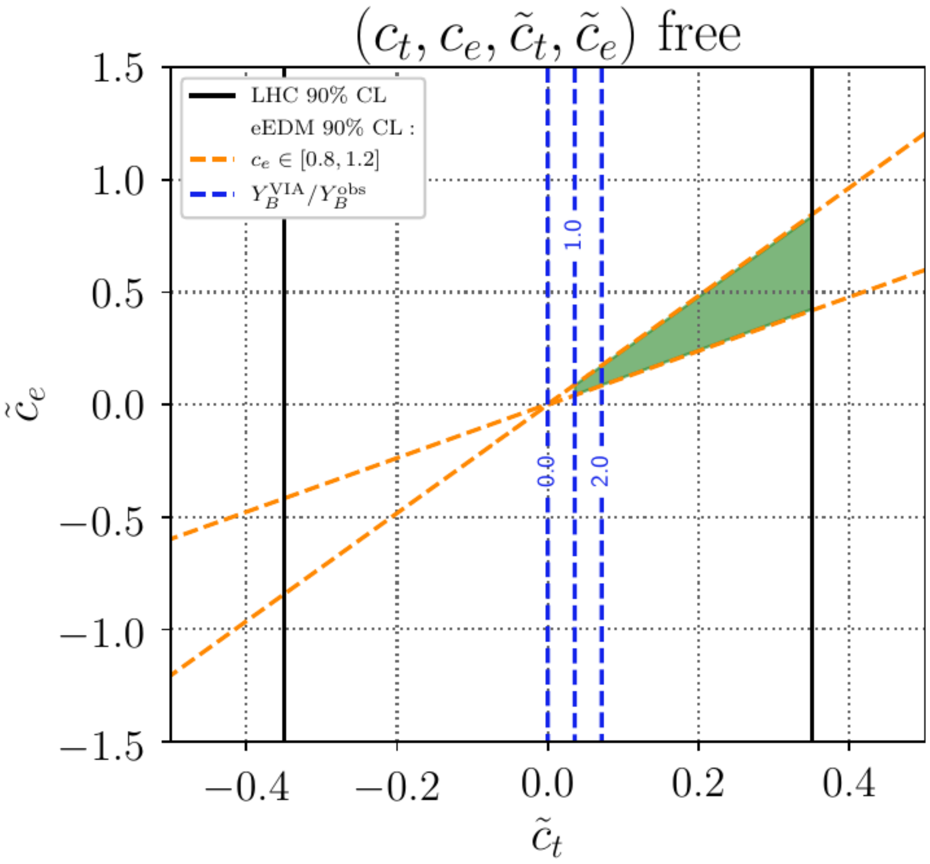
**Minimal** scales for maximally **allowed** T (collider, EDM)

$\Lambda/\sqrt{X_R^f},\ \Lambda/\sqrt{X_I^f} \gtrsim$

- τ: 2.4 TeV, 3.1 TeV
- b: 1.5 TeV, 1.7 TeV
- t: 8.7 TeV from EDM
- μ: 10 TeV, 12 TeV

# Role of the electron




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

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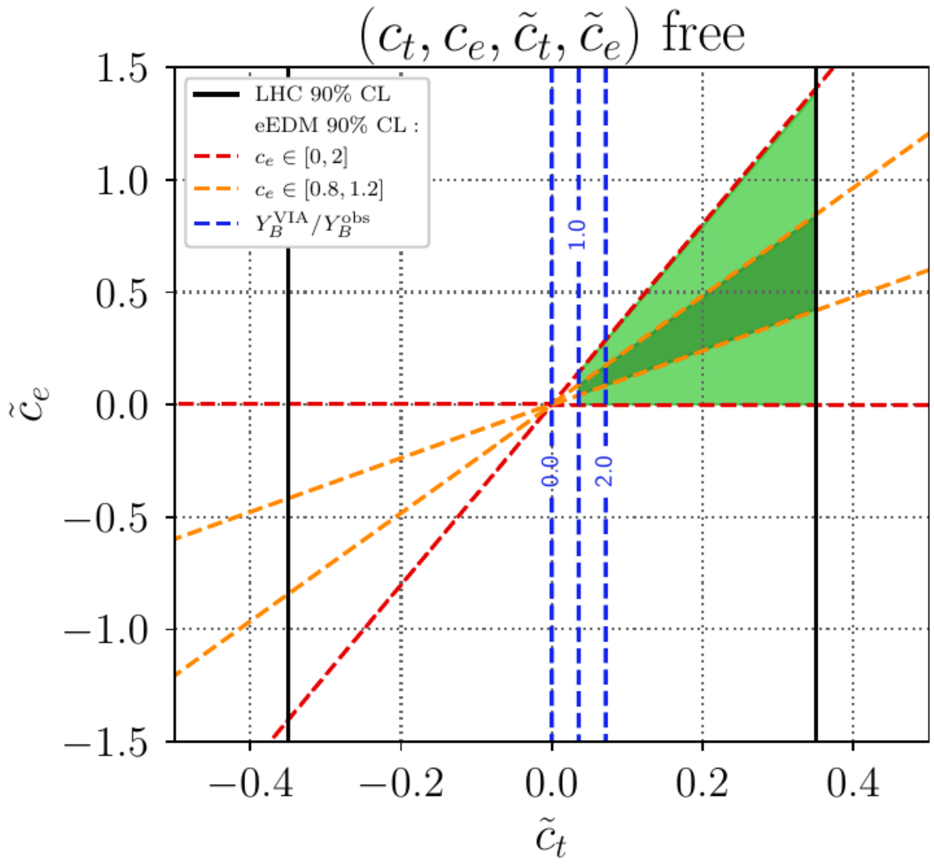


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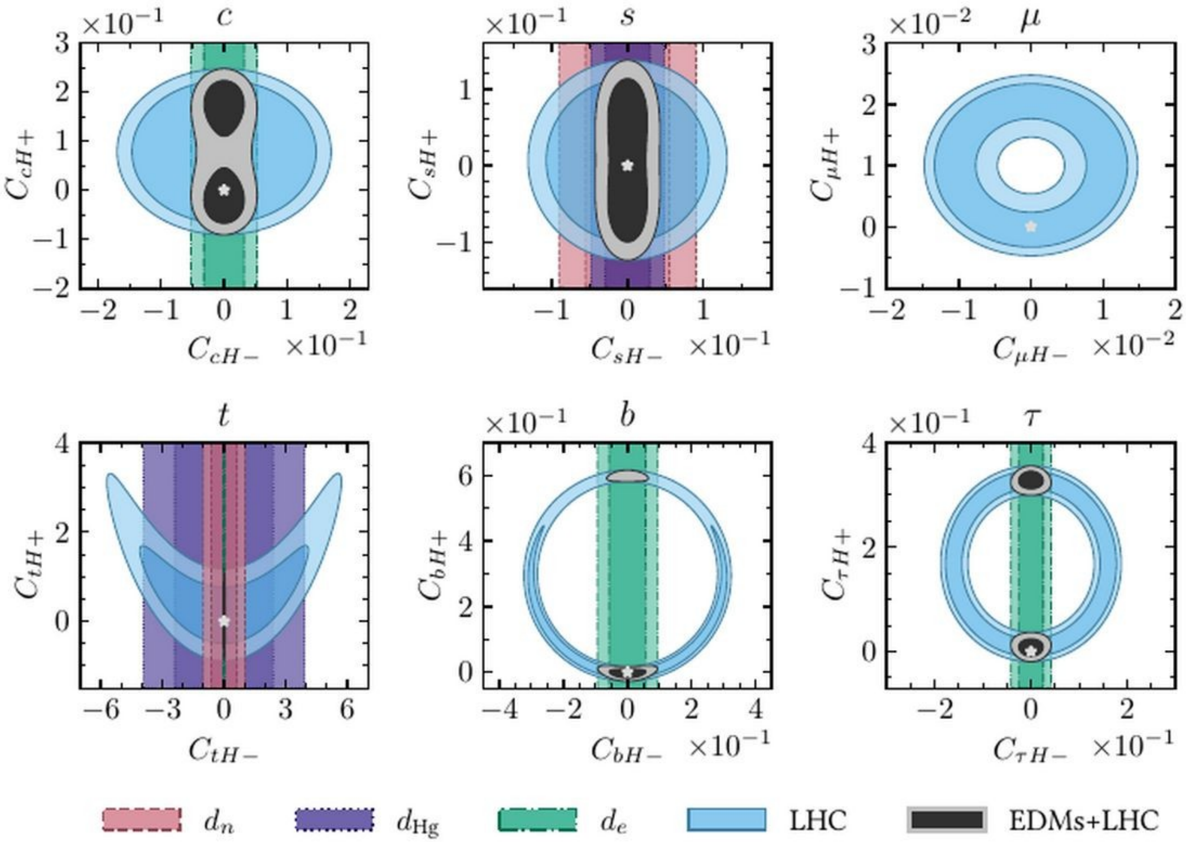
# EDMs and CPC LHC Higgs rates




