Constraining the CP structure of Higgs-fermion couplings with a global LHC fit, EDM and baryogenesis

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PTB

Our Goal

Consider different BSM models with free Higgs-fermion couplings

Collider constraints:
Higgs signal rate analysis
Angular analysis of $H \to \tau\tau$

Find viable regions

Constraints from the electron electric dipole moment

Calculate baryon asymmetry Y_B from CP-odd Yukawa couplings

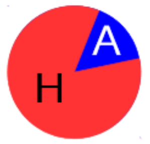
Investigated models

- One free Higgs-fermion coupling, rest SM-like
- Two free Higgs-fermion couplings, rest SM-like
- Shared phases between fermions, leptons, quarks
- Additionally: Free Higgs-weak gauge boson coupling
- Additionally: Free Higgs-gluon & Higgs-photon coupling

Full set of models: Bahl, Bechtle, Fuchs, Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein (in preparation)

Higgs Characterization Model

- Higgs ϕ assumed to be mixed CP state



- Yukawa coupling: $\mathcal{L}_{\mathrm{Yuk}} = -\sum_f \frac{g_f}{\sqrt{2}} \bar{\psi}_f \left(c_f + i\gamma_5 \tilde{c}_f \right) \psi_f \phi$

- Higgs-gauge coupling: $\mathcal{L}_{HV} = c_V \left(2 \frac{m_W^2}{v} W_\mu^+ W^{\mu -} + \frac{m_Z^2}{v} Z_\mu Z^\mu \right)$

Artoisenet, de Aquino, Demartin et al. (2013)

- Measurable: $g_f^2 = c_f^2 + \tilde{c}_f^2, \tan\alpha = {}^{\tilde{c}_f}/_{c_f}$

- SM for $c_f = 1, \tilde{c}_f = 0$

Higgs Characterization Model

- Parameterize ggH and $H\gamma\gamma$ interactions in terms of Yukawa modifiers:

Freitas, Schwaller (2013)

$$\mu_{ggH} = 1.11c_t^2 + 2.56\tilde{c}_t^2 - 0.12c_t c_b - 0.20\tilde{c}_t\tilde{c}_b + 0.01c_b^2 + 0.01\tilde{c}_b^2$$

$$\mu_{H\gamma\gamma} = 0.08c_t^2 + 0.18\tilde{c}_t^2 + 1.62c_V^2 - 0.71c_V c_t + \mathcal{O}(\leq 10^{-3})$$

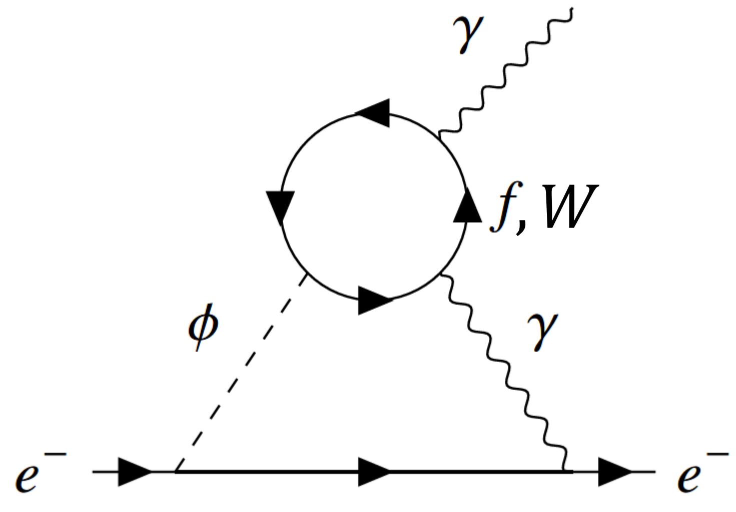
- Analogeously for associated production modes (ggZh, ttH, tH, tWH)

Bahl, Bechtle, Heinemeyer, Katzy, Klingl, Peters, Saimpert, Stefaniak, Weiglein (2020)

Electron Electric Dipole Moment

Experimental upper limit:
$|d_e| < 1.1 \times 10^{-29}\, e$ cm (90% CL)

ACME Collaboration (2018)



