CP violation in Higgs couplings for baryogenesis

Henning Bahl, EF, Sven Heinemeyer, Judith Katzy, Marco Menen, Krisztian Peters, Matthias Saimpert and Georg Weiglein
2202.11753 (global fit) [EPJC]

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

Higgs Working Group Workshop
WG2 – CPV
CERN, November 29, 2022

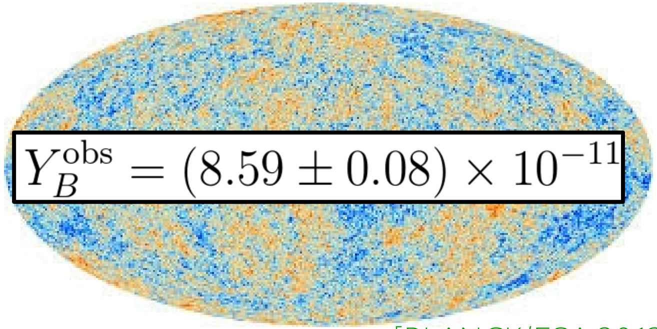
BSM CP violation for baryon asymmetry

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

Need CP violation beyond the SM

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

Many activities in the field of CPV

- Systematic, basis-independent investigation of invariants for CP violation in SMEFT Bonnefoy, Gendy, Grojean, Ruderman '21

$$\text{CPV} \iff \text{Im}\,(\text{something independent of the field basis}) \neq 0\ .$$

- Machine Learning, e.g. symbolic regression Butter, Plehn, Soybelman, Brehmer '21

  → WG3 and joint WG2/3 activities

- CPV in SM extensions

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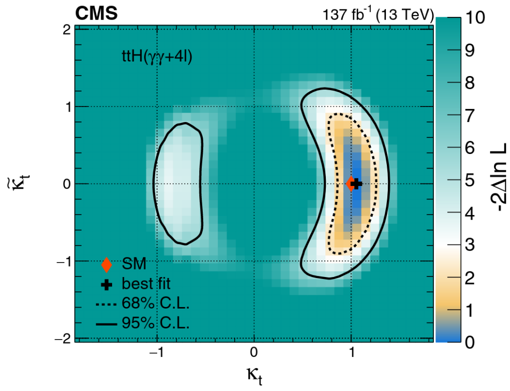
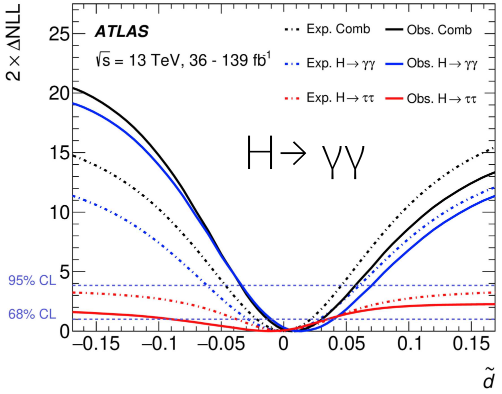
- CPV in SM extensions → WG3 and joint WG2/3 activities
- Experimental analyses

CMS '21



ATLAS '22



Timely: CP-odd observables at LHC

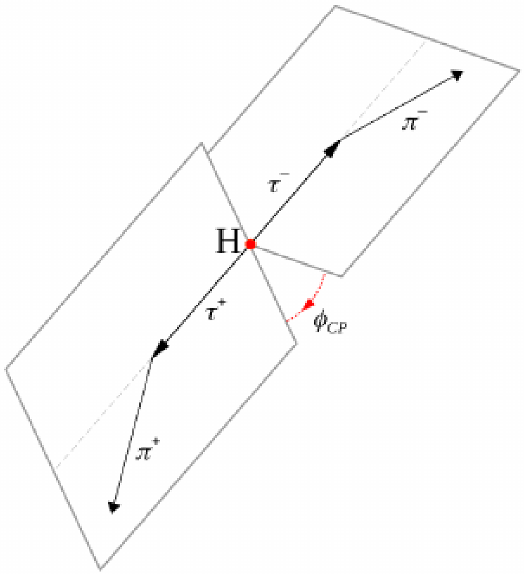
CMS 2110.04836, CMS-HIG-20-006
ATLAS-CONF-2022-032

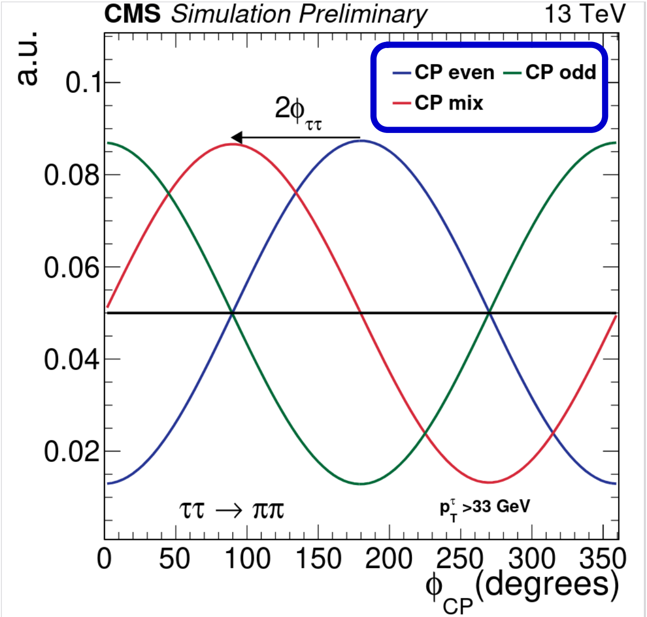
CMS and ATLAS H→ ττ angular analyses

Consider complex couplings → CPV

$$\mathcal{L}_Y = -\frac{m_\tau H}{v}\left(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i \gamma_5 \tau\right)$$

$$\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$





Learn about the CP structure of the Higgs couplings

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 $X \equiv \pm i Y_f$

- Subset of SMEFT as a starting point

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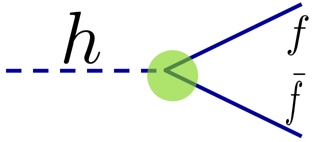
$$\mathcal{L}_f = \frac{y_f v}{\sqrt{2}}\left[1 + \frac{v^2}{2\Lambda^2}\frac{X_R^f + iX_I^f}{y_f}\right]\overline{f_L} f_R + \frac{y_f}{\sqrt{2}}\left[1 + \frac{3v^2}{2\Lambda^2}\frac{X_R^f + iX_I^f}{y_f}\right]\overline{f_L} f_R h$$
$$+ \frac{3v}{2\sqrt{2}\Lambda^2}(X_R^f + iX_I^f)\overline{f_L} f_R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

→ focus on Yukawa & mass terms

Higgs characterization model

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

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



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 $\mathcal{L}_{\rm Yuk} = -\sum_f y_f \overline{F_L} F_R H + \frac{1}{\Lambda^2}(X_R^f + i X_I^f)|H|^2 \overline{F_L} F_R H + \text{h.c.}$

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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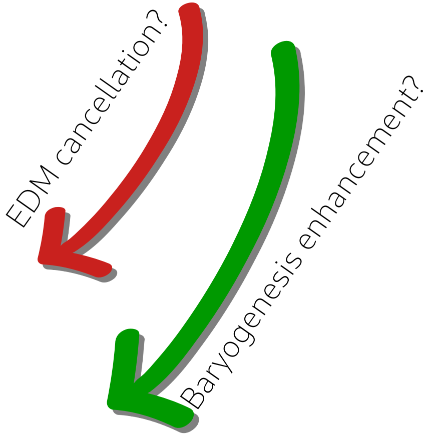

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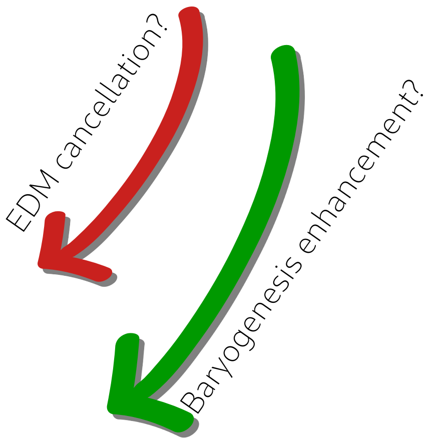

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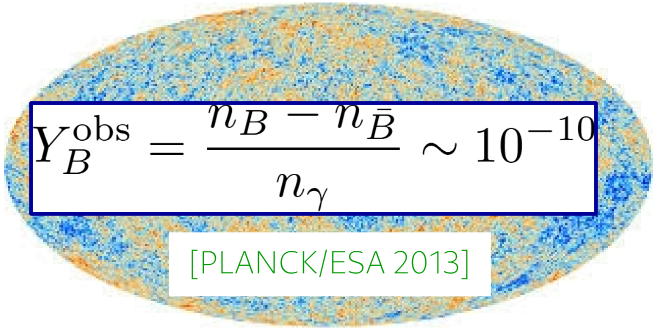
BSM for baryogenesis: focus here on CPV, assume electroweak phase transition can be enhanced separately → WG3

Electroweak baryogenesis



$$Y_B^{\text{obs}} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

[PLANCK/ESA 2013]

Lots of literature, e.g.
Joyce, Prokopec, Turok '95; Cline '06;Morissey, Ramsey-Musolf '12; Konstandin '13; White '16; de Vries, Postma, van de Vis, White '16; de Vries, Postma, van de Vis '18; Garbrecht '18; Bödeker, Buchmüller '20; Alonso-Gonzalez, Giorgio, Merlo, Pokorski '21...

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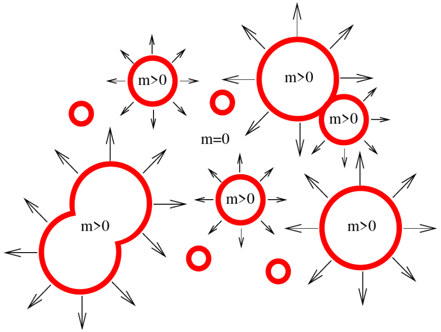

Bubbles of the broken phase expand

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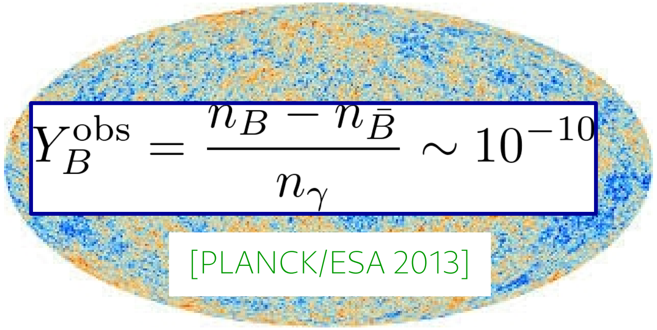

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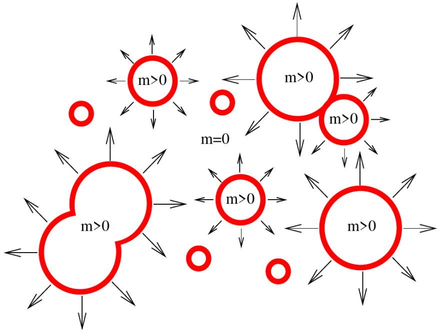

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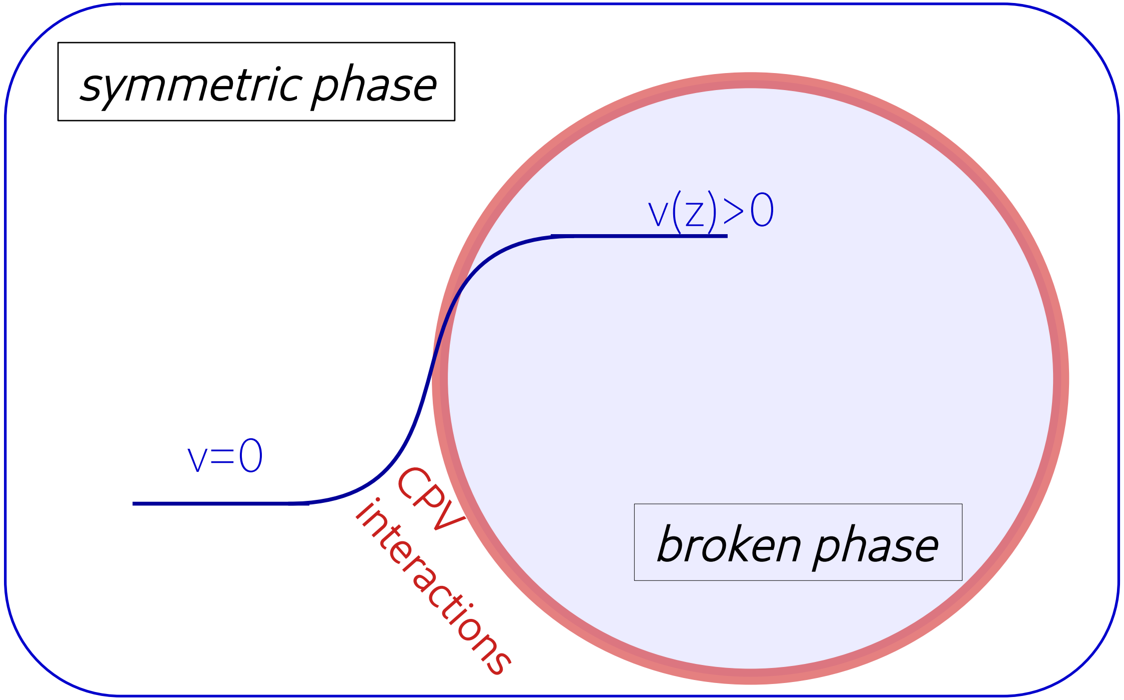