Λ=1 TeV

Brod, Cornell, Skodras, Stamou 2203.03736

Global fit in SMEFT
in mass eigenstate basis

n, Hg, e EDMs

- RG evolution
- $d_e$ most sensitive to c and 3rd gen.
- From 90% upper limit to likelihood: assuming Gaussian distribution of exp. uncertainty

LHC Higgs rates

- CP-conserving

# Directions to improve tests of CPV

- Long-standing discrepancy in EWBG calculation
  - Perturbative VIA gives much larger prediction of $Y_B$ than WKB, up to orders of magnitude
- Need likelihood from EDM bounds for global fit
- Improve (HL-)LHC studies of CPV in Higgs couplings
  - CP-odd observables
  - Machine Learning
- LHC HXSWG CPV subgroup in WG2, e.g.
  - CPV Benchmarks for UV models and EFT
  - Interplay of LHC and EDMs

Investigate further to which extent CPV in Higgs couplings can account for EWBG

# Conclusions

- Complementarity of EDM, EWBG and LHC Higgs physics
- H→ττ CP analysis excludes large $\tilde{c}_\tau$, but τ remains viable EWBG source (VIA LO)
- LHC constrains cosmological scenarios, separates flavors; now also 2nd gen.
- Cancellations and enhancements with 2 fermions, e.g. t+b: few % → ~40% of obs. $Y_B$
- Electron Yukawa has big impact on interpretation of electron EDM
- SMEFT generates Yukawa modifications, preferred scale $\Lambda/\sqrt{X_I} \sim$ few-10-20 TeV

THANK YOU!

# BACKUP

# $T_R, T_I, Y_f$

Relation between SM mass and Yukawa fixes $Y_f$ (a priori free coefficient of dim-4 term)

$T_R, T_I, Y_f$ → **2 free parameters** per fermion: **$T_R$ , $T_I$**

Modification of each vertex w.r.t. SM $r_f(T_R^f, T_I^f) \equiv \frac{|\lambda_f|^2/|\lambda_f^{\mathrm{SM}}|^2}{|m_f|^2/|m_f^{\mathrm{SM}}|^2} = \frac{(1+3T_R^f)^2 + 9T_I^{f2}}{(1+T_R^f)^2 + T_I^{f2}}$

production, decay

Total Higgs width

$$\Gamma_h/\Gamma_h^{\mathrm{SM}} = 1 + \mathrm{BR}_f^{\mathrm{SM}}(r_f - 1)$$

# Transport equations

$$\partial f \equiv \partial_\mu f^\mu \approx v_w f' - D_f f''$$ Diffusion approximation

$$\partial t = -\Gamma^t_M \mu^t_M - \Gamma^t_Y \mu^t_Y + \Gamma_{ss}\mu_{ss} + S_t$$
$$\partial b = -\Gamma^b_M \mu^b_M - \Gamma^b_Y \mu^b_Y + \Gamma_{ss}\mu_{ss} + S_b$$
$$\partial q = -\partial t - \partial b$$
$$\partial \tau = -\Gamma^\tau_M \mu^\tau_M - \Gamma^\tau_Y \mu^\tau_Y + S_\tau$$
$$\partial l = -\partial \tau$$
$$\partial h = +\Gamma^t_Y \mu^t_Y - \Gamma^b_Y \mu^b_Y - \Gamma^\tau_Y \mu^\tau_Y$$
$$\partial u = +\Gamma_{ss}\mu_{ss} \,.$$

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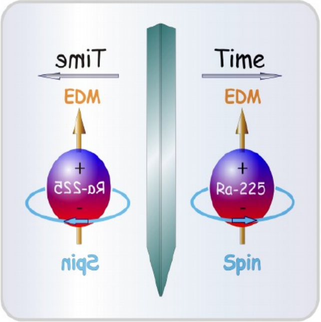
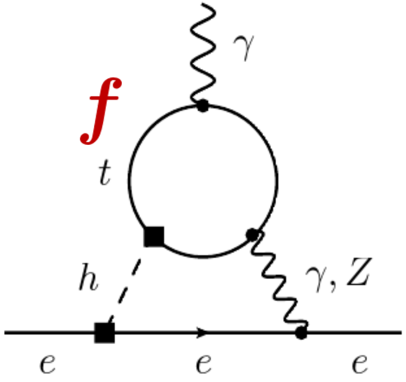
[Hewett, Weerts et al '12]




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

$\Rightarrow \not{\mathcal{CP}}$

$$\frac{d_e^f}{e} \propto \left(\frac{Y^f}{Y^f_{\rm SM}}\right)^2 T_I^f$$

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$$\frac{d_e^{(\ell)}}{e} \simeq -4Q_\ell^2 \frac{e^2}{(16\pi^2)^2}\frac{m_e m_\ell}{m_h^2}\frac{v}{\Lambda^2}\boldsymbol{X_I^\ell}\left(\frac{\pi^2}{3} + \ln^2\frac{m_\ell^2}{m_h^2}\right), \quad \boldsymbol{\ell = \tau, \mu}$$

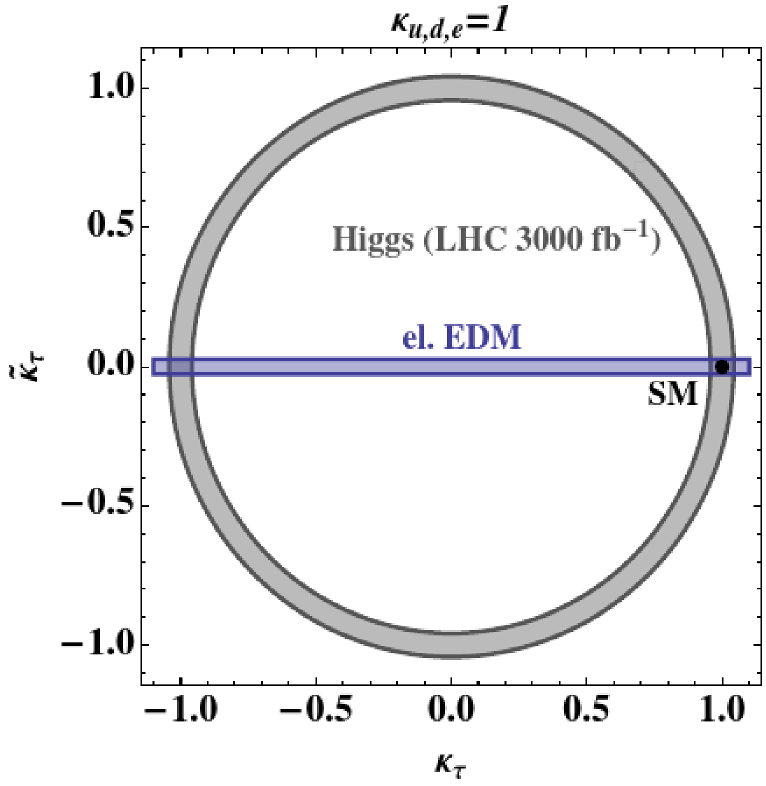
$$\frac{d_e^{(b)}}{e} \simeq -4N_c Q_b^2 \frac{e^2}{(16\pi^2)^2}\frac{m_e m_b}{m_h^2}\frac{v}{\Lambda^2}\boldsymbol{X_I^b}\left(\frac{\pi^2}{3} + \ln^2\frac{m_b^2}{m_h^2}\right)$$

$$\frac{d_e^{(t)}}{e} \simeq -\frac{16}{3}\frac{e^2}{(16\pi^2)^2}\frac{m_e}{m_t}\frac{v}{\Lambda^2}\boldsymbol{X_I^t}\left(2 + \ln\frac{m_t^2}{m_h^2}\right)$$

# EDM & LHC limits CPV Yukawas

tau

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




projection ~O($10^{-30}$)

$d_e$ [e cm]:

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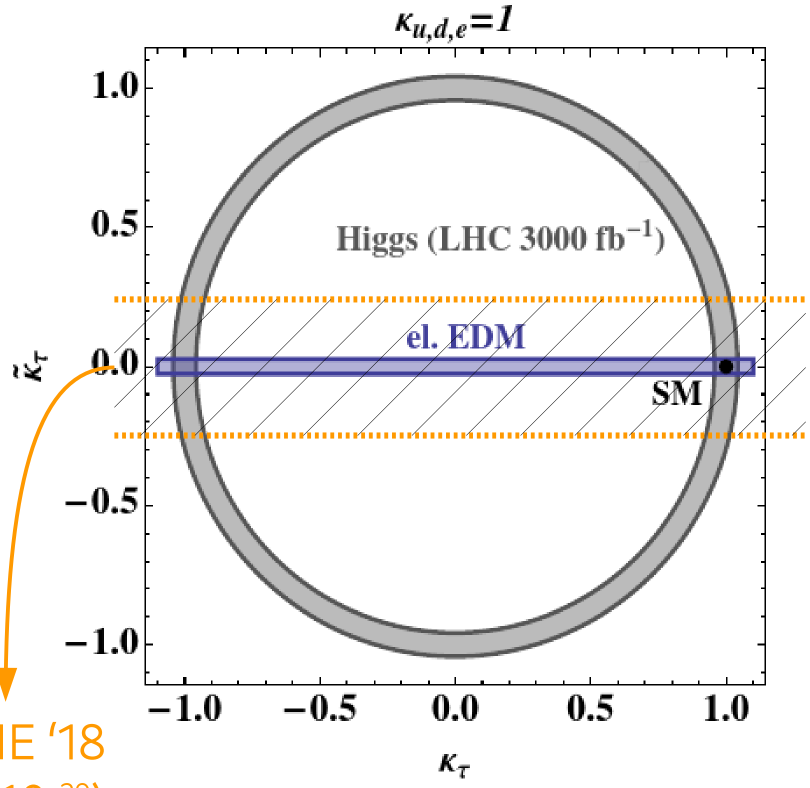