Numerical evaluation of contributing Barr-Zee diagrams:

$$\left| d_e / d_e^{\mathrm{ACME}} \right| = c_e\left(870.0\tilde{c}_t + 3.9\tilde{c}_b + 3.4\tilde{c}_\tau + 2.8\tilde{c}_c + 0.03\tilde{c}_\mu + 0.01\tilde{c}_s + \cdots\right)$$
$$+\tilde{c}_e\left(610.1c_t + 3.1c_b + 2.8c_\tau + 2.3c_c + 0.02c_\mu + 0.01c_s + \cdots - 1082.6c_V\right) +$$
$$2 \cdot 10^{-6} c_e \tilde{c}_e$$

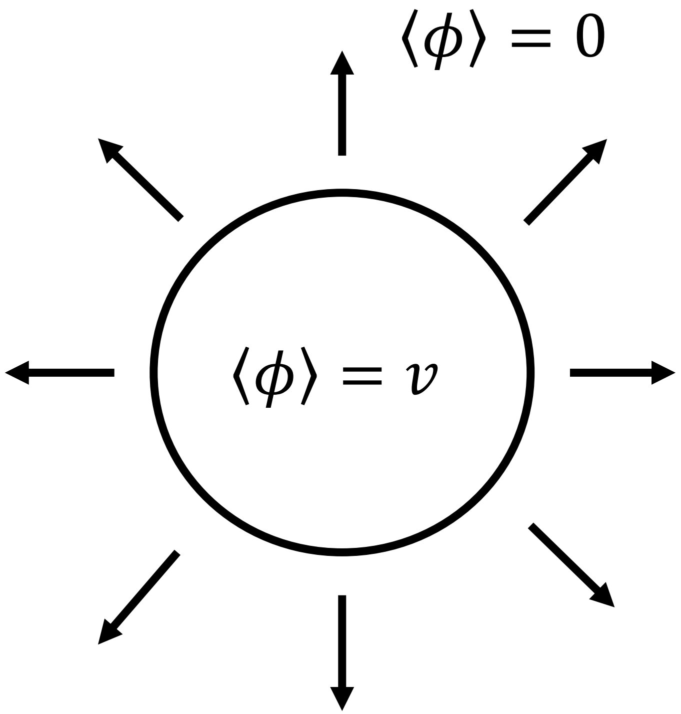
Analytical evaluation: Brod, Haisch, Zupan (2013); Altmannshofer, Brod, Schmaltz (2015); Panico, Pomarol, Riembau (2019) & Altmannshofer (2020)

Electroweak Baryogenesis

- EW symmetry broken in expanding bubbles

- EWSB in the VEV Insertion Approximation (VIA) with optimal bubble parameters

➢ "Upper limit" of achievable baryon asymmetry for given CP violation



Numerical evaluation:

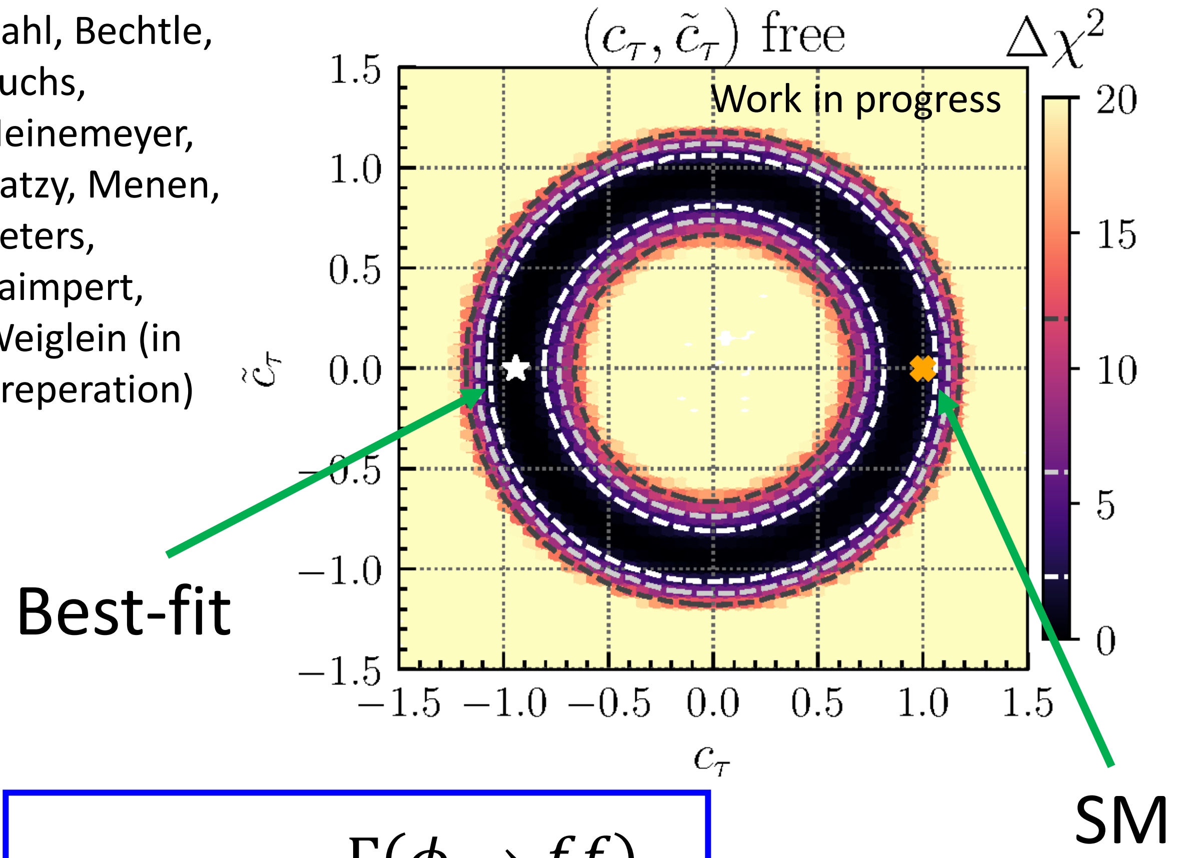
$$Y_B^{\mathrm{VIA}} \Big/ Y_B^{\mathrm{obs}} = 28\tilde{c}_t - 11\tilde{c}_\tau - 0.2\tilde{c}_b - 0.1\tilde{c}_\mu - 0.03\tilde{c}_c - 0.0002\tilde{c}_s - \cdots$$

Fuchs, Losada, Nir, Viernik (2020)
Shapira (2021)

τ-Yukawa CP structure: LHC constraints

Global signal rate fit with HiggsSignals:

Bahl, Bechtle, Fuchs, Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein (in preperation)



$$c_f^2 + \tilde{c}_f^2 \propto \frac{\Gamma(\phi \to ff)}{\Gamma(H^{SM} \to ff)}$$