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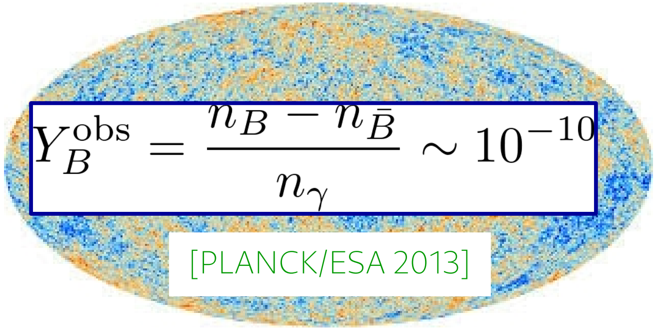

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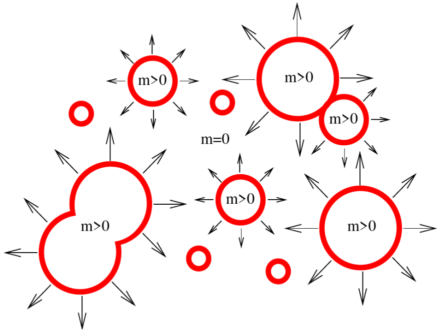

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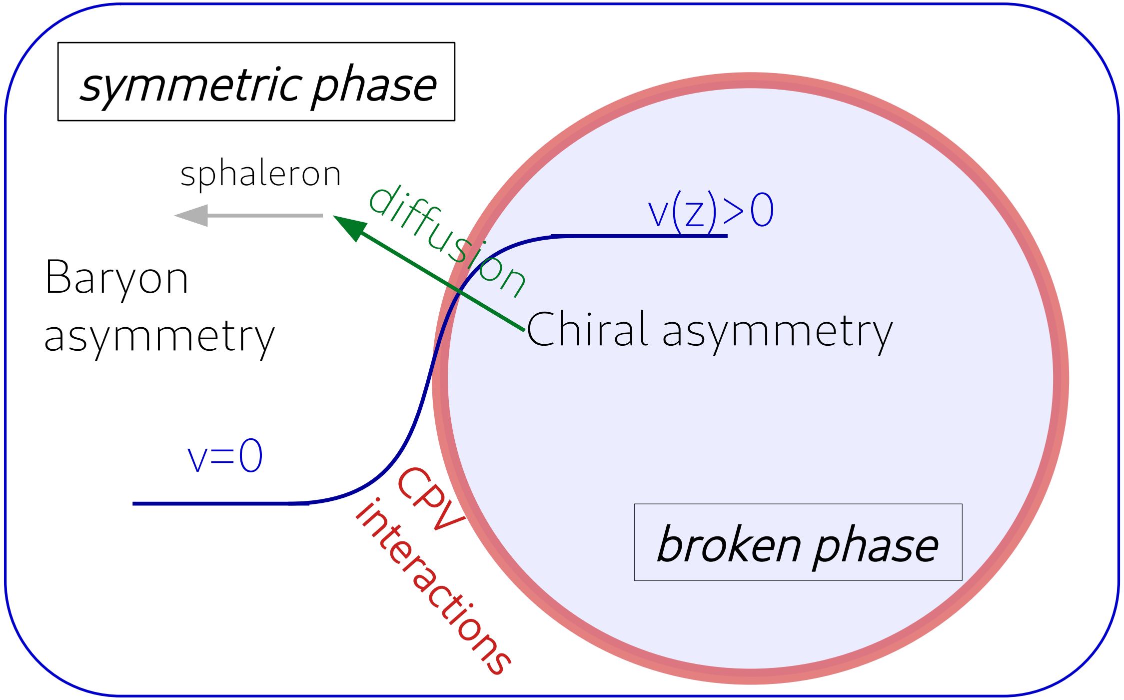

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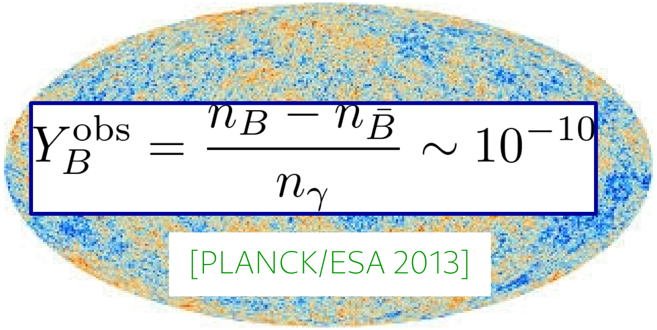

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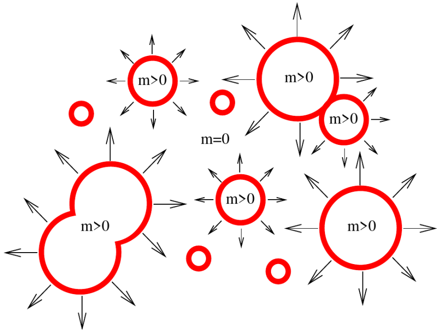

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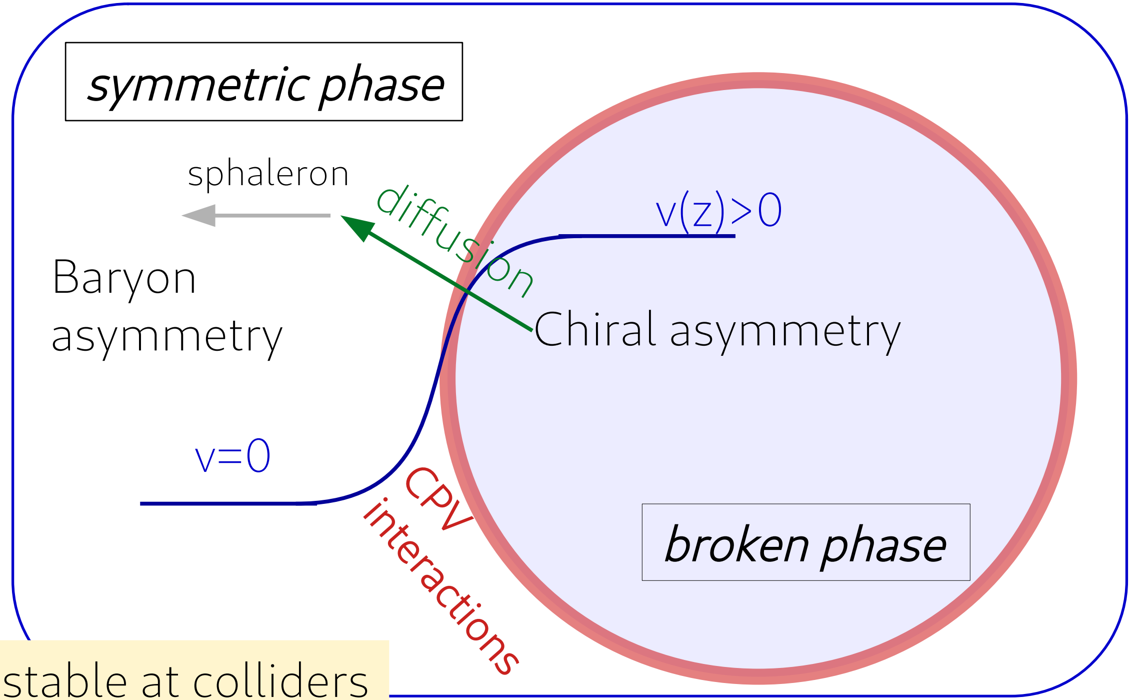

Higgs physics → testable at colliders

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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Approximations
- vev-insertion (VIA)
  caveat: VIA – WKB discrepancy (appendix)
- thin wall
- diffusion

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

Same scaling as EDM

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$\tilde{c}_f$: 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
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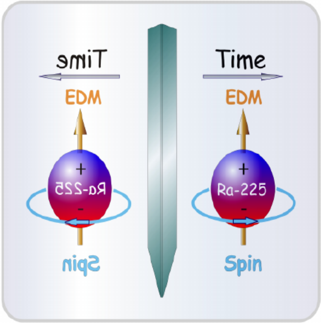
Electron's Electric Dipole Moment



[Hewett, Weerts et al '12]

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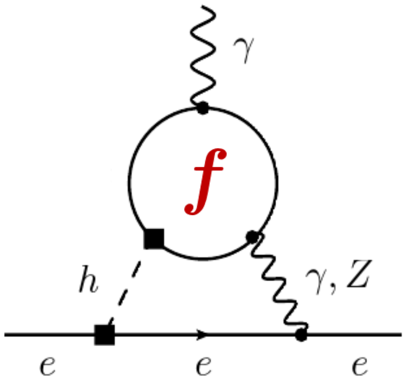

ACME [Nature '18]:

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

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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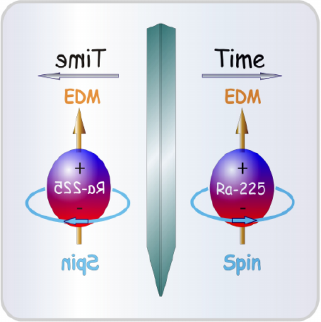

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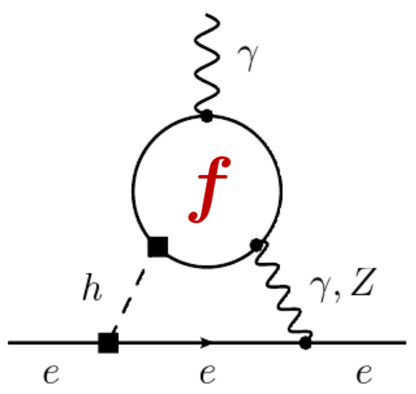

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$$\frac{d_e}{d_e^{\mathrm{ACME}}} = c_e\left(870.0\tilde{c}_t + 3.9\tilde{c}_b + 2.8\tilde{c}_c + 0.01\tilde{c}_s + 8\cdot 10^{-5}\tilde{c}_u + 7\cdot 10^{-5}\tilde{c}_d + 3.4\tilde{c}_\tau + 0.03\tilde{c}_\mu\right)$$
$$+\tilde{c}_e\left(610.1c_t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