$d_e$ [e cm]:

ACME ‘18
~O($10^{-29}$)

projection
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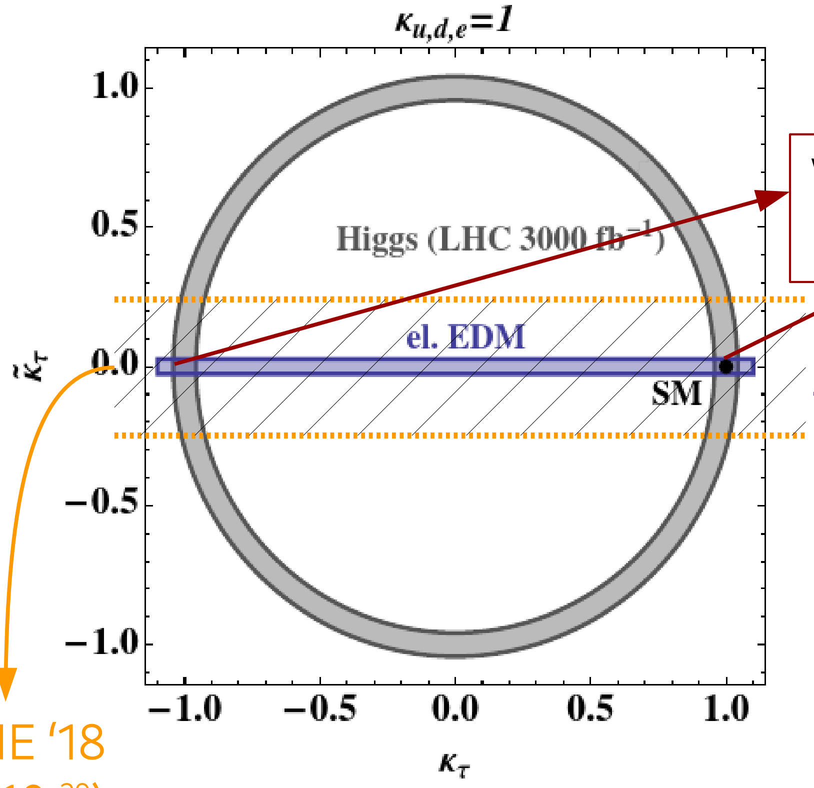



What is $Y_B$ in these remaining areas?

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

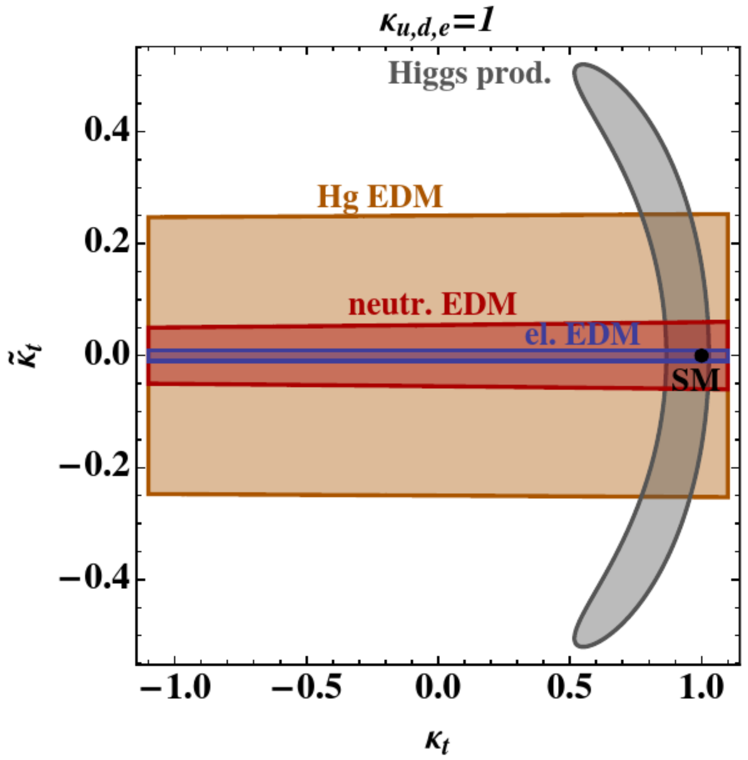
projection ~O($10^{-30}$)

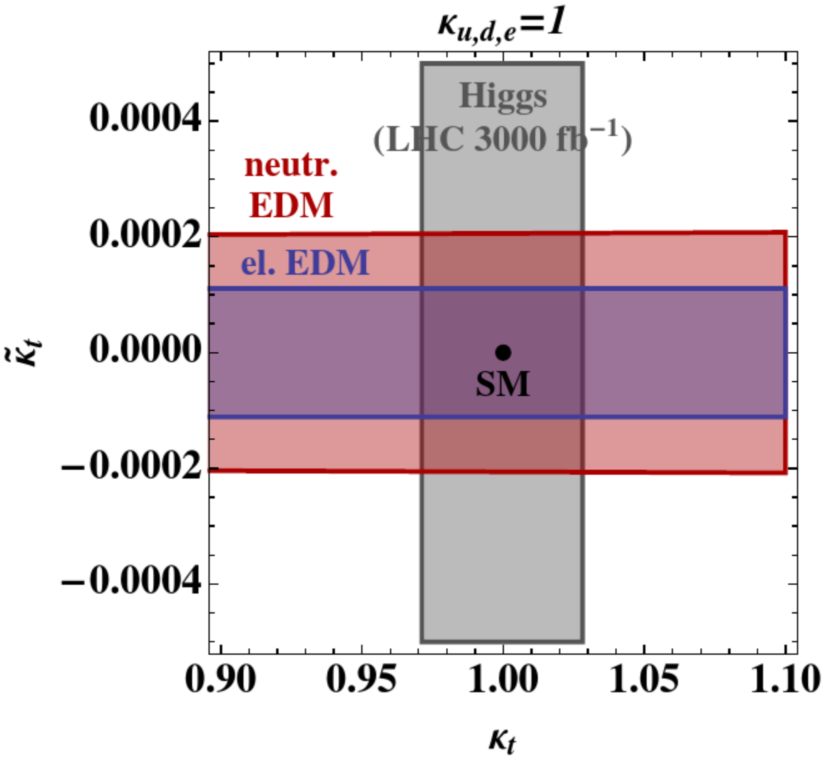
$d_e$ [e cm]:

# EDM & LHC limits CPV Yukawas

top

Brod, Haisch, Zupan '13

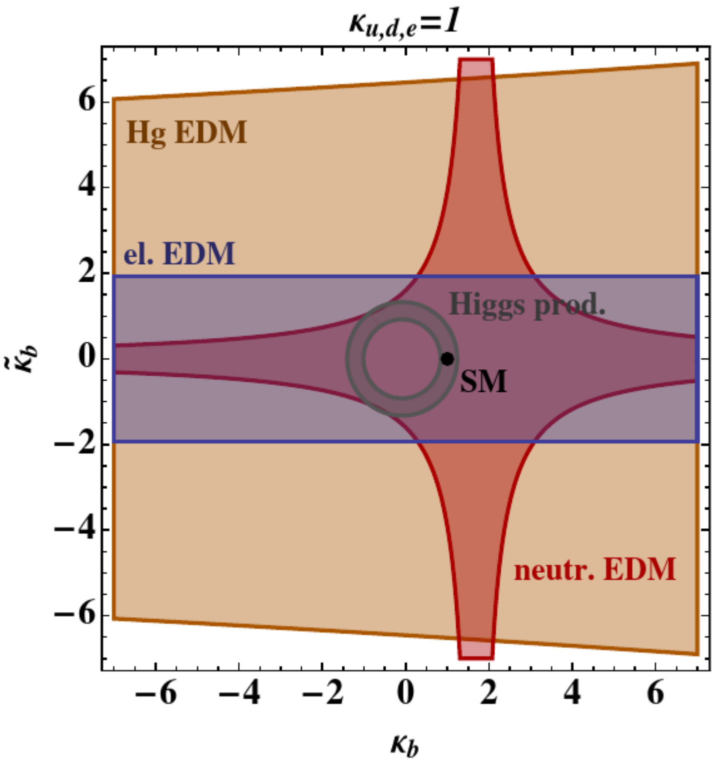


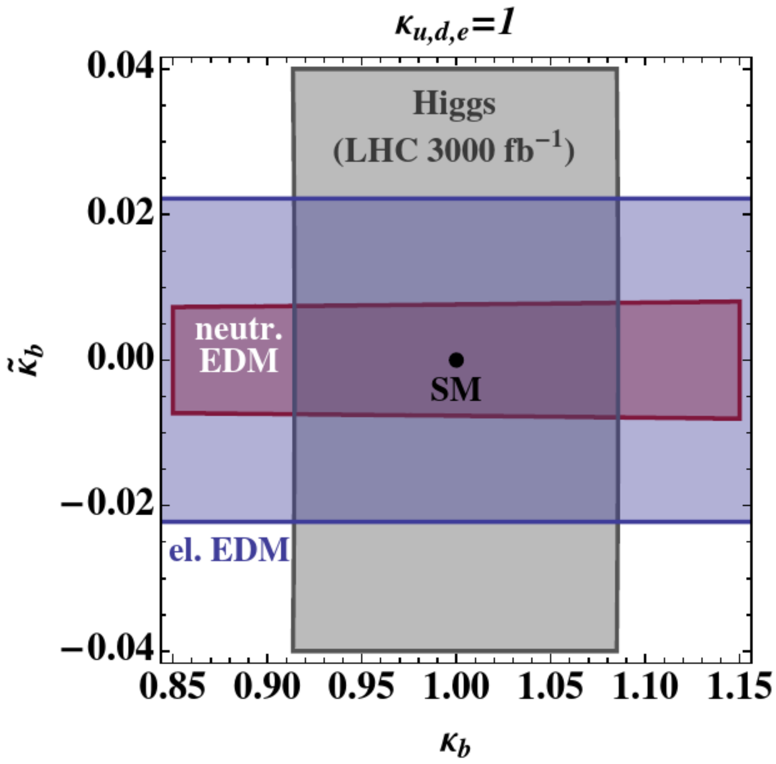



# EDM & LHC limits CPV Yukawas

bottom

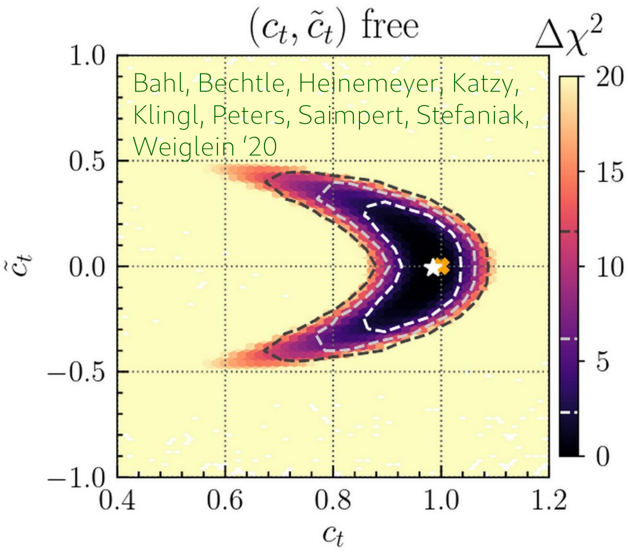
Brod, Haisch, Zupan '13



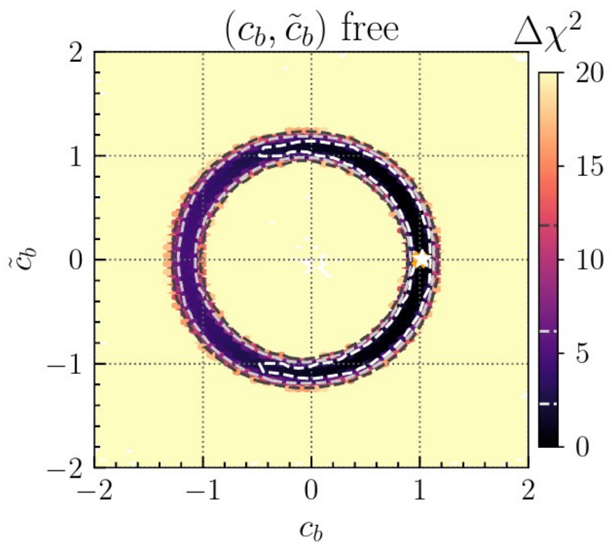



# Top, bottom, and their combination

Bahl, **EF,** Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein '22




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

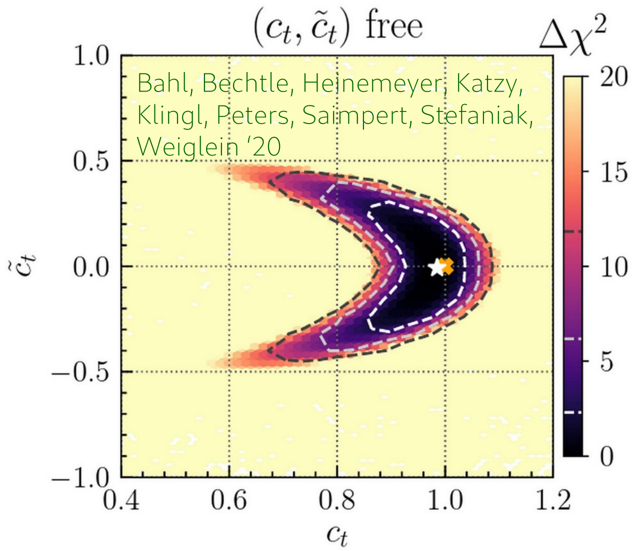


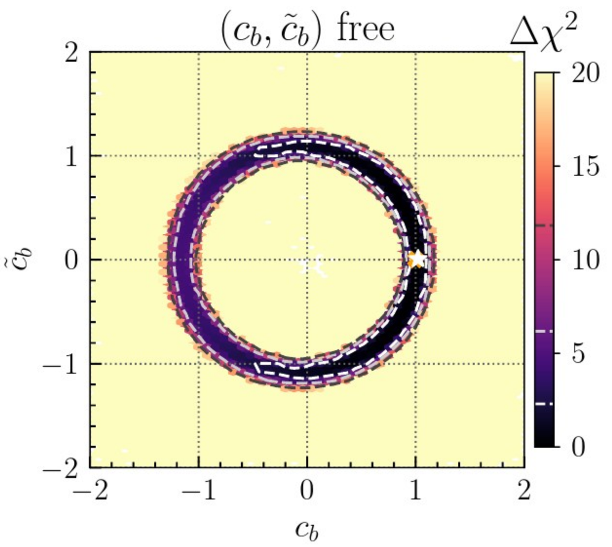

Bottom: ring (h→ bb) reduced by ggF (positive interference with t)