➢ circle

τ-Yukawa CP structure: LHC constraints

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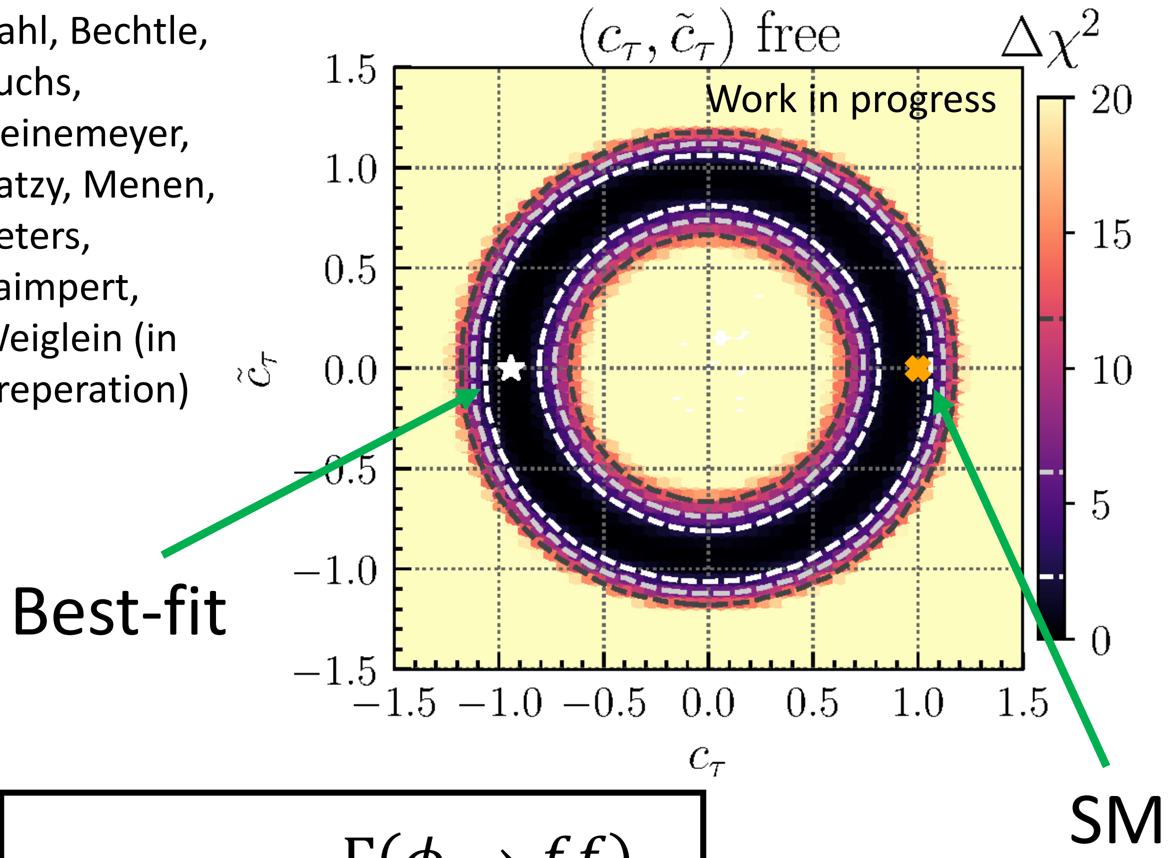
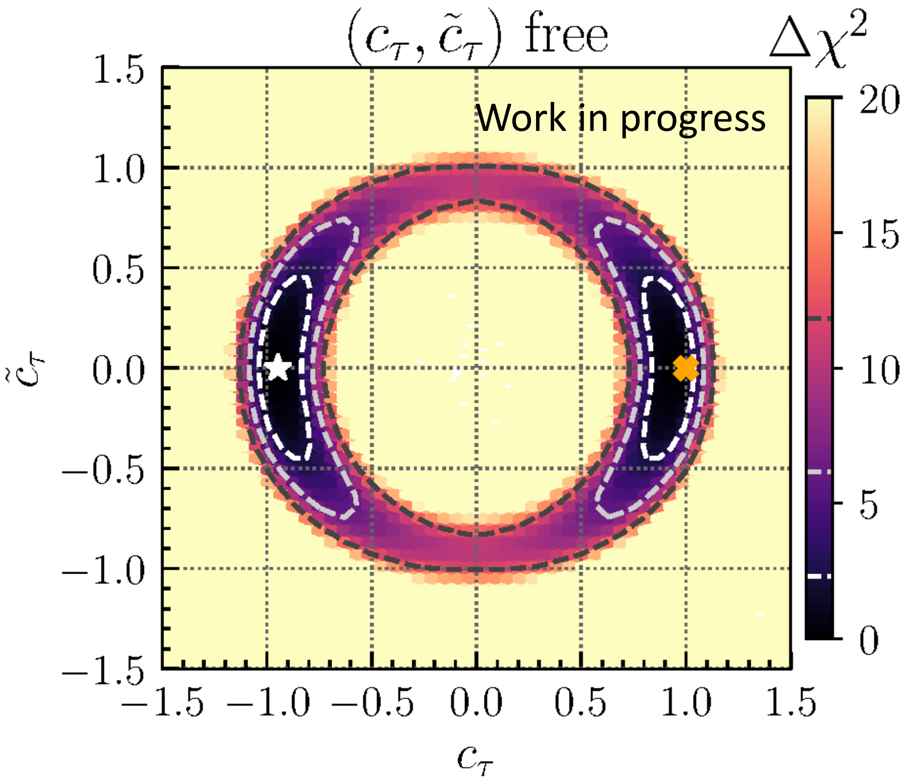


+ CMS CP analysis:



$$c_f^2 + \tilde{c}_f^2 \propto \frac{\Gamma(\phi \to ff)}{\Gamma(H^{SM} \to ff)}$$