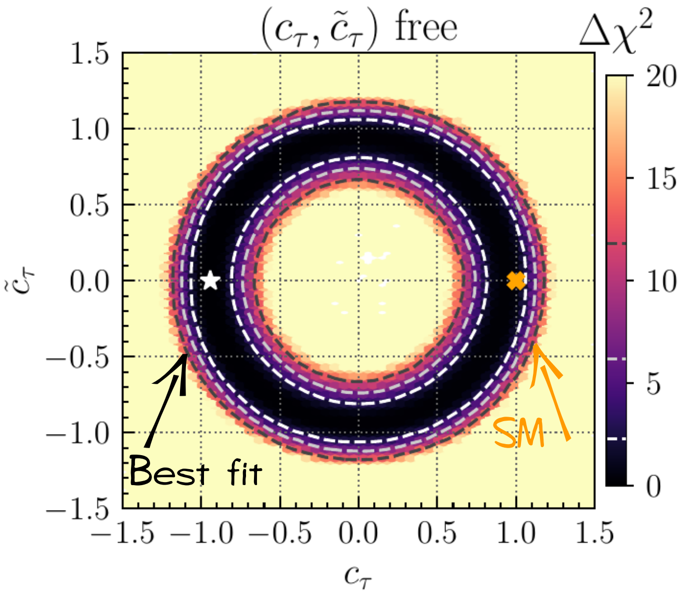
Cancellations possible

CP structure of Higgs couplings - τ

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

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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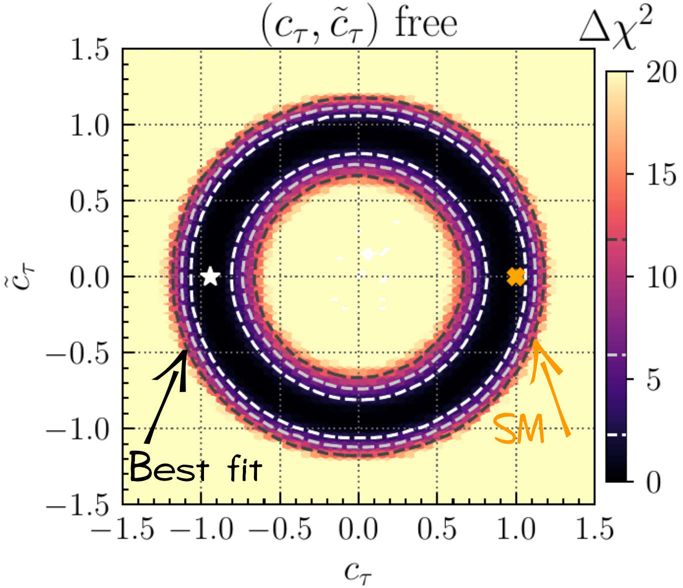
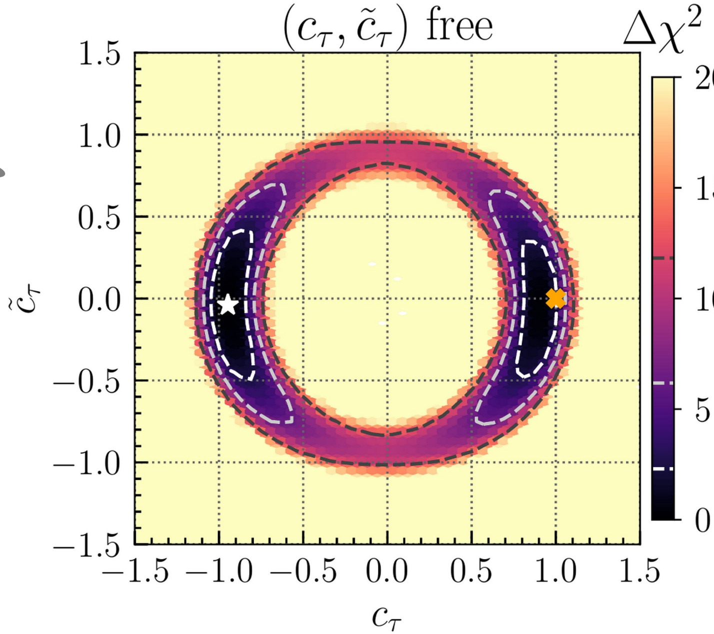


CMS '21
h→ ττ CPV analysis



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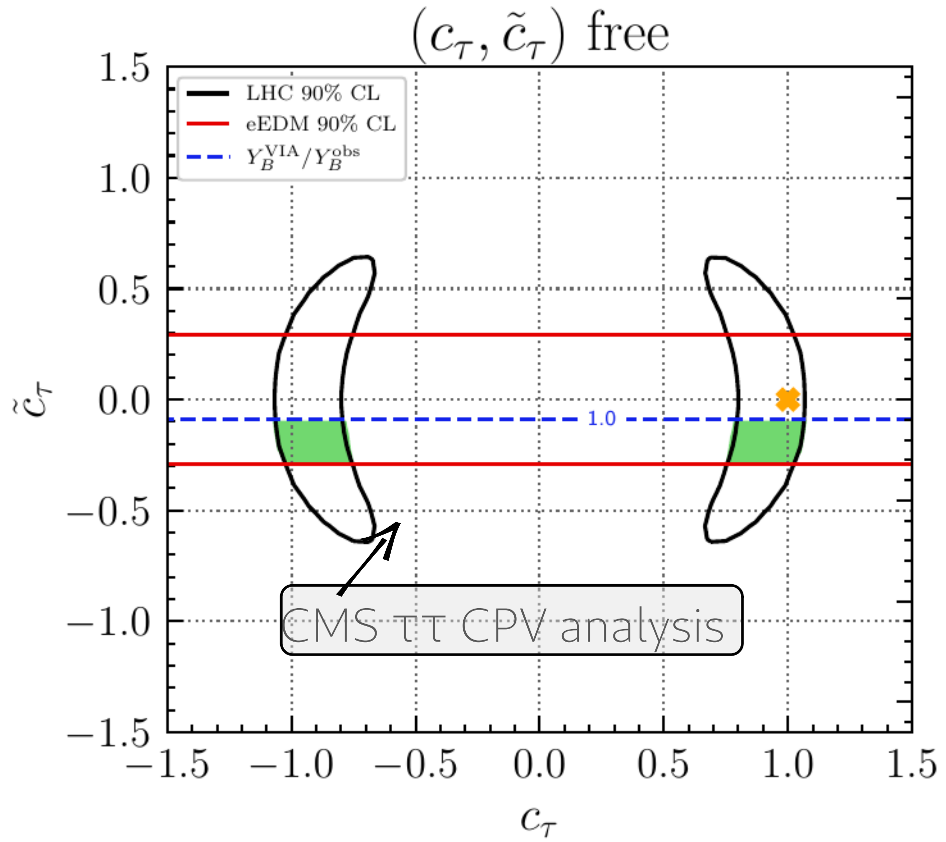
Ring-structure from upper/lower bound on BR

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

Complementary (τ): LHC, EDM, EWBG

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



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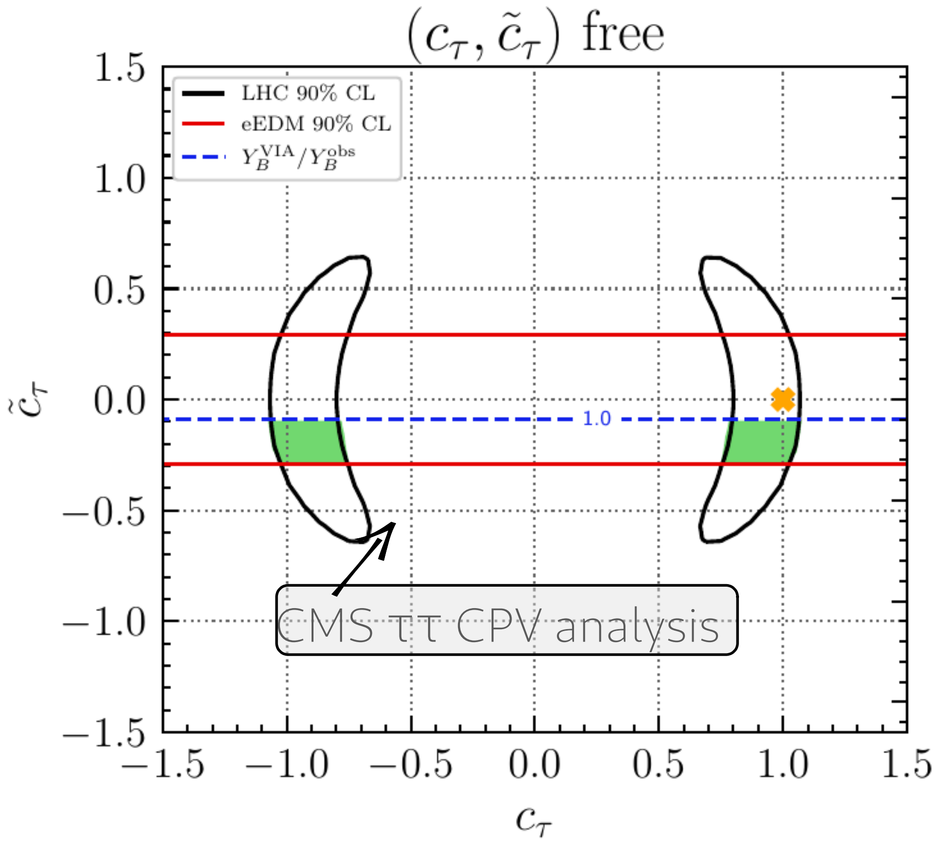
Electron electric dipole moment $d_e \propto \tilde{c}_f$



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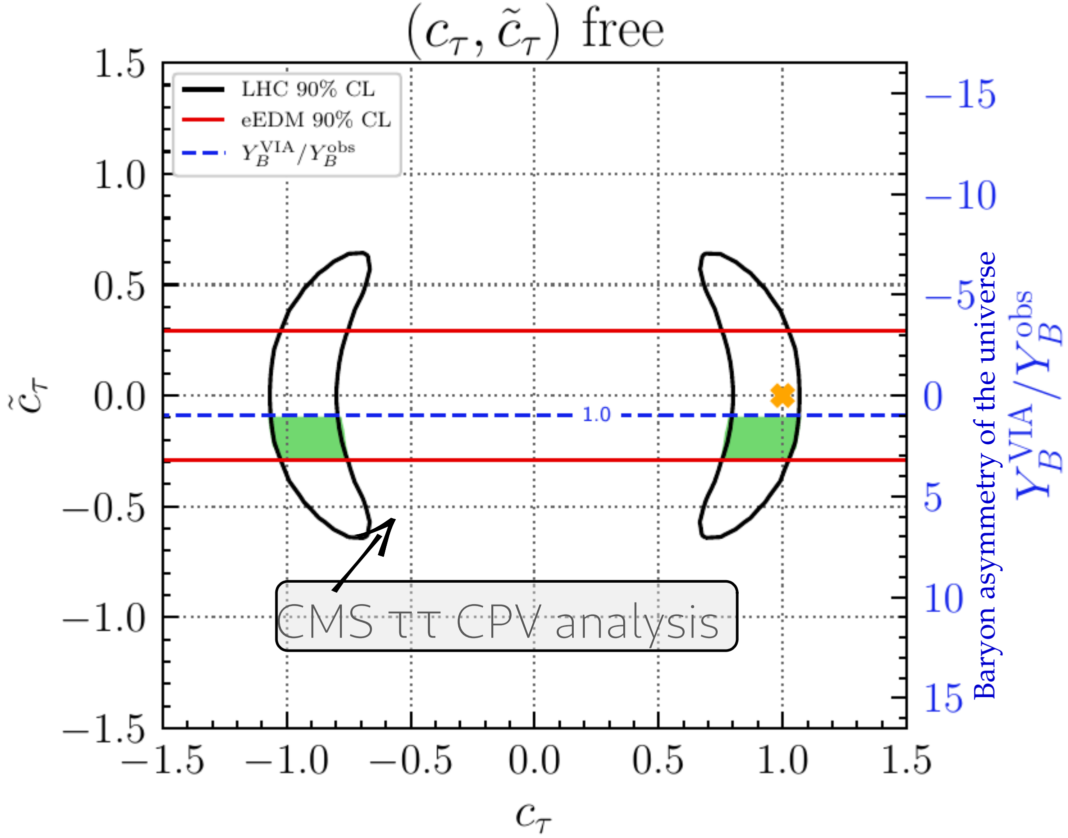

See also
Brod, Haisch, Zupan '13
De Vries, Postma, van de Vis '18
EF, Losada, Nir, Viernik '19, '20, '20
Aharony-Shapira '21
Brod, Cornell, Skodras, Stamou '22

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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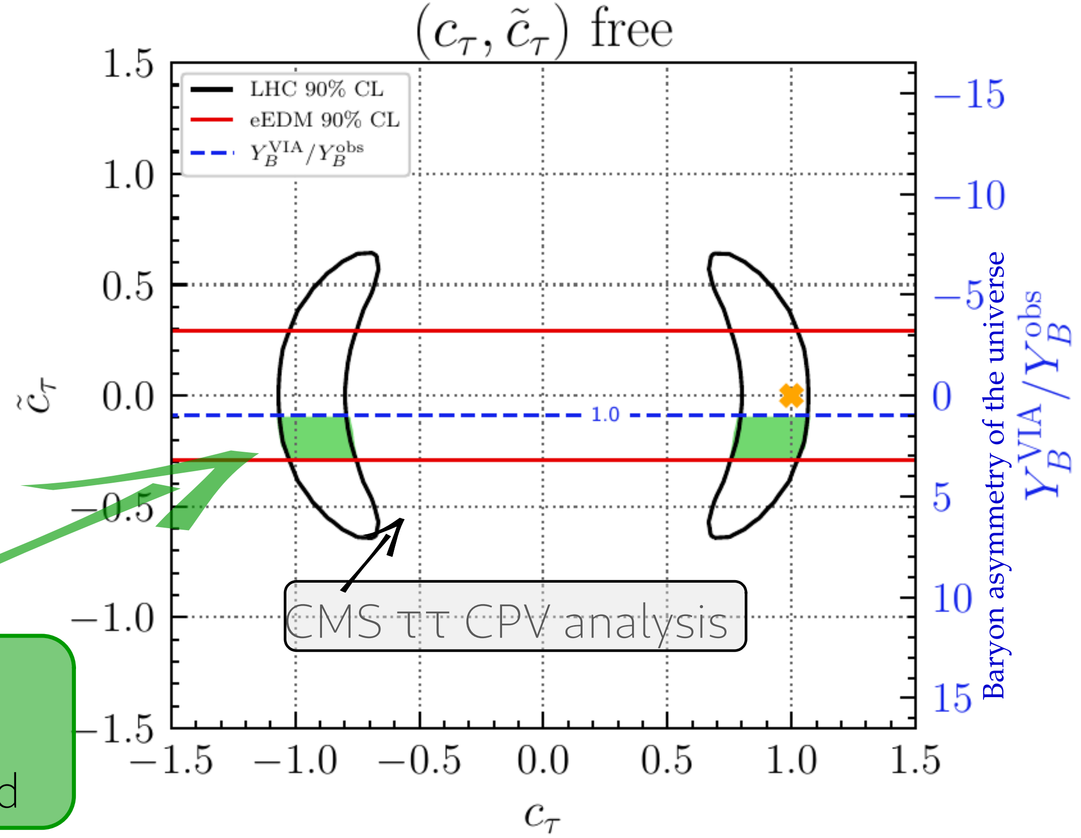