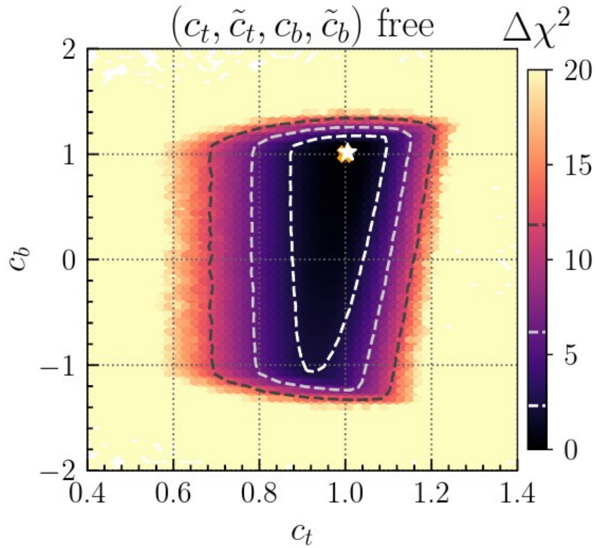
# Top, bottom, and their combination

Bahl, **EF,** Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein '22

Floating several coupling modifiers simultaneously



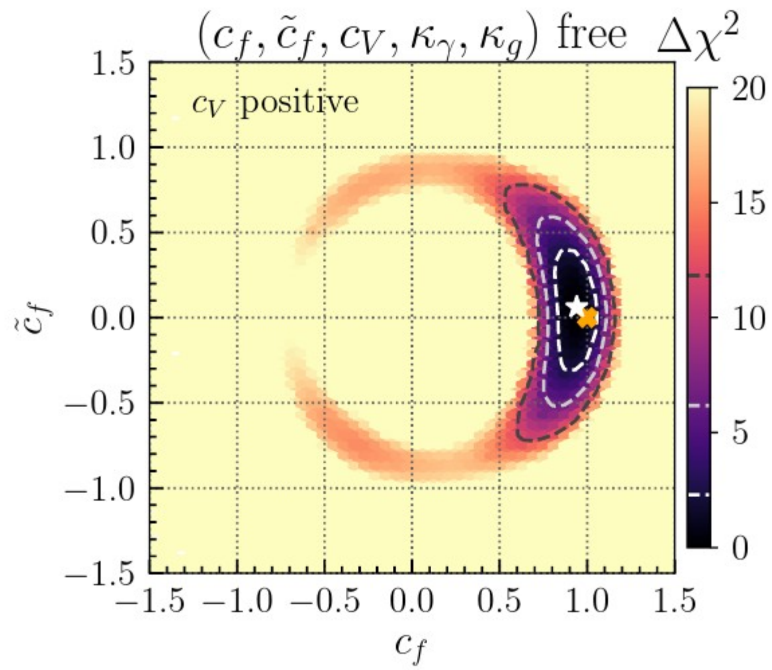

Top: ellipse (ggF) cut off by $h \to \gamma\gamma$

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

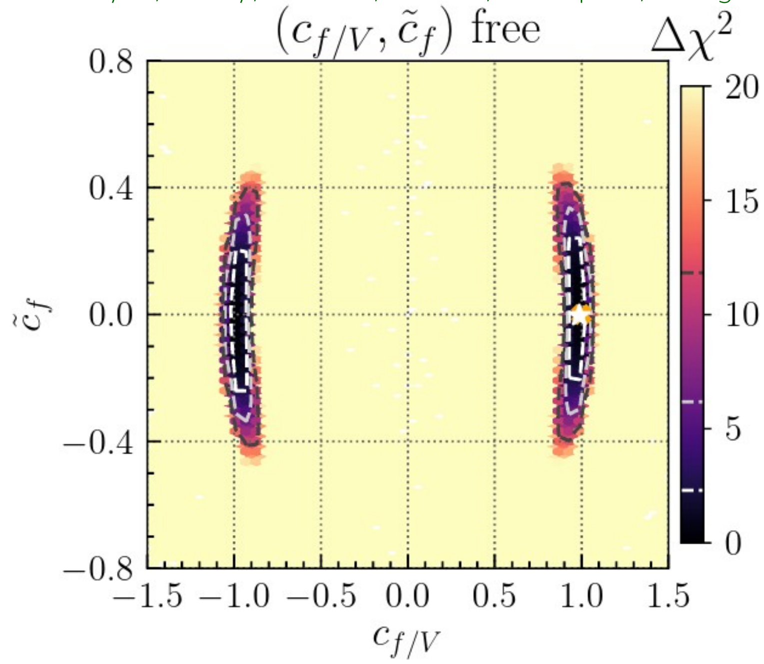
t+b: small $c_b$ can be compensated by $\tilde{c}_b$

# Varying vector couplings

Bahl, **EF,** Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein ‘22



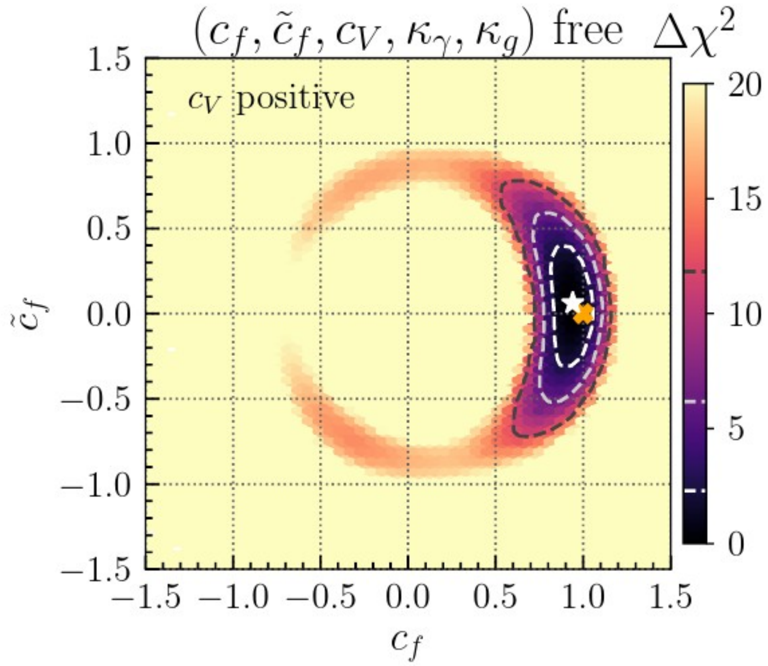

Universal fermion coupling modifier: Dominated by top

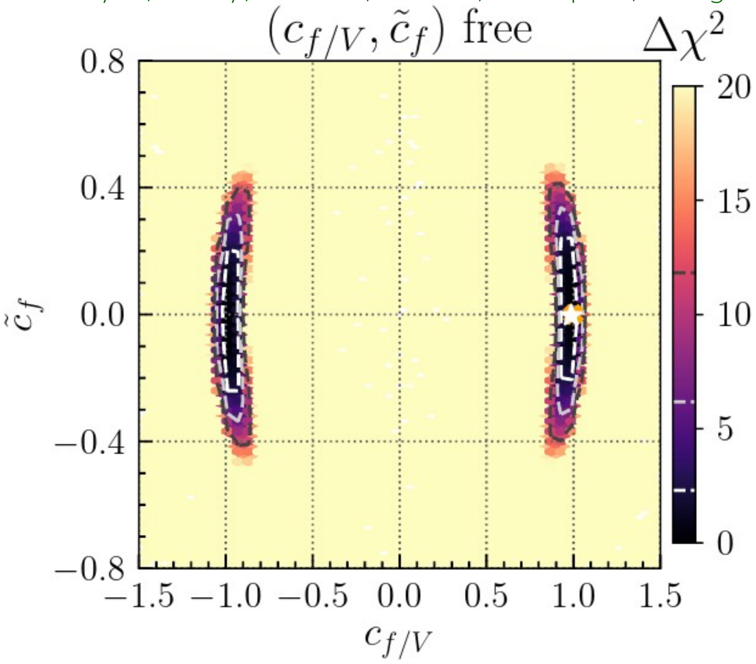



General mixing scenario: $c_f = c_V$
No CPV included in vector couplings

# Varying vector couplings

Bahl, **EF,** Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein '22




Universal fermion coupling modifier: Dominated by top

+ fitted more models with up to 9 free parameters

General mixing scenario: $c_f = c_V$
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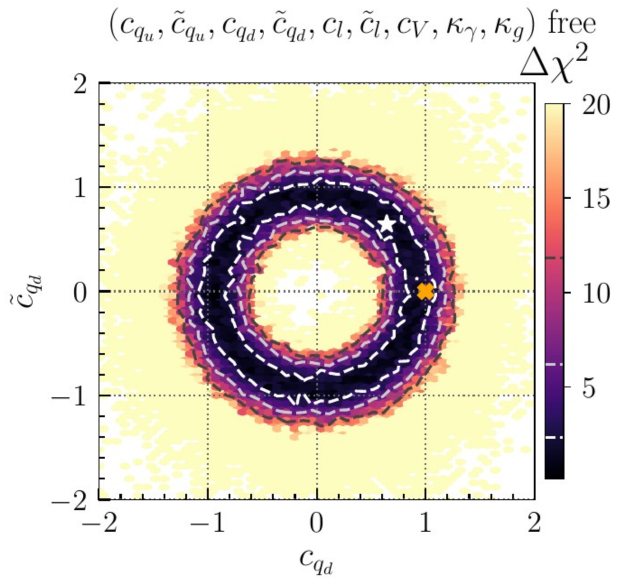
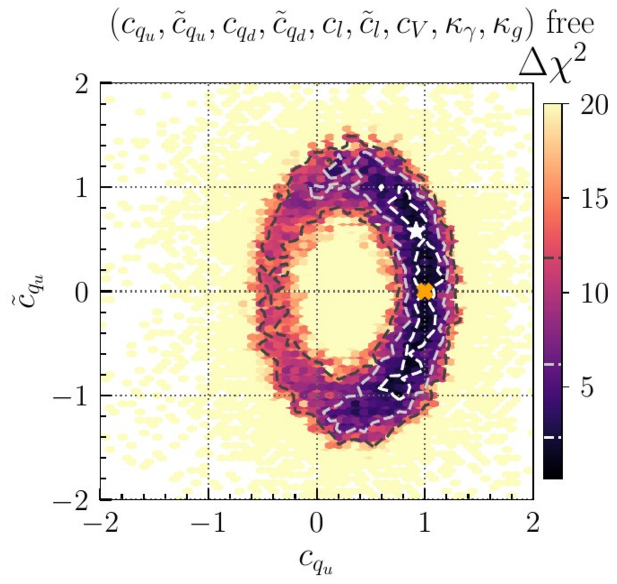
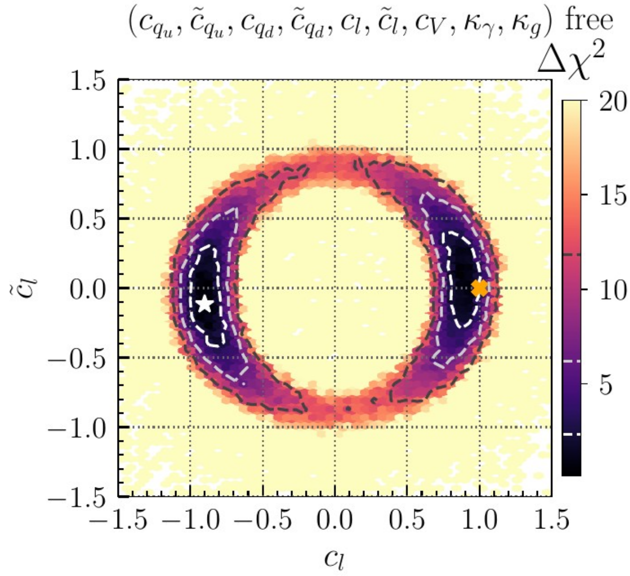
# General model: 9-parameter fit