➢ circle

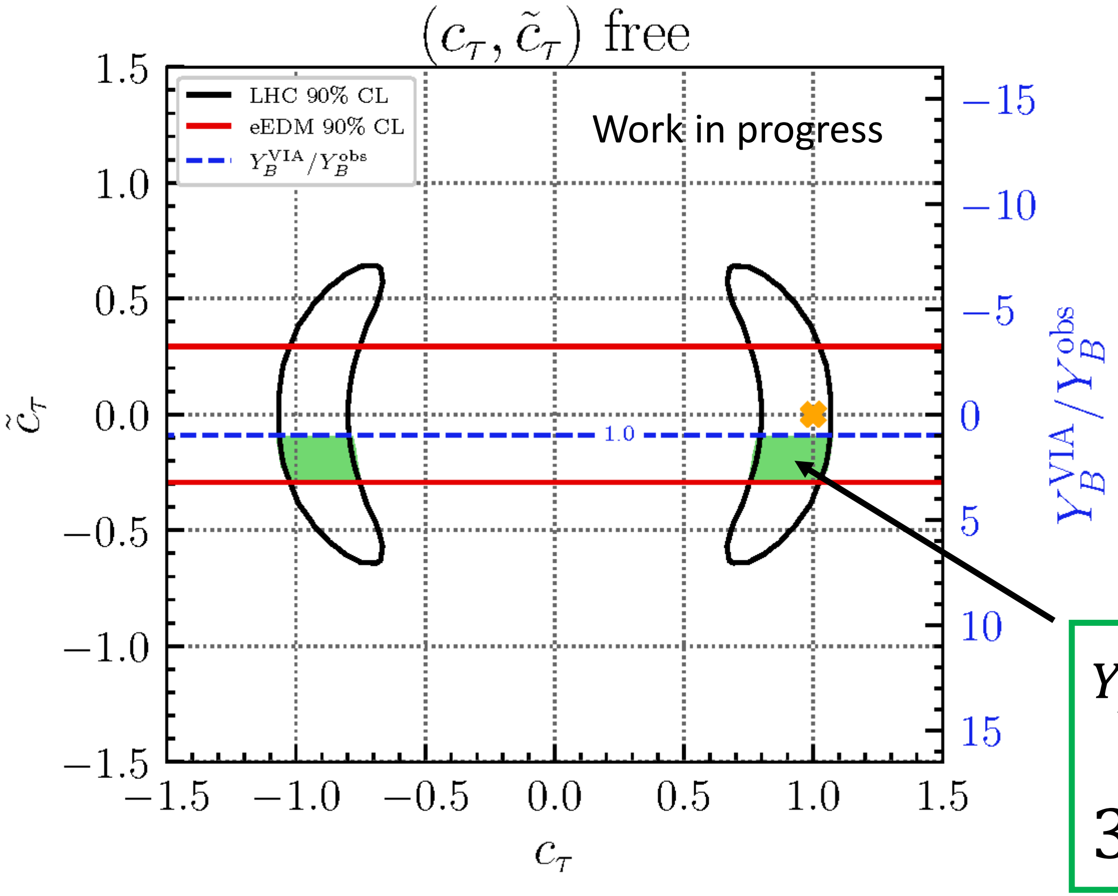
$$\alpha^{H\tau\tau} = \arctan\left(\frac{\tilde{c}_\tau}{c_\tau}\right) = (-1 \pm 19)^\circ \text{ at } 1\sigma$$

CMS Collaboration (2021)

τ-Yukawa CP structure: LHC, eEDM, BAU

$d_e / d_e^{\mathrm{ACME}} \propto \tilde{c}_\tau$
(for $\tilde{c}_e = 0$)