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Allowed by LHC,
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(if VIA estimate restored

Basler, Mühlleitner, Müller '20
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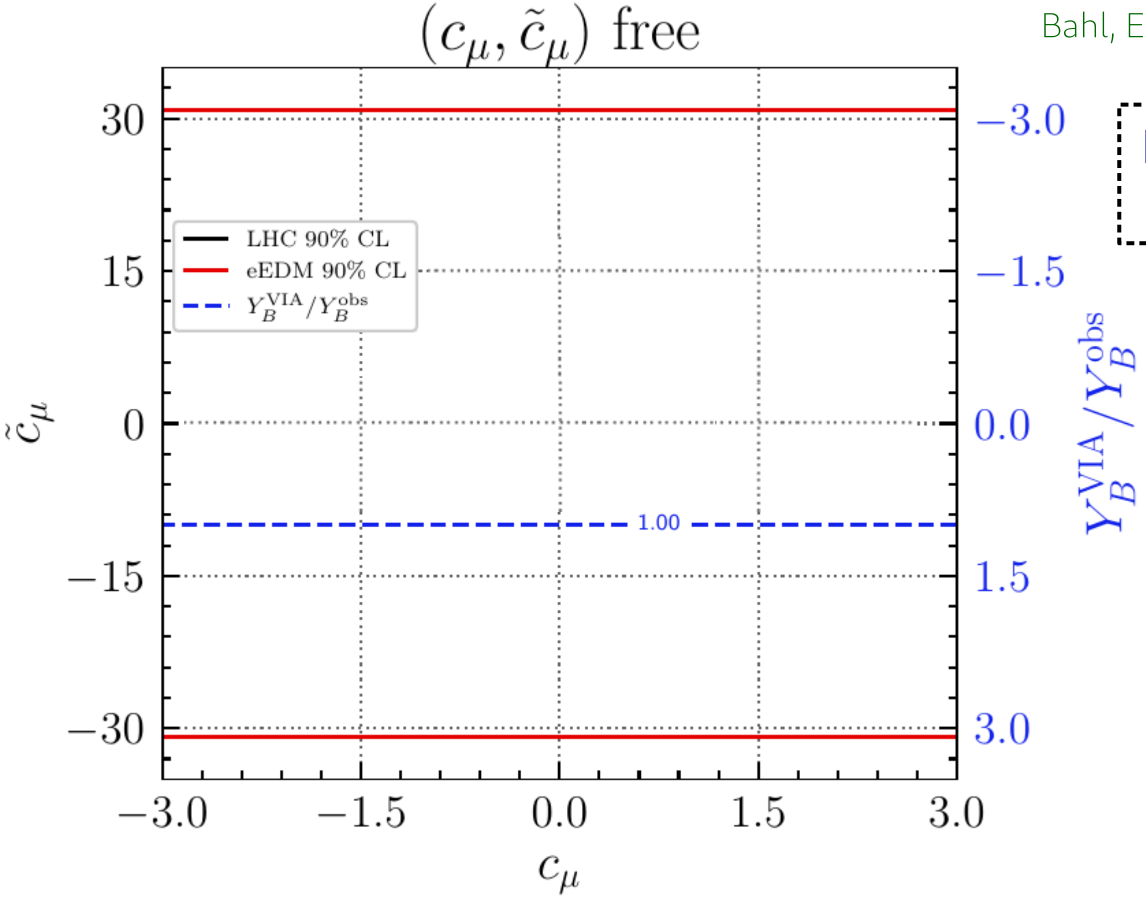
Role of muon

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



EWBG from μ allowed by EDM

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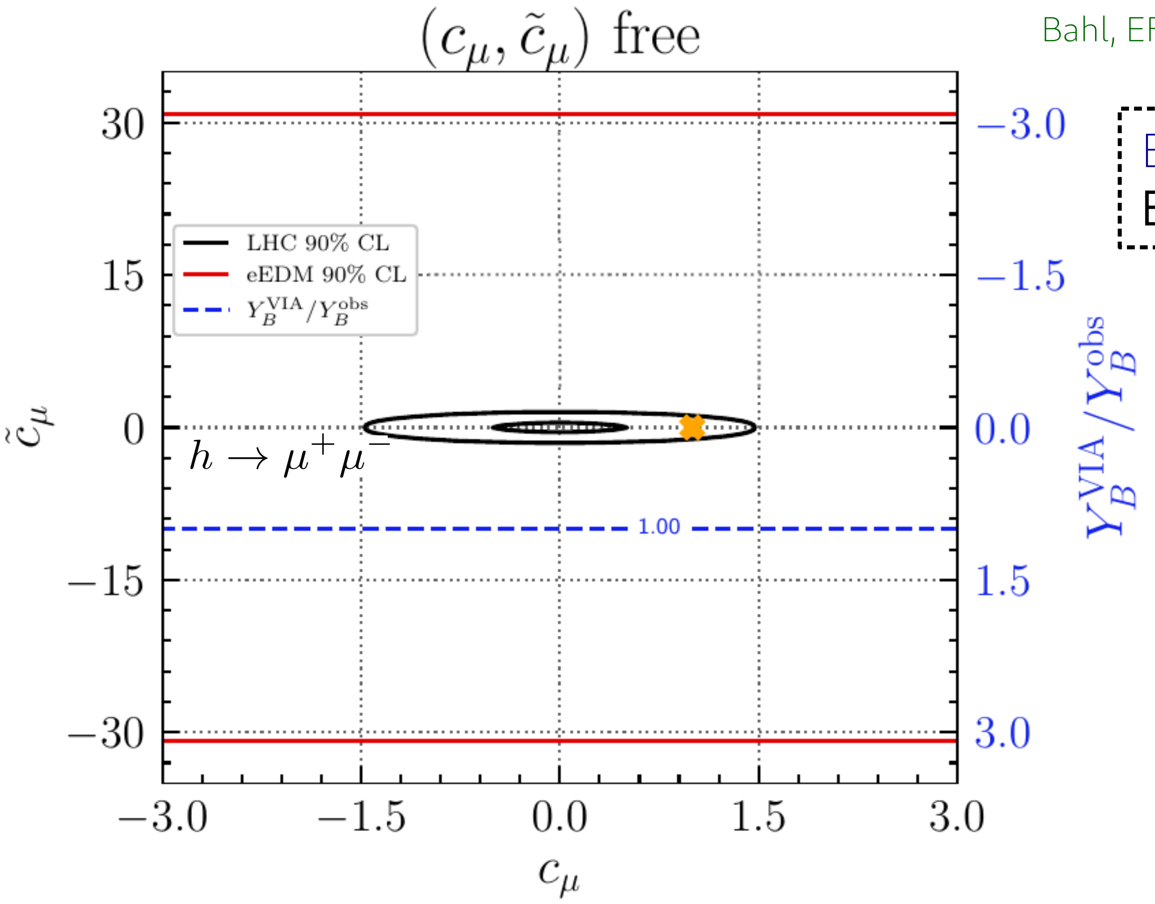


Bahl, EF, Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein '22

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

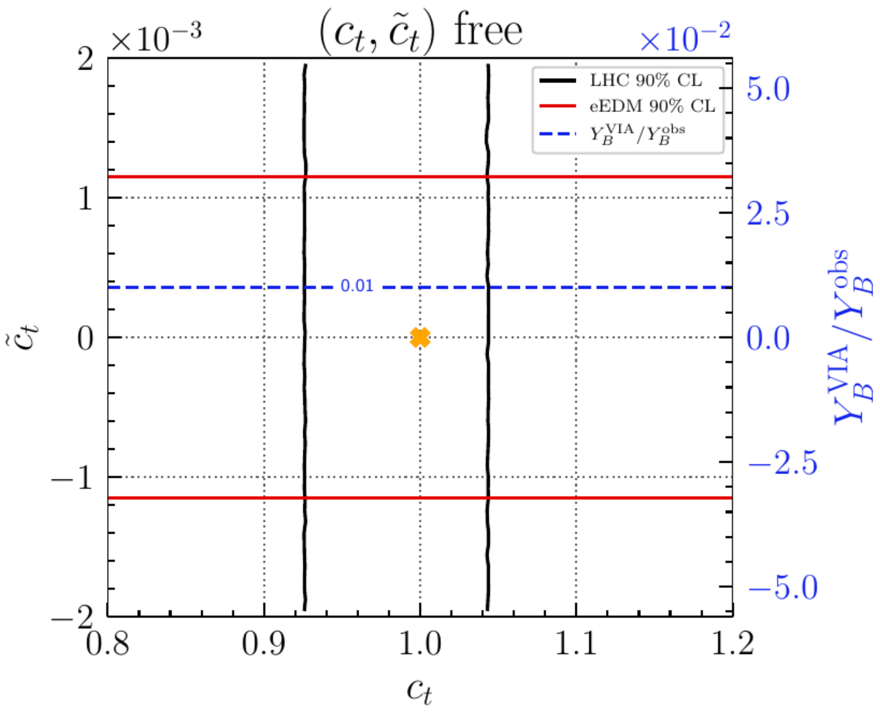
Confirmation of EF, Losada, Nir, Viernik [PRL 2020]

LHC stronger than EDM

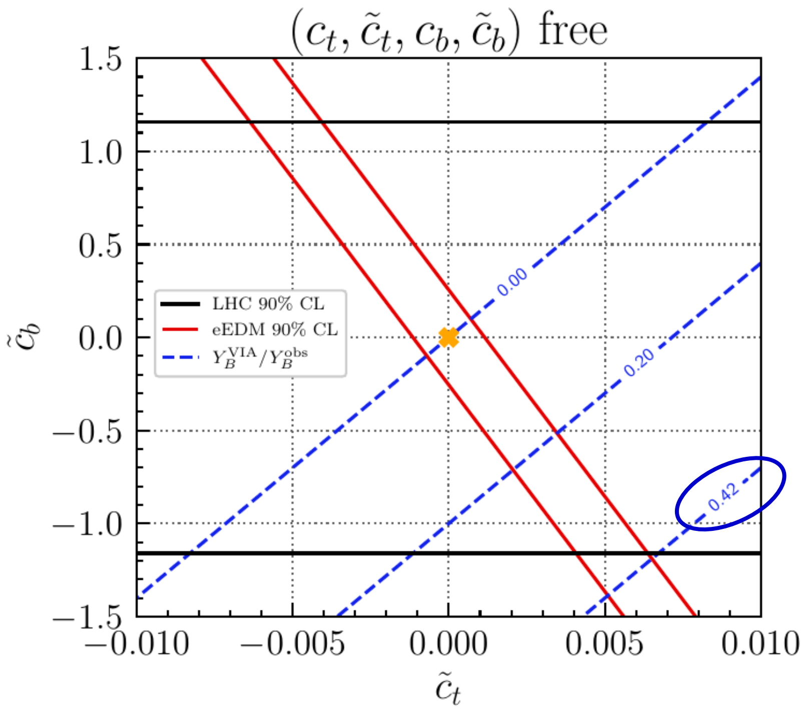
LHC probes cosmology

Combining 2 sources: t, b

Top: EDM very constraining



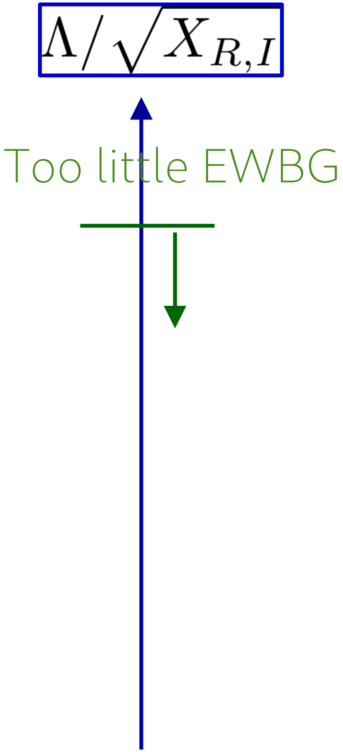
t, b: cancellations of EDM allow larger CPV