Bahl, **EF,** Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein '22



# Lepton vs Quark Source

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  - No strong sphaleron washout
  - Large diffusion
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  - Quarks larger uncertainties
- Benchmark choices:
  - Wall velocity, thickness, ...
  - → investigated impact in 2007.06940, see also Postma, van de Vis, White '16; de Vries, Postma, van de Vis '18;

# 2-step: baryon density from L density

Solve for left-handed particle density or directly baryon density

$$n_b''(z) - \frac{v_w}{D_q} n_b'(z) = \frac{\Gamma_{ws}(z)}{D_q}\left(\mathcal{R} n_b(z) + \frac{3}{2} n_L(z)\right) \equiv \frac{\Gamma_{ws}(z)}{D_q}\mathcal{R} n_b + f(z)$$

$$Y_B = \frac{n_b(z>0)}{s} = \frac{A_1}{s} = \frac{1}{s}\left(1 - \frac{\alpha_-}{\alpha_+}\right) B_1 = \frac{k}{D_q \alpha_+ s} B_1$$
$$= \frac{3\Gamma_{ws}}{2 D_q \alpha_+ s} \int_0^{-\infty} e^{-\alpha_- x} n_L(x) dx \,.$$

# Chemical potentials

$$\mu_M^t = \frac{t}{k_t} - \frac{q}{k_q}\,, \qquad \mu_M^b = \frac{b}{k_b} - \frac{q}{k_q}\,, \qquad \mu_M^\tau = \frac{\tau}{k_\tau} - \frac{l}{k_l}\,,$$

$$\mu_Y^t = \frac{t}{k_t} - \frac{q}{k_q} - \frac{h}{k_h}\,, \qquad \mu_Y^b = \frac{b}{k_b} - \frac{q}{k_q} + \frac{h}{k_h}\,, \qquad \mu_Y^\tau = \frac{\tau}{k_\tau} - \frac{l}{k_l} + \frac{h}{k_h}\,,$$

$$\mu_{ss} = \sum_{i=1}^{3} \frac{2q_i}{k_{q_i}} - \frac{u_i}{k_{u_i}} - \frac{d_i}{k_{d_i}}\,.$$

# Matrix formalism: o.d.e. 1st order

$$\begin{pmatrix} t' \\ b' \\ \vdots \\ g'_t \\ g'_b \\ \vdots \end{pmatrix} - \begin{pmatrix} 0 & & & 1 & & \\ & 0 & & & 1 & \\ & & \ddots & & & \ddots \\ & & & \frac{v_w}{D_t} & & \\ & & & & \frac{v_w}{D_b} & \\ & & & & & \ddots \end{pmatrix} \begin{pmatrix} t \\ b \\ \vdots \\ g_t \\ g_b \\ \vdots \end{pmatrix} = \begin{pmatrix} 0 & & & & \\ & \ddots & & & \\ \frac{\Gamma_t}{D_t k_t} & & & & \\ & \frac{\Gamma_b}{D_b k_b} & & \ddots & \\ & & \ddots & & 0 \end{pmatrix} \begin{pmatrix} t \\ b \\ \vdots \\ g_t \\ g_b \\ \vdots \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \vdots \\ S_t/D_t \\ S_b/D_b \\ \vdots \end{pmatrix}$$

$$\Longleftrightarrow \quad \bar{\chi}' - K\bar{\chi} = \bar{S}\,, \qquad K \equiv \begin{pmatrix} 0 & I_N \\ \Gamma & V \end{pmatrix}.$$

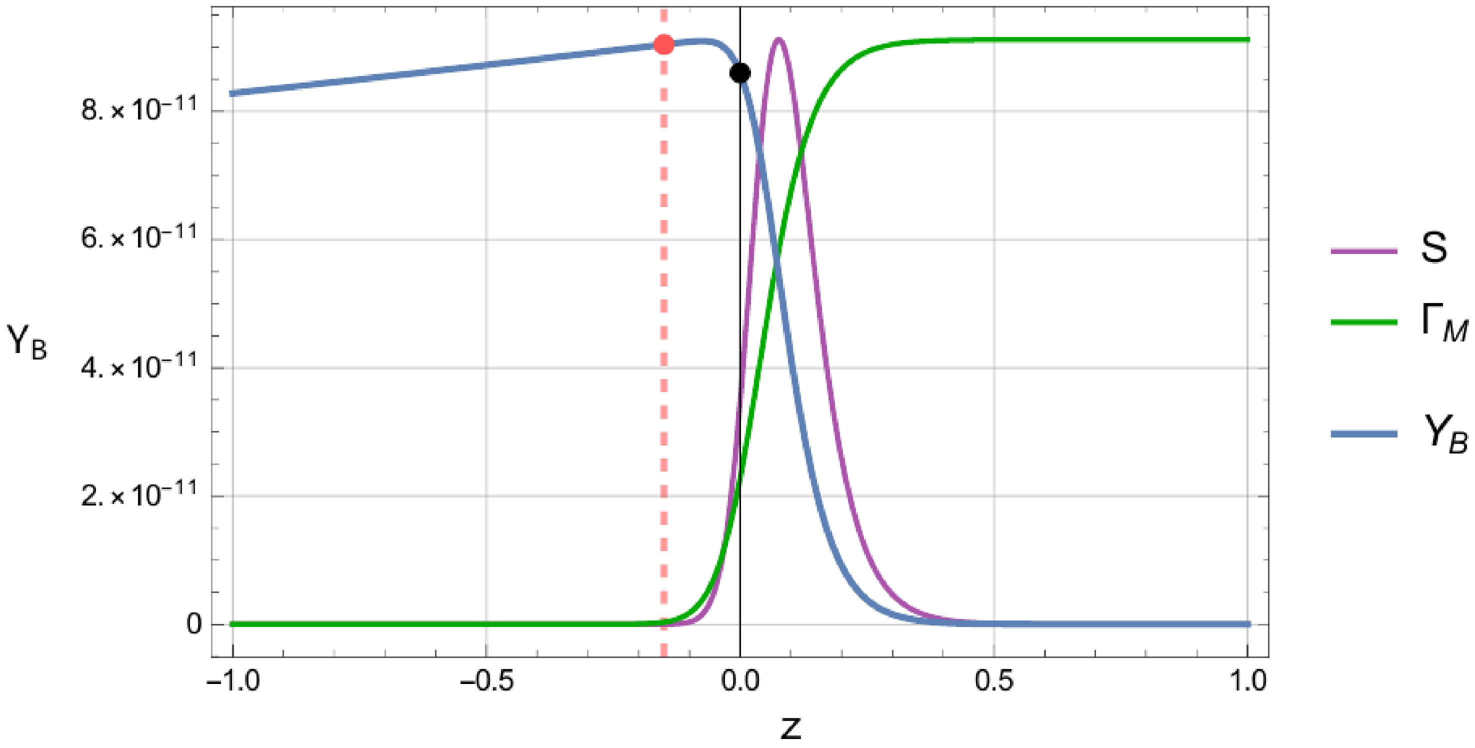
$$\det(K) = \det(-\Gamma) = (-1)^N \det(\Gamma)$$

Fuchs, Losada, Nir, Viernik '20

# Particle dynamics

- CPV interactions across the expanding bubble wall **generate a chiral asymmetry**
- CPC interactions **wash out** the generated asymmetry
- Strong sphaleron process produces further washout in the quark sector
- Some of the remaining asymmetry diffuses into the symmetric phase; more efficient for leptons than quarks.
- Weak sphaleron process is efficient only in the symmetric phase, acting on left-handed multiplets and changing baryon number.
- Finally, the bubble wall catches up and freezes in the resulting baryon number density in the broken phase.