$Y_B^{\mathrm{VIA}} / Y_B^{\mathrm{obs}} \propto \tilde{c}_\tau$

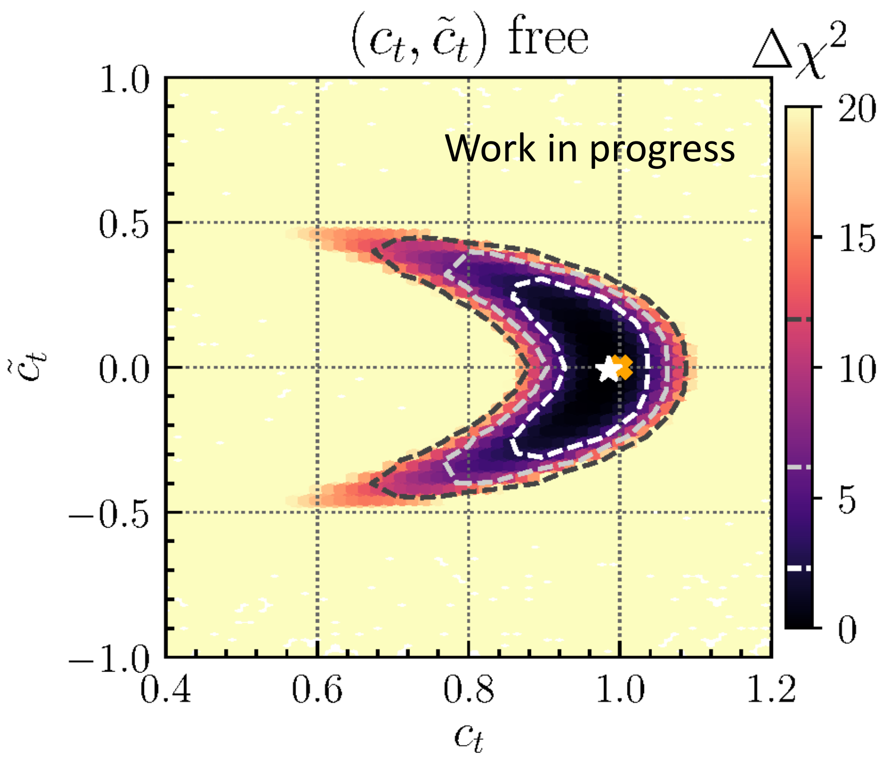


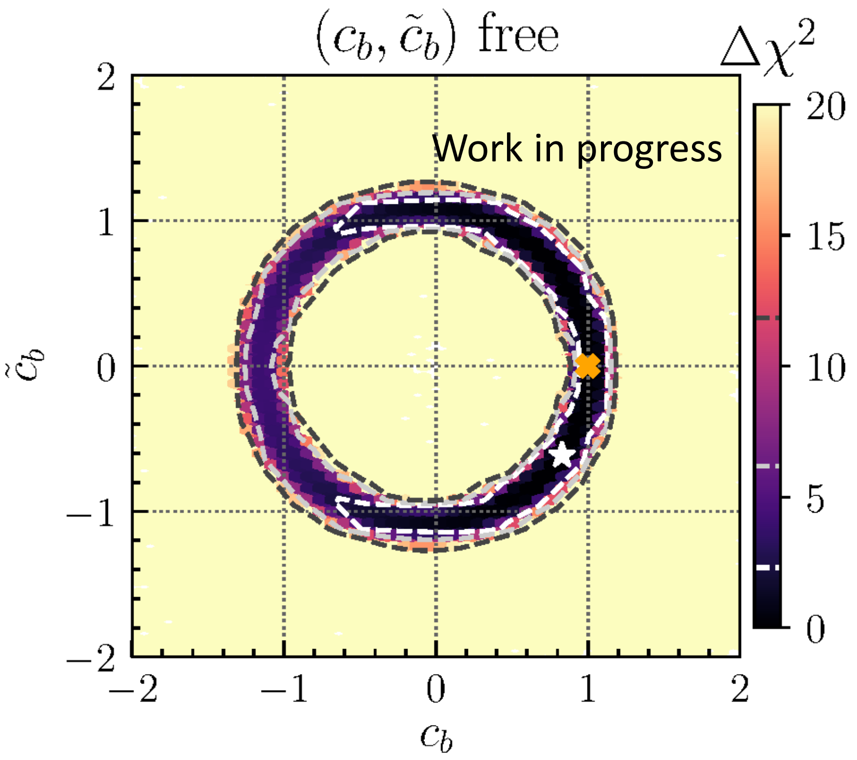
LHC 90% CL
eEDM 90% CL
$Y_B^{\mathrm{VIA}}/Y_B^{\mathrm{obs}}$