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

Combined: **max. 42%** of observed BAU

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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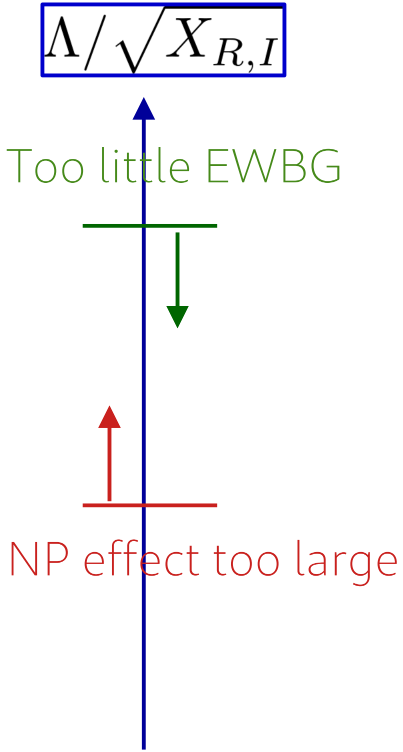

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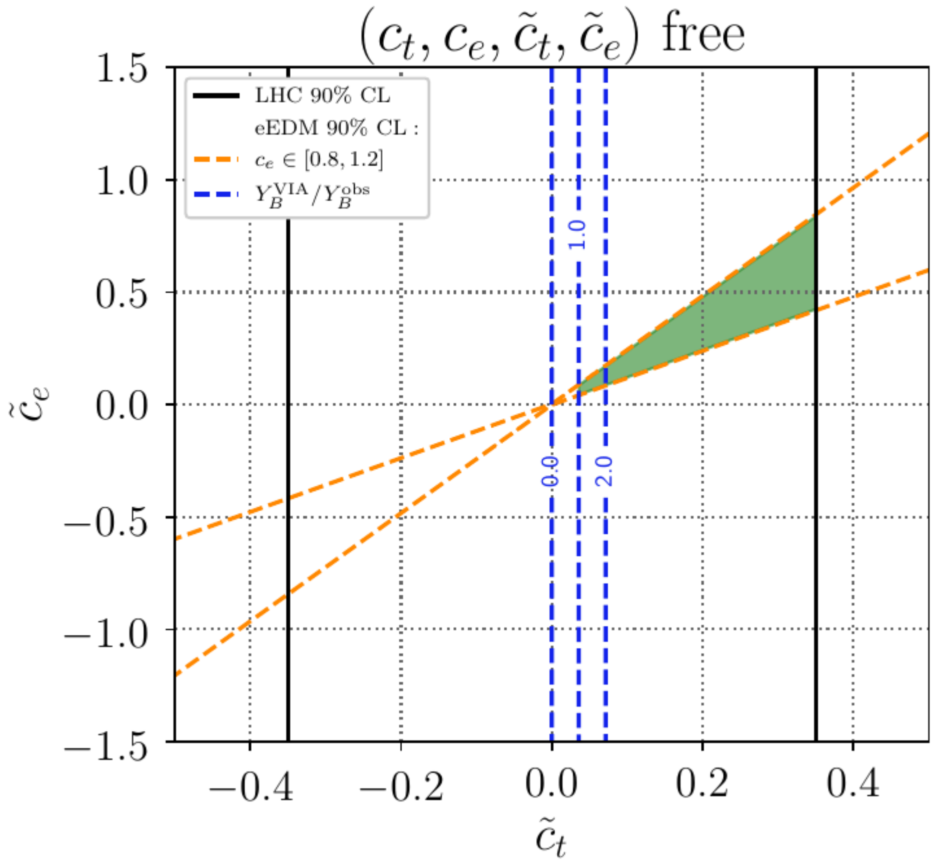
Minimal scales for maximally **allowed** T (collider, EDM)

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

- 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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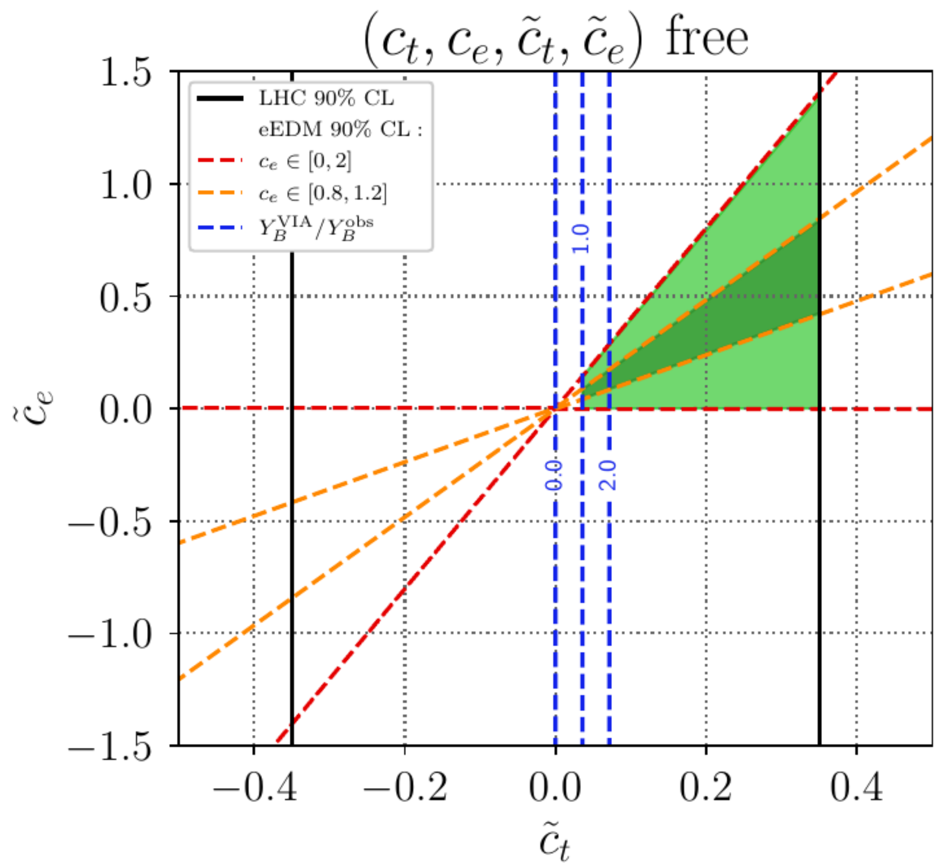

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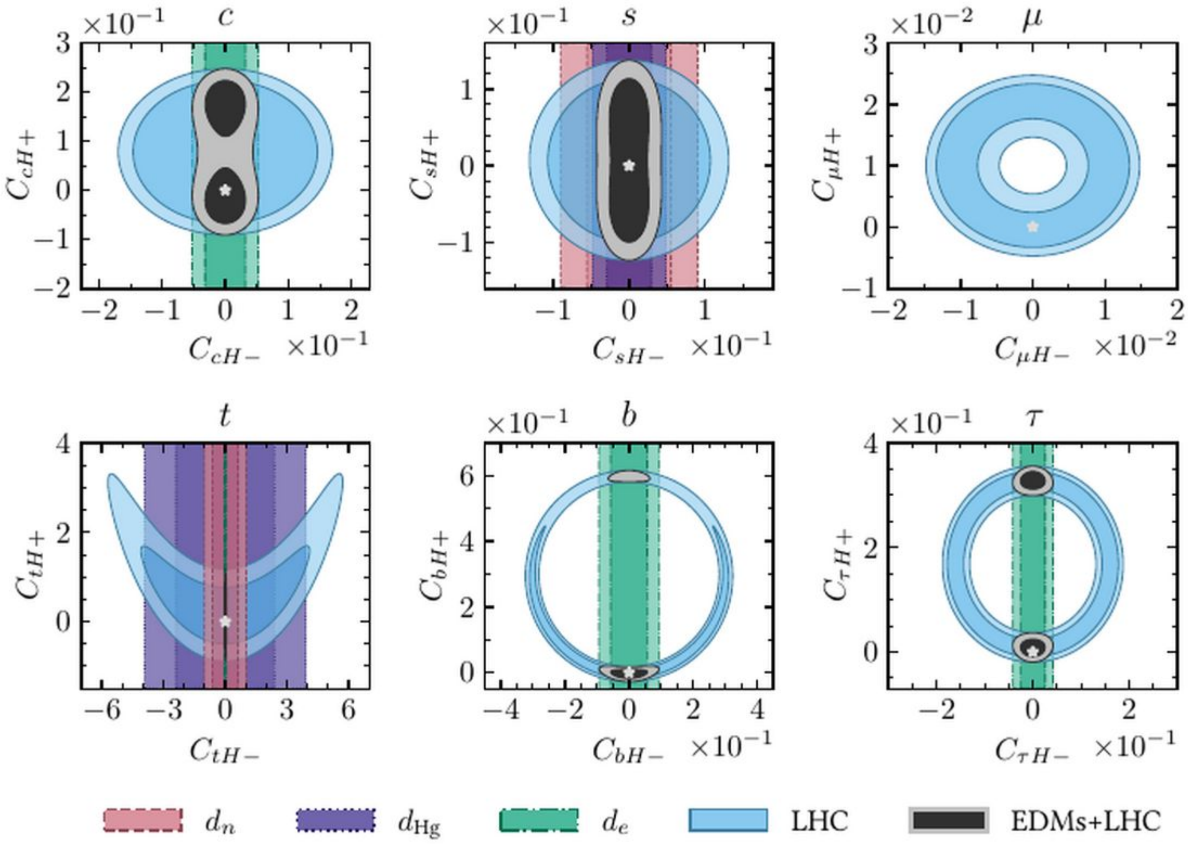
EDMs and CPC LHC Higgs rates



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 information

Λ=1 TeV

Enhancing sensitivity to CPV with ML

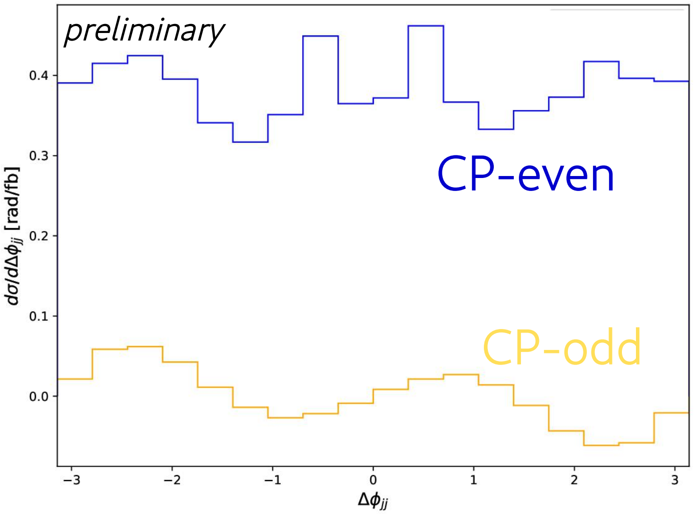
[H. Bahl, EF, M. Menen; work in progress]

Goal: probe complex effective hgg interaction

$$\mathcal{L} \supset -\frac{1}{4}\left(c_g g_{Hgg} G^a_{\mu\nu} G^{\mu\nu,a} + \tilde{c}_g g_{Agg} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}\right)\Phi$$