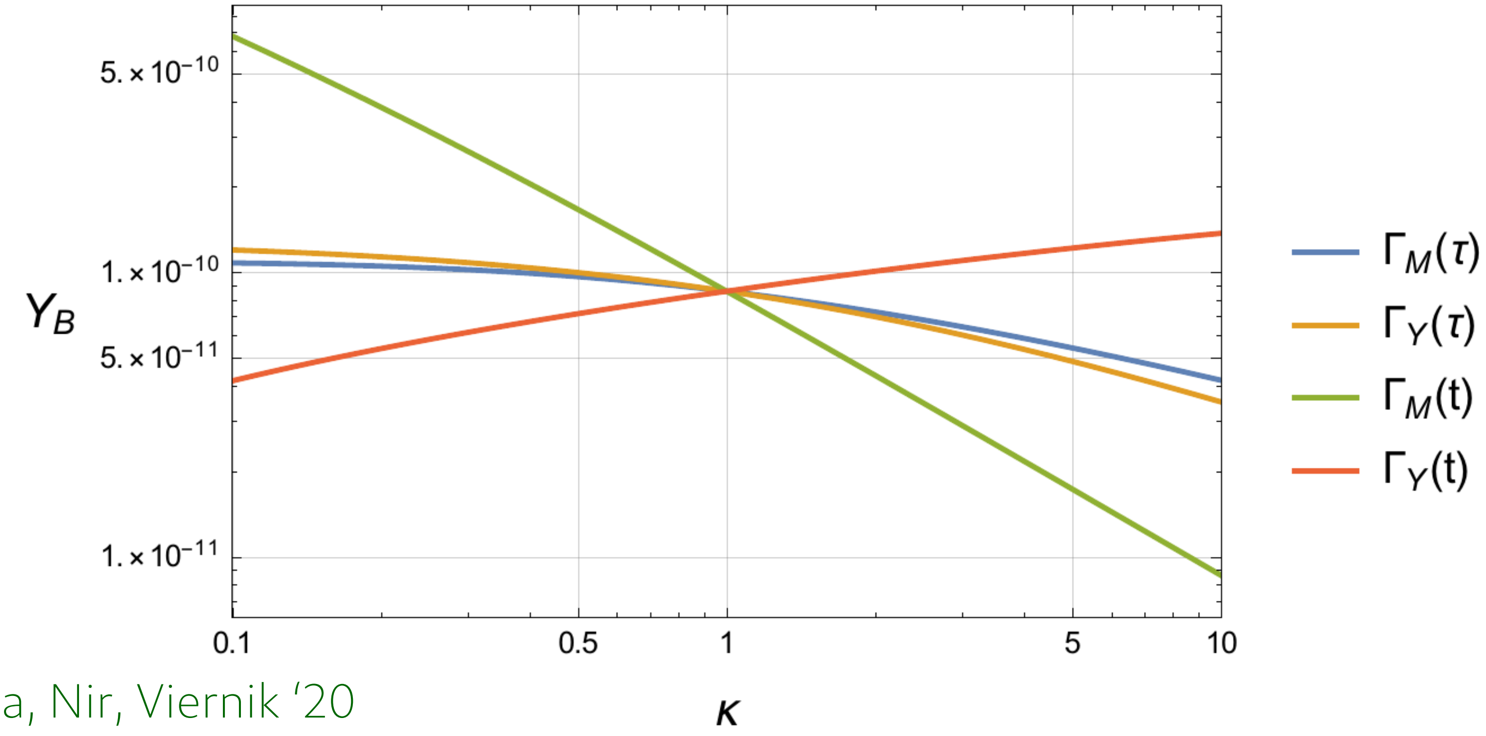
# Thin-wall approximation




Fuchs, Losada, Nir, Viernik '20

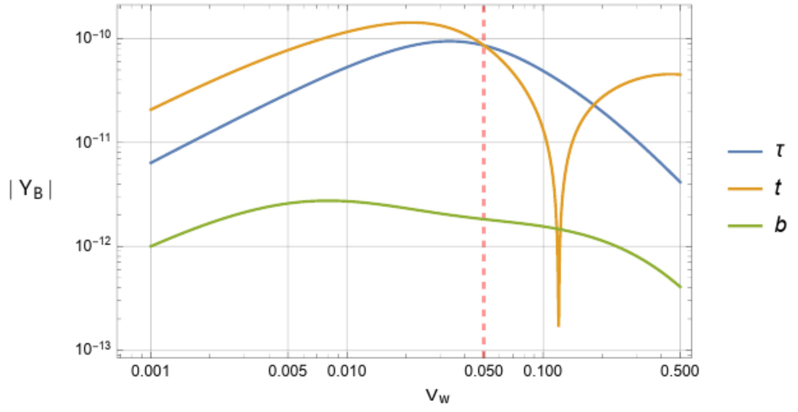
# Uncertainty of $Y_B$ from input rates

$$\Gamma^f_{M/Y} \to \kappa^f_{M/Y} \Gamma^f_{M/Y}$$

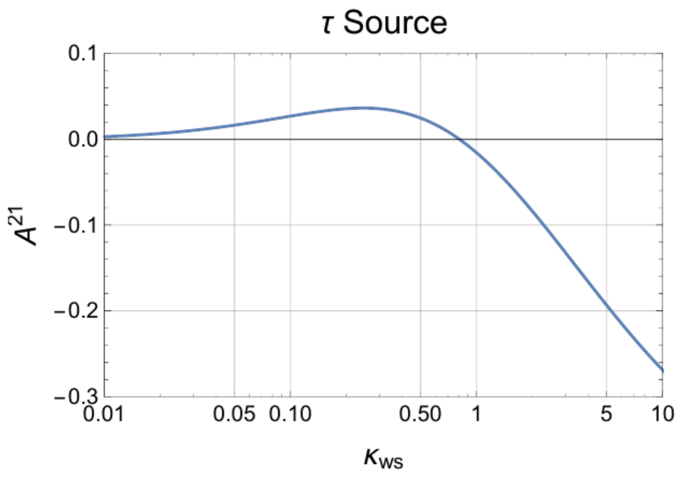


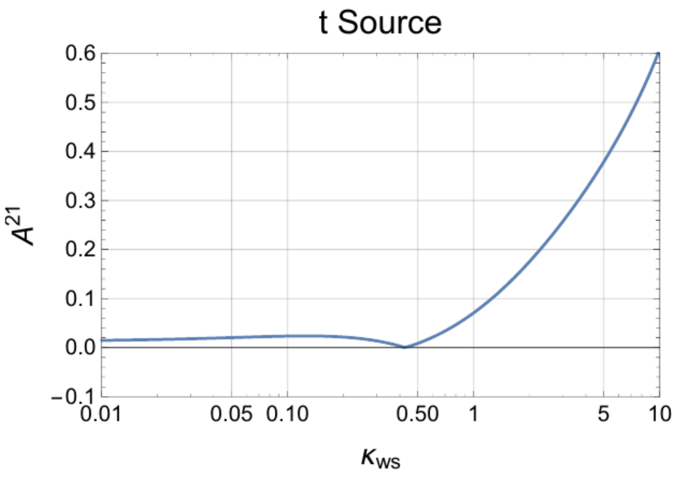

Fuchs, Losada, Nir, Viernik '20

# Parameter dependence; 1-/2-step




Fuchs, Losada, Nir, Viernik '20



# CP violation in the Higgs sector

- Discovered Higgs compatible with $J^{PC}=0^{++}$
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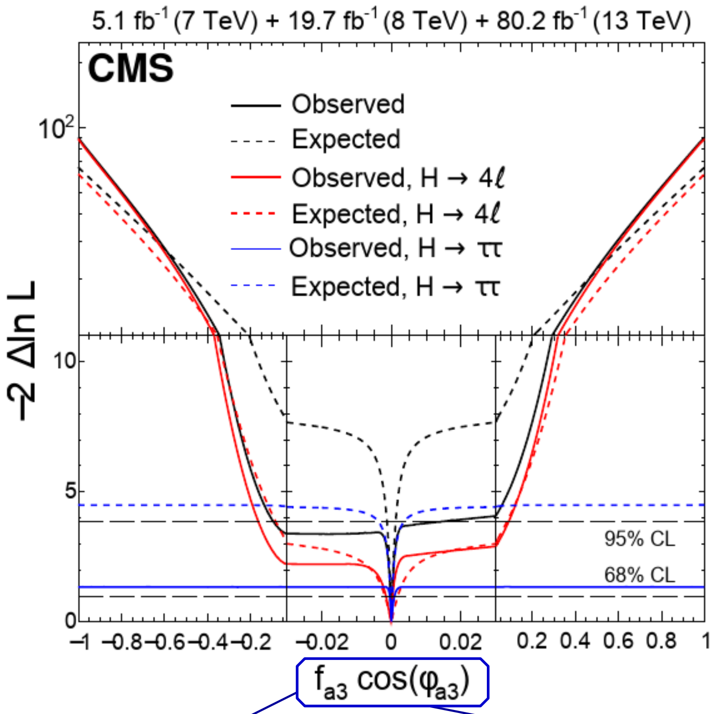
Until recently: mostly searches for CPV in hVV