by CP-odd observable in gg → Hjj

Important variable: angle between the 2 jets



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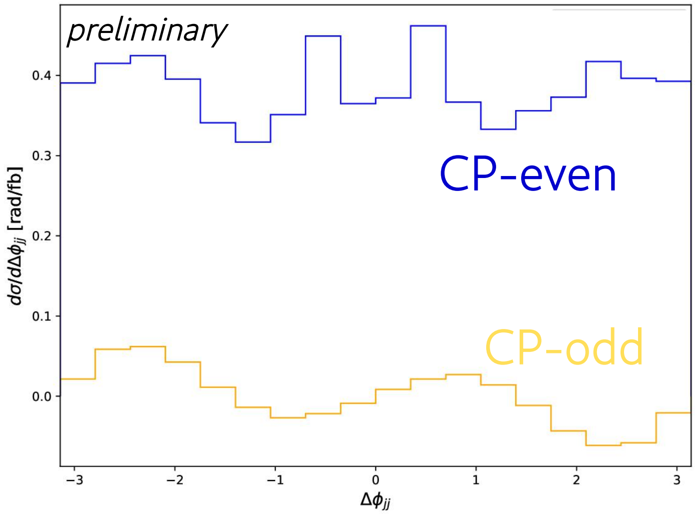
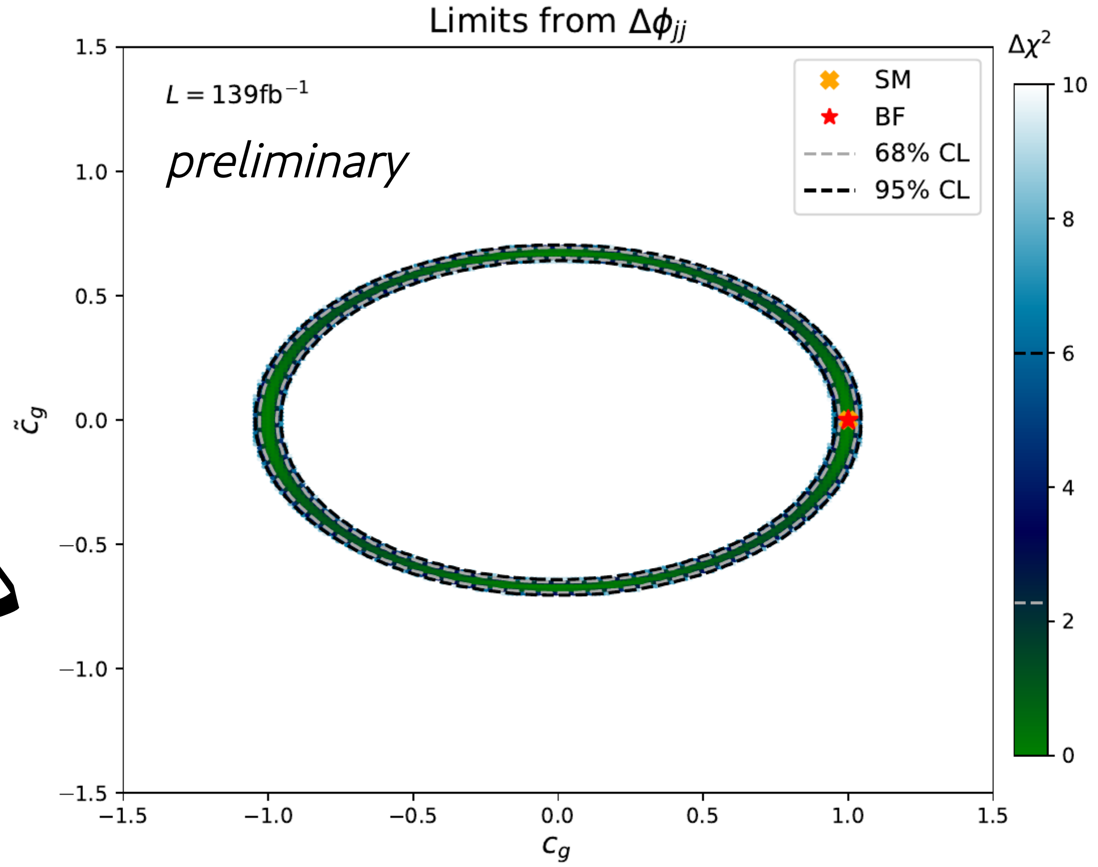


limit



Enhancing sensitivity to CPV with ML

[H. Bahl, **EF**, M. Menen; work in progress]

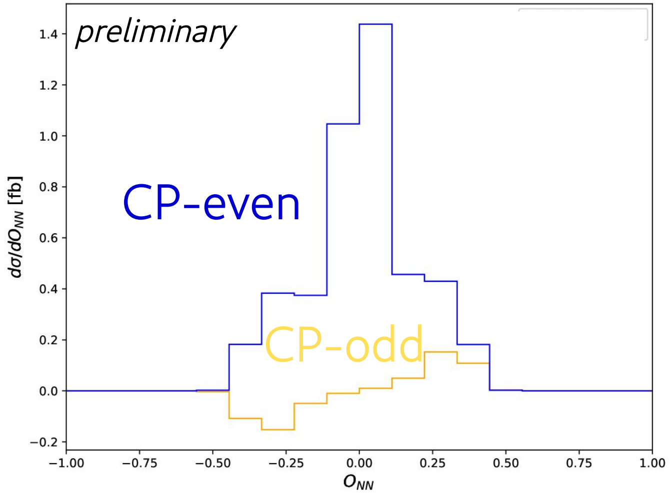
Train 2 Neural Networks:

1) Signal-background separation
2) **CP-odd interference** term vs CP-even terms

$$O_{NN} = P_+ - P_-$$

$P_{+/-}$ = probability for positive/ negative interference event

[cf Bhardwaj, Englert, Hankache, Pilkington for HVV]



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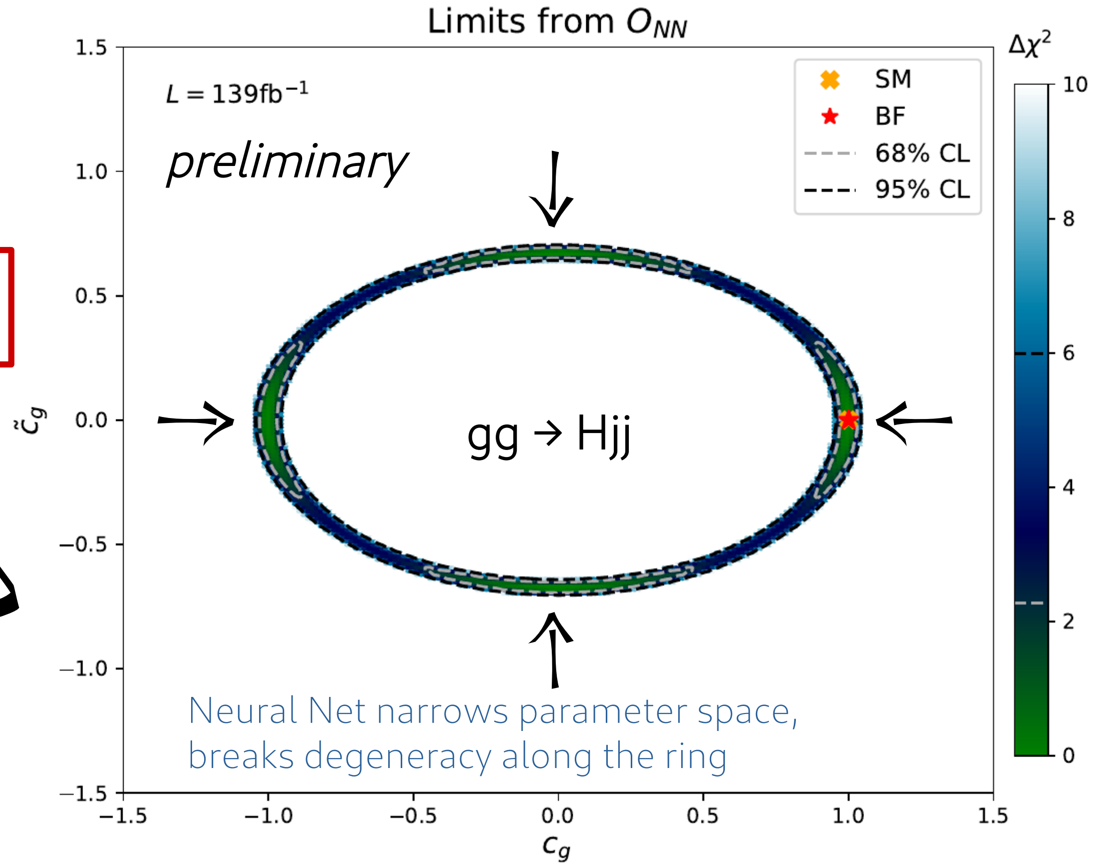


Directions to improve tests of CPV

- 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
- Combine CPV in H-fermion and H-vector boson interactions

WG2 CPV subgroup: → Ken Mimasu's talk Monday

- CPV Benchmarks for UV models and EFT
- Complementarity with EDMs
- STXS bins for CPV
- Common parametrizations
- ttH studies
- WG2&3 activity

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

Conclusions

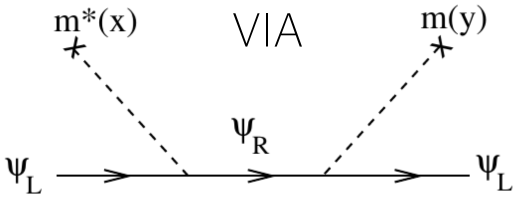
- Complementarity of EDM, EWBG and LHC Higgs physics
- $H\to\tau\tau$ CP analysis excludes large $\tilde{c}_\tau$, but τ remains viable EWBG source (VIA LO)
- LHC constrains cosmological scenarios, separates flavors; now also 2^{nd} gen.
- Cancellations and enhancements with 2 fermions, e.g. t+b: few % → ~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

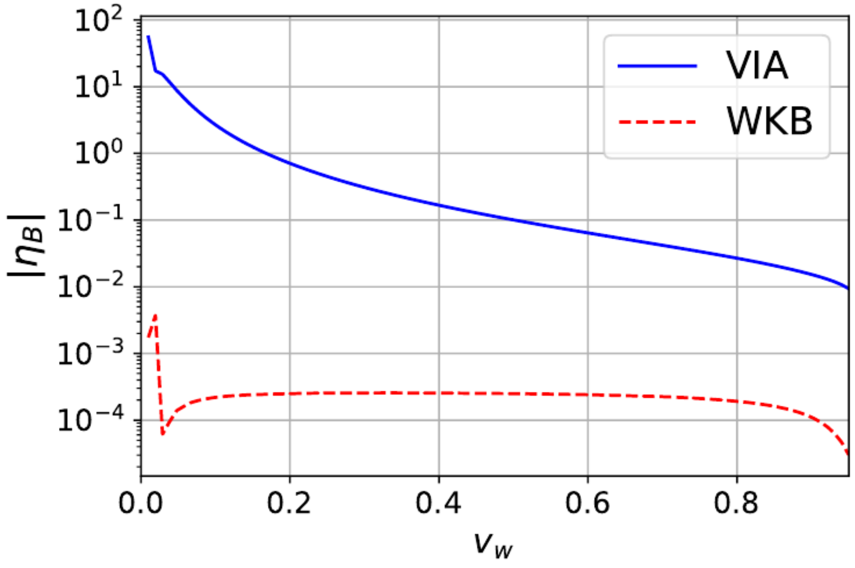
Uncertainties in EWBG calculation

Cline, Laurent '21



Discrepancy between VIA and WKB approaches

Deviation depends on scenario



Postma, van de Vis, White '22

→ see J. v.d. Vis' talk at DESY-T workshop: link

- VIA source term vanishes in the first order of the gradient expansion
- Problem not from expansion in vev: also the resummed source term vanishes
- VIA might be restored in higher orders of the gradient expansion

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**

$$m_f \overline{f_L} f_R$$

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

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

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

$$r_f(T_R^f, T_I^f) \equiv \frac{|\lambda_f|^2/|\lambda_f^{\rm SM}|^2}{|m_f|^2/|m_f^{\rm SM}|^2} = \frac{(1+3T_R^f)^2 + 9T_I^{f\,2}}{(1+T_R^f)^2 + T_I^{f\,2}}$$

production,
decay

Total Higgs width

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

Transport equations

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

$$\partial t = -\Gamma^t_M \mu^t_M - \Gamma^t_Y \mu^t_Y + \Gamma_{ss}\mu_{ss} + S_t$$

$$\partial b = -\Gamma^b_M \mu^b_M - \Gamma^b_Y \mu^b_Y + \Gamma_{ss}\mu_{ss} + S_b$$

$$\partial q = -\partial t - \partial b$$

$$\partial \tau = -\Gamma^\tau_M \mu^\tau_M - \Gamma^\tau_Y \mu^\tau_Y + S_\tau$$

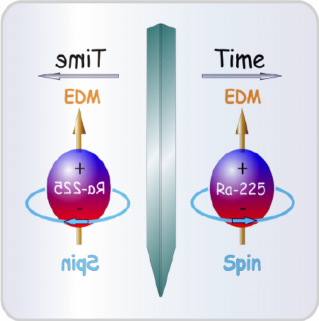
$$\partial l = -\partial \tau$$

$$\partial h = +\Gamma^t_Y \mu^t_Y - \Gamma^b_Y \mu^b_Y - \Gamma^\tau_Y \mu^\tau_Y$$

$$\partial u = +\Gamma_{ss}\mu_{ss}\,.$$

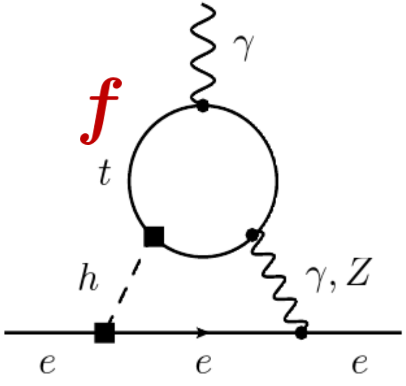
Electron's Electric Dipole Moment

[Hewett, Weerts et al '12]



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

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



ACME [Nature '18]:

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

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

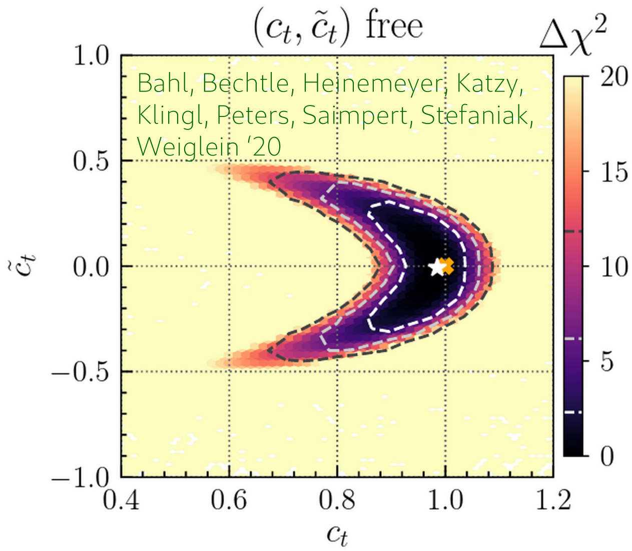
$$\frac{d_e^{(\ell)}}{e} \simeq -4Q_\ell^2 \frac{e^2}{(16\pi^2)^2}\frac{m_e m_\ell}{m_h^2}\frac{v}{\Lambda^2} \boldsymbol{X_I^\ell} \left(\frac{\pi^2}{3} + \ln^2\frac{m_\ell^2}{m_h^2}\right), \quad \boldsymbol{\ell = \tau, \mu}$$

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

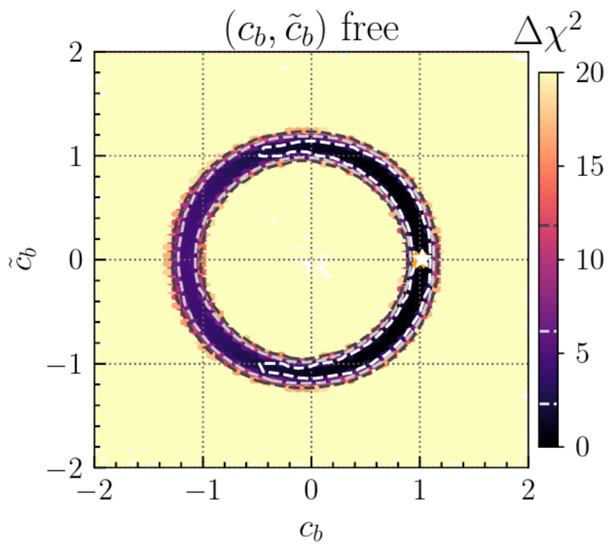
$$\frac{d_e^{(t)}}{e} \simeq -\frac{16}{3}\frac{e^2}{(16\pi^2)^2}\frac{m_e}{m_t}\frac{v}{\Lambda^2} \boldsymbol{X_I^t} \left(2 + \ln\frac{m_t^2}{m_h^2}\right)$$

Top, bottom, and their combination

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



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

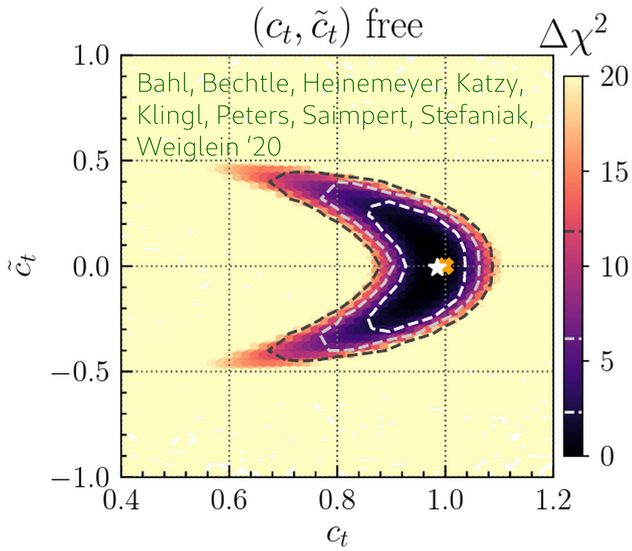


Bottom: ring (h→ bb) reduced by ggF (positive interference with t)

Top, bottom, and their combination

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

Floating several coupling modifiers simultaneously



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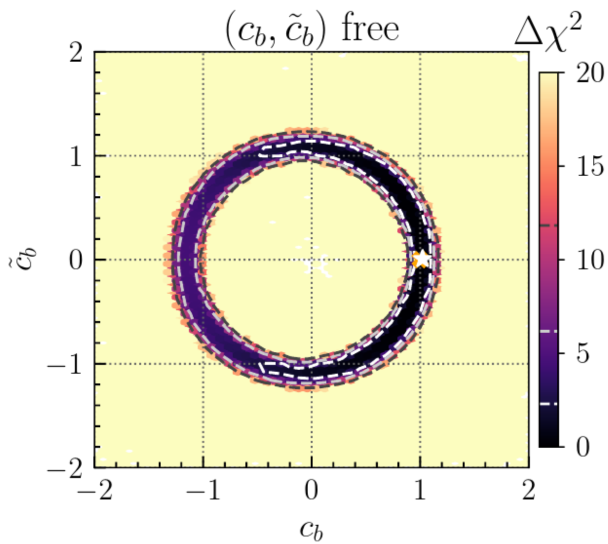

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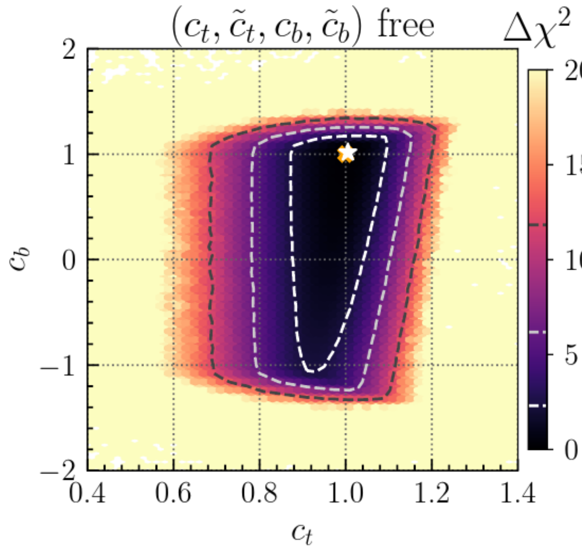
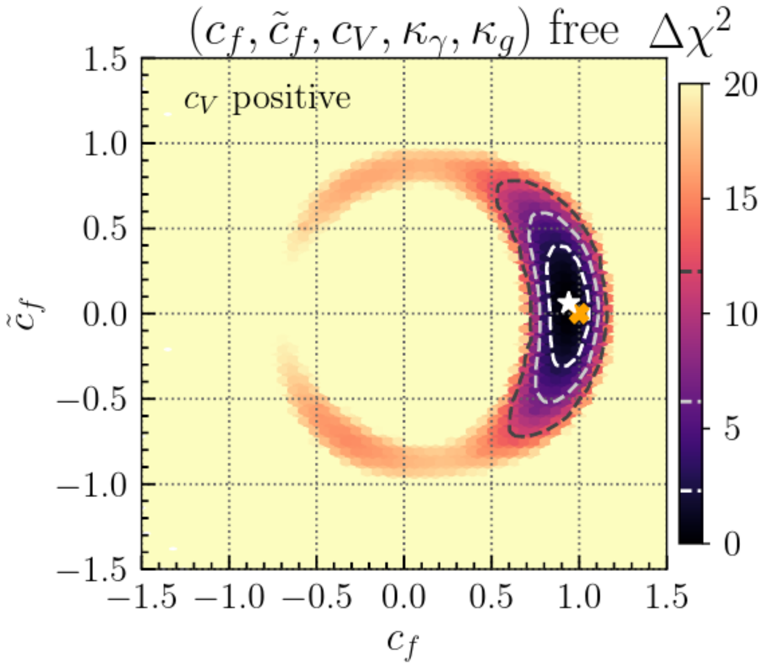


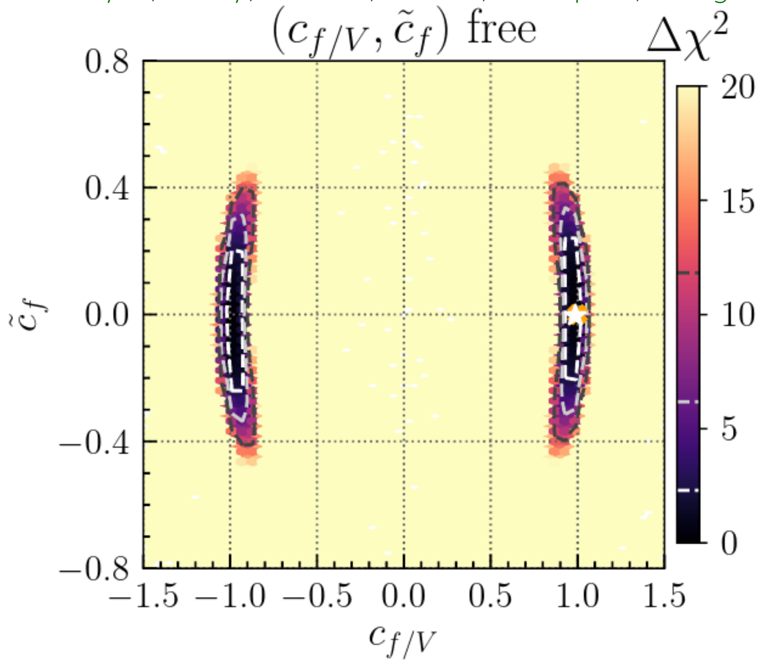
t+b: small c_b can be compensated by $\tilde{c}_b$

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

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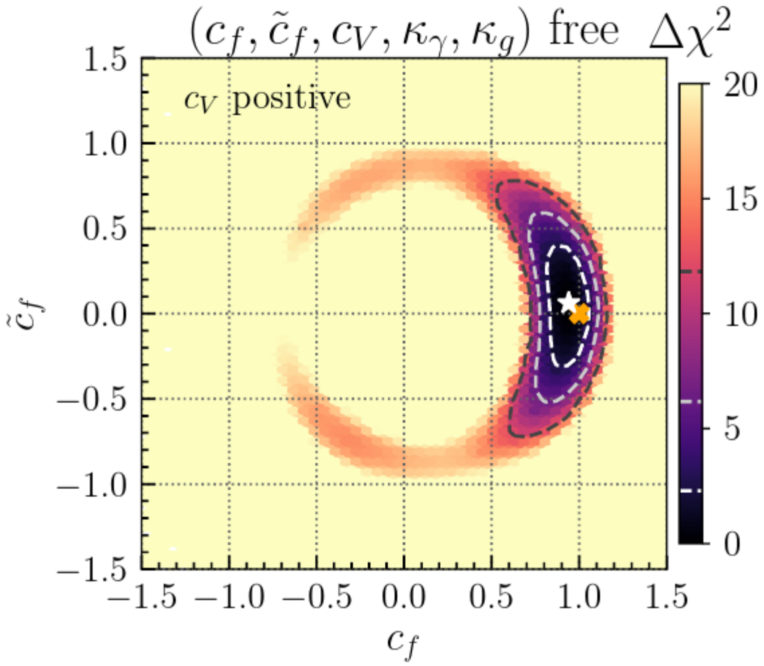
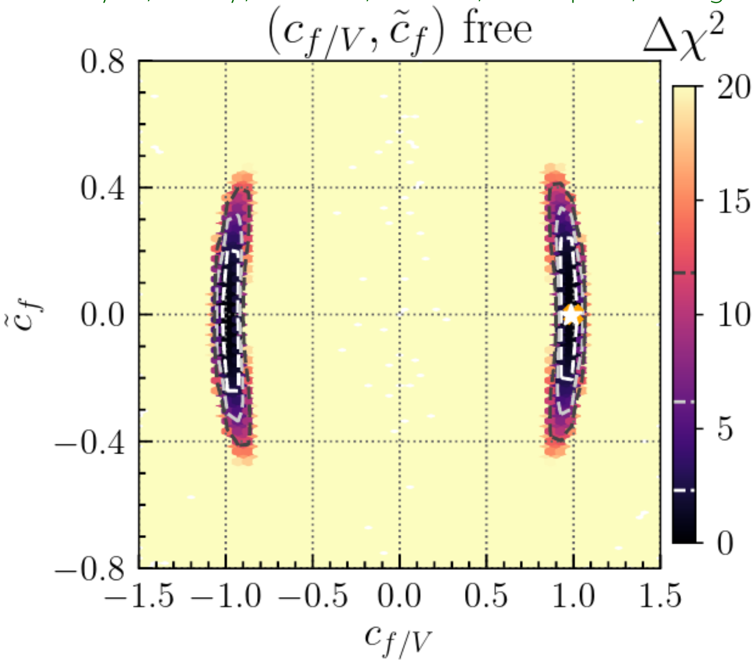
Bahl, EF, Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein '22