CMS 1903.06973: HVV anomalous couplings




Fraction of CP-odd cross section contribution

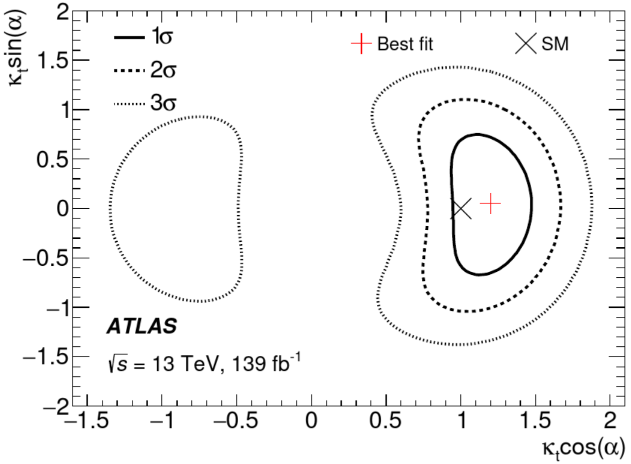
Phase of CP-odd coefficient

# 2020: LHC bounds on CPV in Yukawas

top $tth + th, h \to \gamma\gamma$

ATLAS 2004.04545

See also
CMS 2003.10866




At 95% CL: $|\alpha| < 43°$ (CP mixing angle)

Pure CP-odd excluded at: 3.9σ

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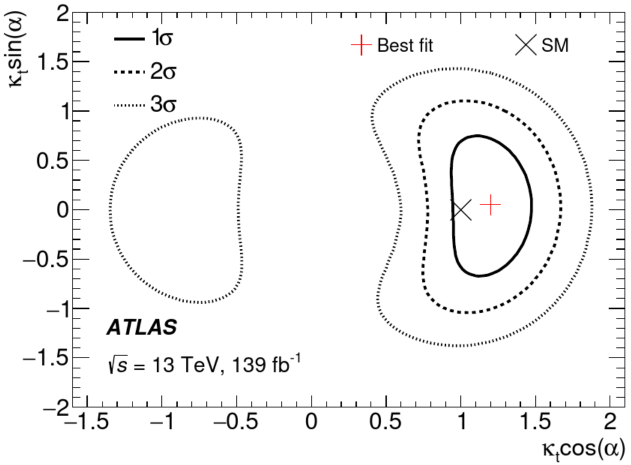


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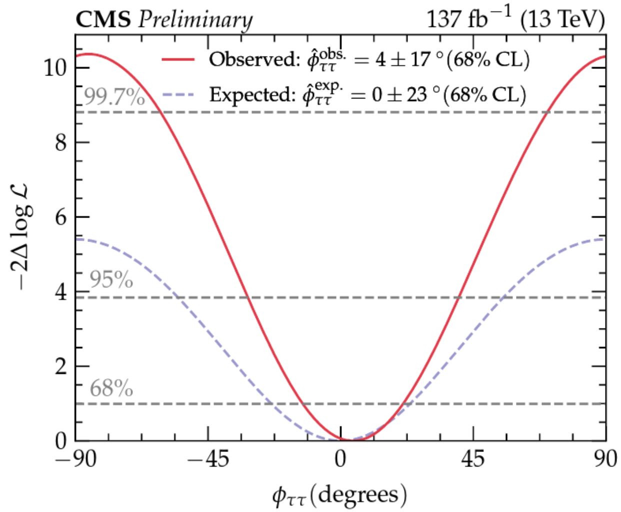
tau CMS HIG-20-006 h→ ττ



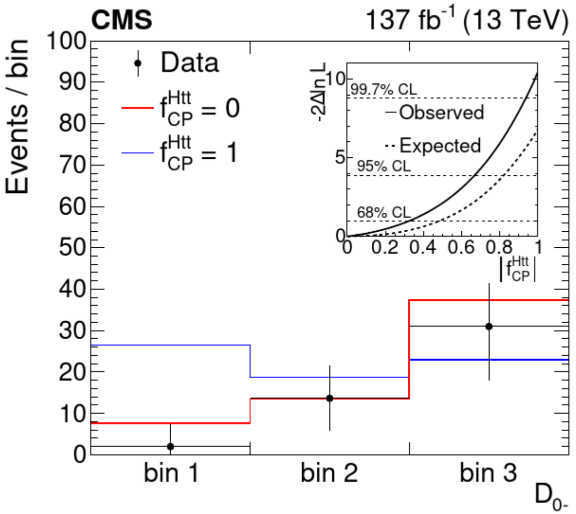

Sensitivity to $\phi_\tau$~4±17°

# CMS htt CPV

$$f_{\rm CP}^{\rm Htt} = \frac{|\tilde\kappa_{\rm t}|^2}{|\kappa_{\rm t}|^2 + |\tilde\kappa_{\rm t}|^2}\,{\rm sign}(\tilde\kappa_{\rm t}/\kappa_{\rm t})$$

$$|f_{\rm CP}^{Htt}| < 0.67$$

CMS 2003.10866



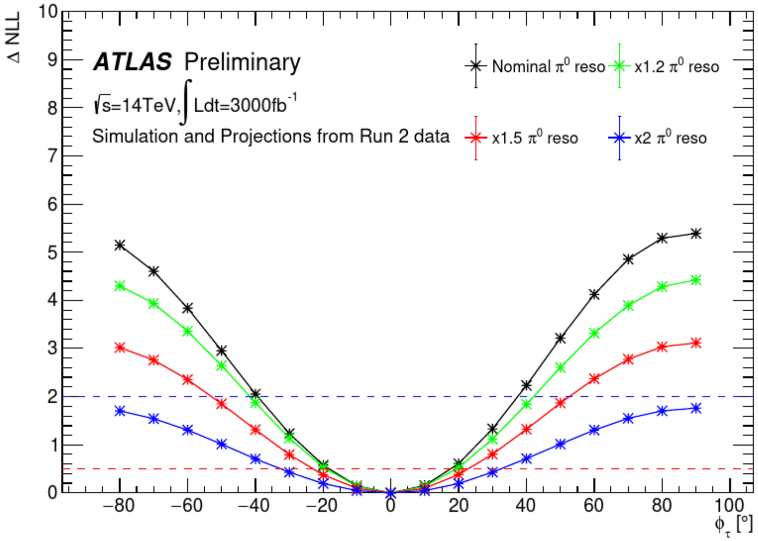

Pure CP-odd excluded at: 3.2σ

Many proposals

Bortolato, Kamenik, Košnik, Smolkovič '20

# CPV ATLAS h→ ττ: Prospects for HL

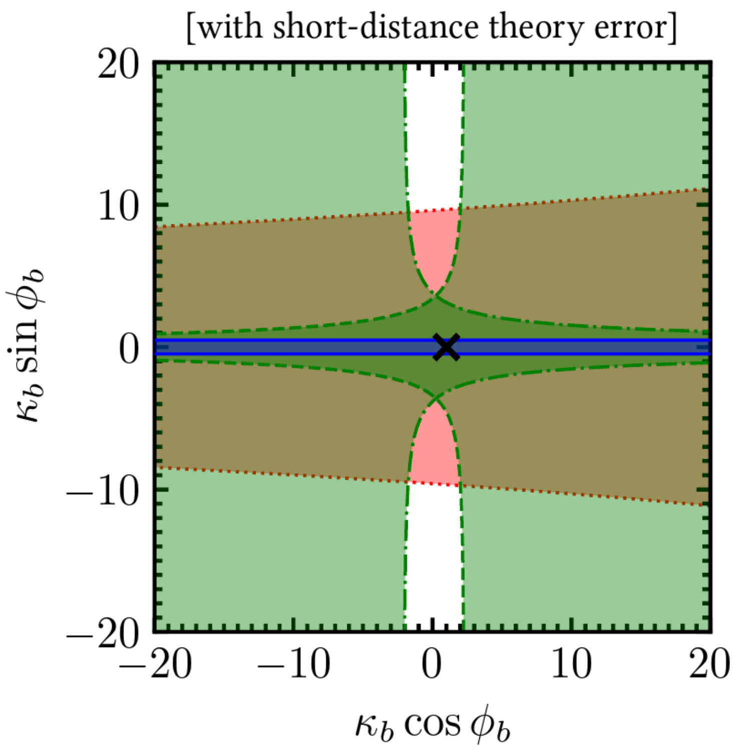
This note presents a study for the prospective measurement of the $\mathcal{CP}$ quantum number of the Higgs boson coupling to $\tau$ leptons with 3000 fb$^{-1}$ of proton–proton collisions at $\sqrt{s} = 14$ TeV using the ATLAS detector at the HL-LHC. Only $H \to \tau\tau$ events where both $\tau$ leptons decay via the $\tau^\pm \to \rho^\pm \nu_\tau \to \pi^0 \pi^\pm \nu_\tau$ chain are analysed and the acoplanarity angle $\varphi^*_{\mathcal{CP}}$, the angle between the planes spanned by the pion pairs, is used to determine the $\mathcal{CP}$-mixing angle. It is shown that considering only statistical uncertainties, a pseudoscalar Higgs boson can be excluded at 95% confidence level. The $\mathcal{CP}$-mixing angle can be measured with a statistical precision ranging between $\pm 18°$ and $\pm 33°$, depending on the precision of the $\pi^0$ reconstruction




$$\mathcal{L} = g_{\tau\tau}(\cos(\phi_\tau)\overline{\tau}\tau + \sin(\phi_\tau)\overline{\tau}i\gamma_5\tau)h$$

ATLAS PHYS-PUB-2019-008

# EDMs: e, n, Hg




Brod, Stamou '18

Electron EDM strongest if $c_e$=1