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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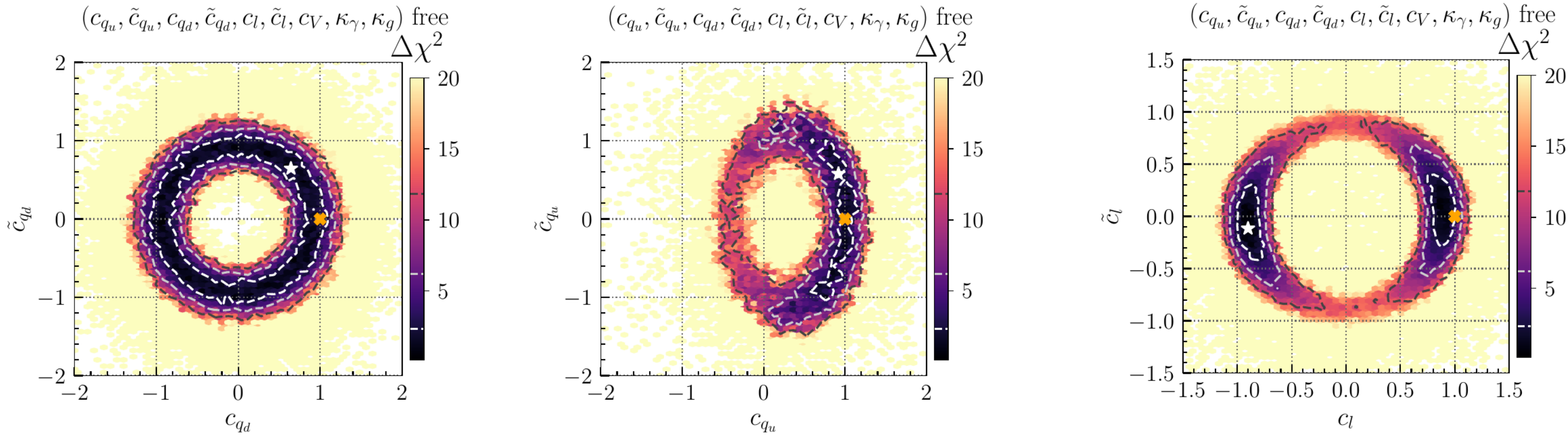
General model: 9-parameter fit

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



Summary of baryogenesis outcome

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

	t	b	c	τ	μ
t	0.03				
b	0.42	0.05			
c	0.37	0.19	0.01		
τ	6.9	6.9	6.9	3.2	
μ	0.18	0.19	0.16	3.2	0.16

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

⟶ Robust upper bound

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

⟶ Disfavored by EWBG/ additional CPV needed

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⟶ 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

Lepton vs Quark Source

Lepton vs Quark Source

- Lepton advantages:
  - No strong sphaleron washout
  - Large diffusion
  - τ: still sizeable Yukawa
  - μ: weak EDM bound

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- **Robustness:** τ overshoots Y_b^{obs}
  - O(1) uncertainties do not change conclusion
  - 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;

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

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

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

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

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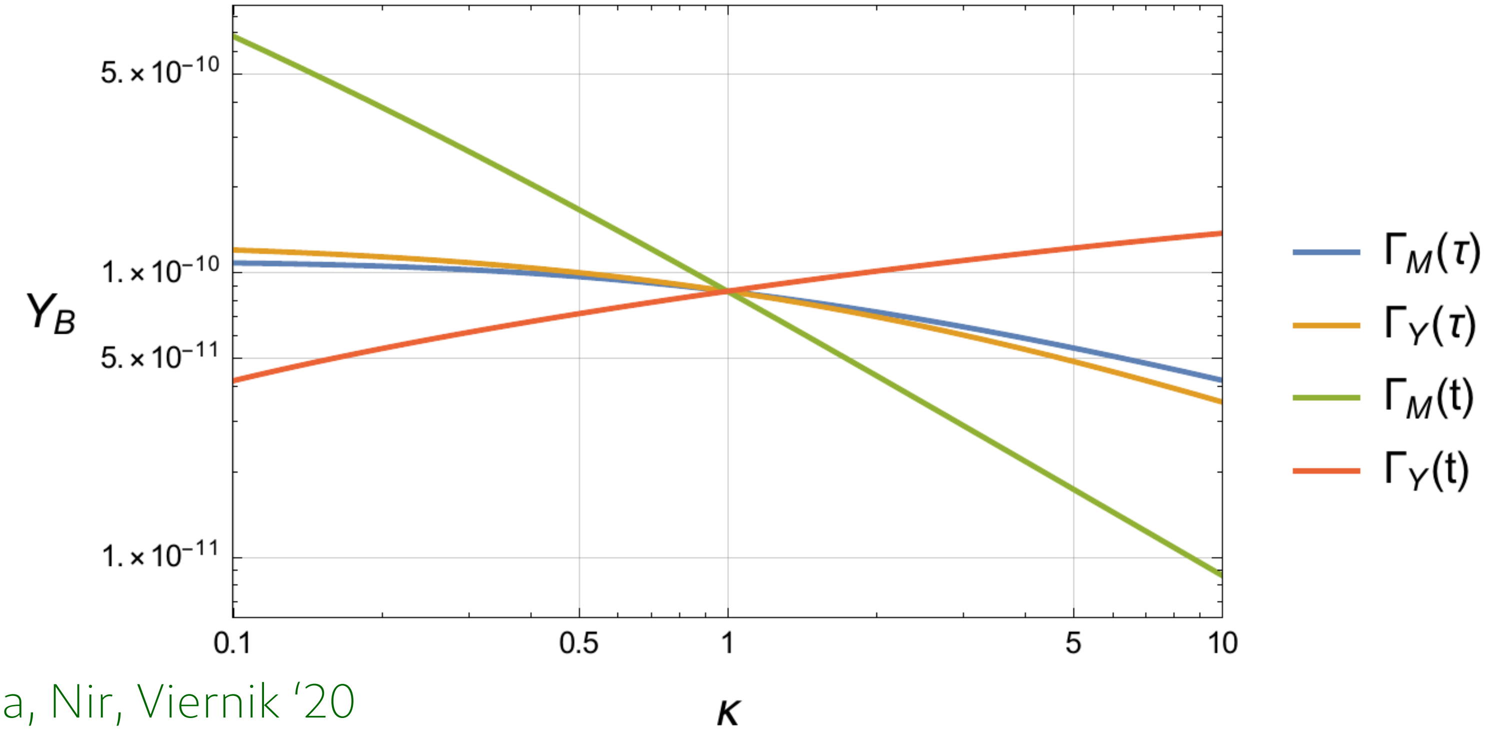
Particle dynamics

- 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.

Uncertainty of Y_B from input rates

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



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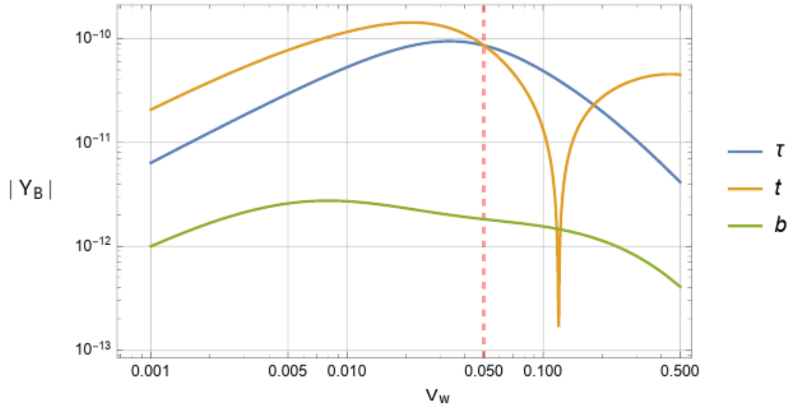
Parameter dependence; 1-/2-step



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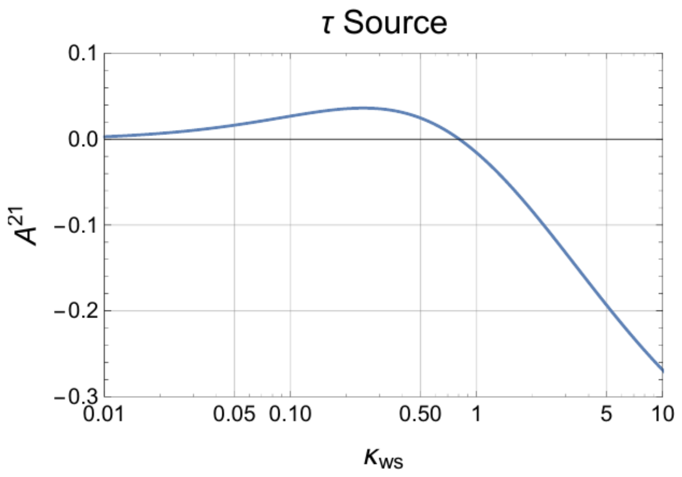
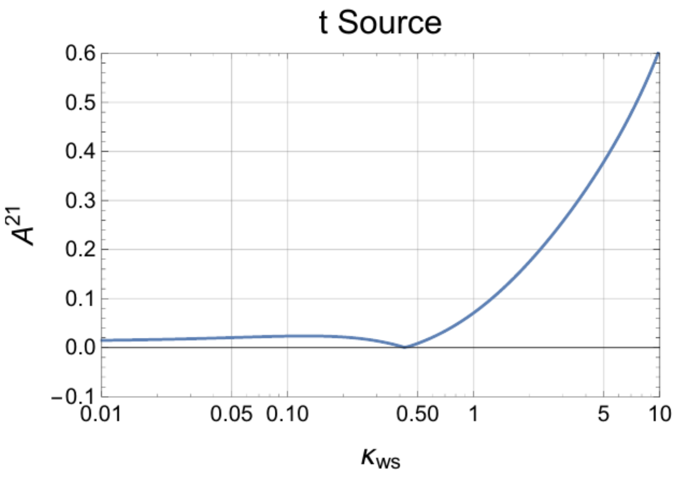
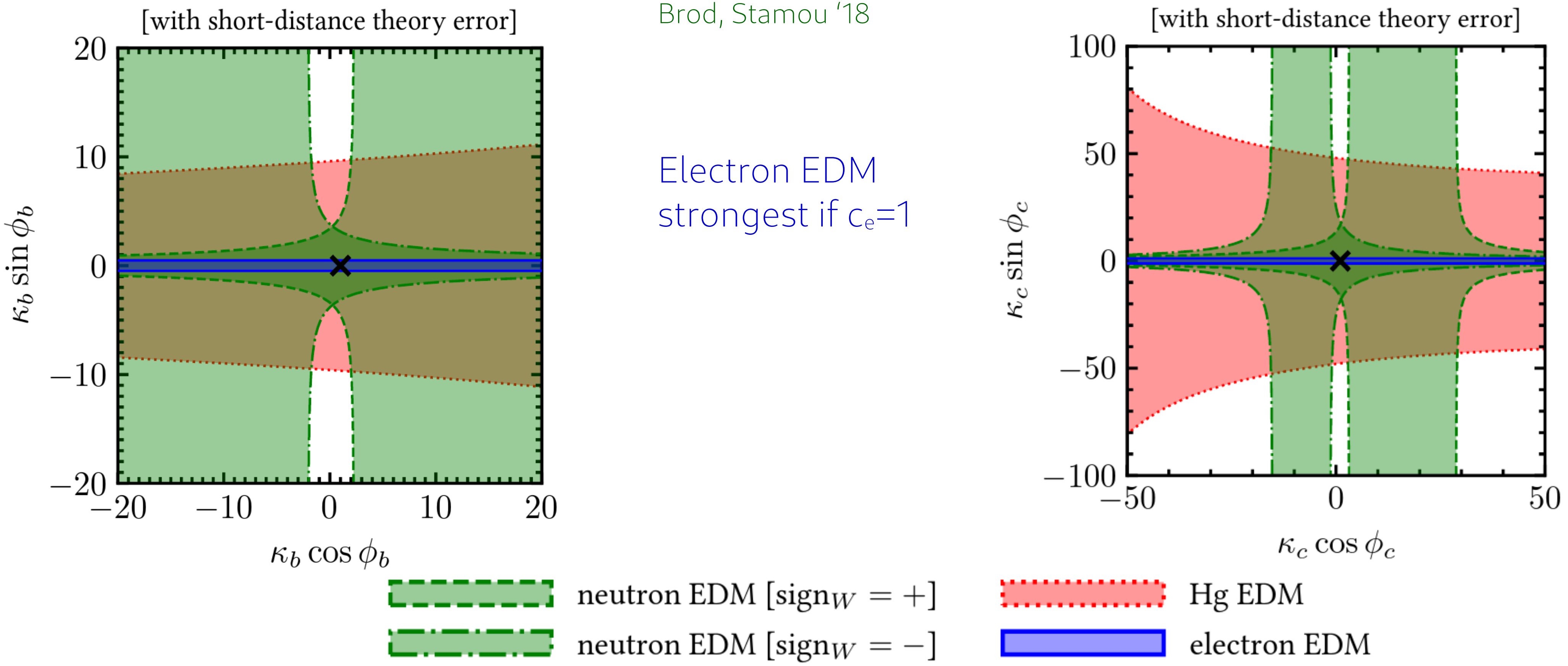




EDMs: e, n, Hg

Brod, Stamou '18

Electron EDM strongest if c_e=1



Input to the Neural Net for gg→ Hjj

- E, p_T, η and ϕ of the Higgs boson and the two leading order jets,
- m_{jj}, $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$ for the two leading order jets,
- the number of jets in the event N_j and
- E of all jets that are not leading or sub-leading.