$Y_B^{\mathrm{VIA}} / Y_B^{\mathrm{obs}} \equiv R_Y \leq$ 3.2 as “upper limit“

Importance of τ-Yukawa coupling shown in earlier works:
De Vries, Postma, van de Vis (2018); Fuchs, Losada, Nir, Viernik (2020) & Shapira (2021)

t,b-Yukawa CP structure: LHC constraints



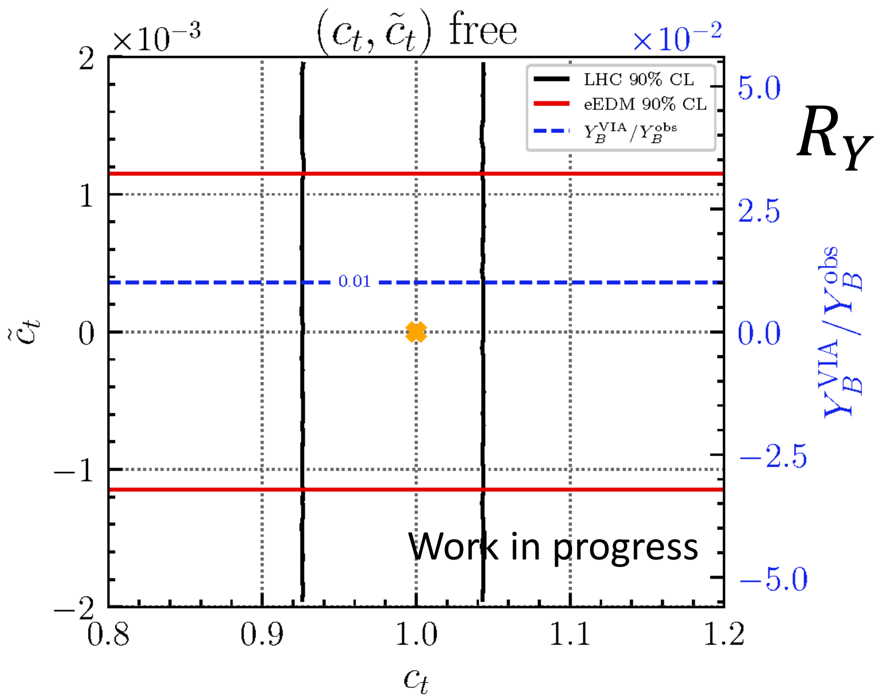


ggH $\propto 1.11c_t^2 + 2.56\tilde{c}_t^2$ → ellipsoid
$H\gamma\gamma \propto 1.62c_V^2 - 0.71c_V c_t$ → cut-off

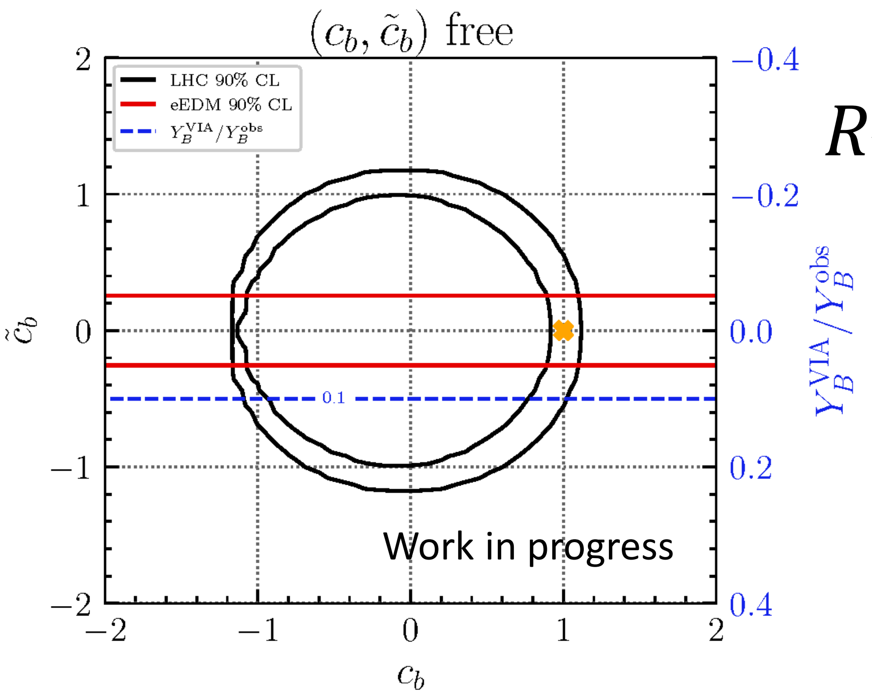
$H \to bb$: Ring
ggH: Small deformation

Well understood: Bahl, Bechtle, Heinemeyer, Katzy, Klingl, Peters, Saimpert, Stefaniak, Weiglein (2020)

t,b-Yukawa CP structure: LHC, eEDM, BAU



$R_Y \leq 3\%$



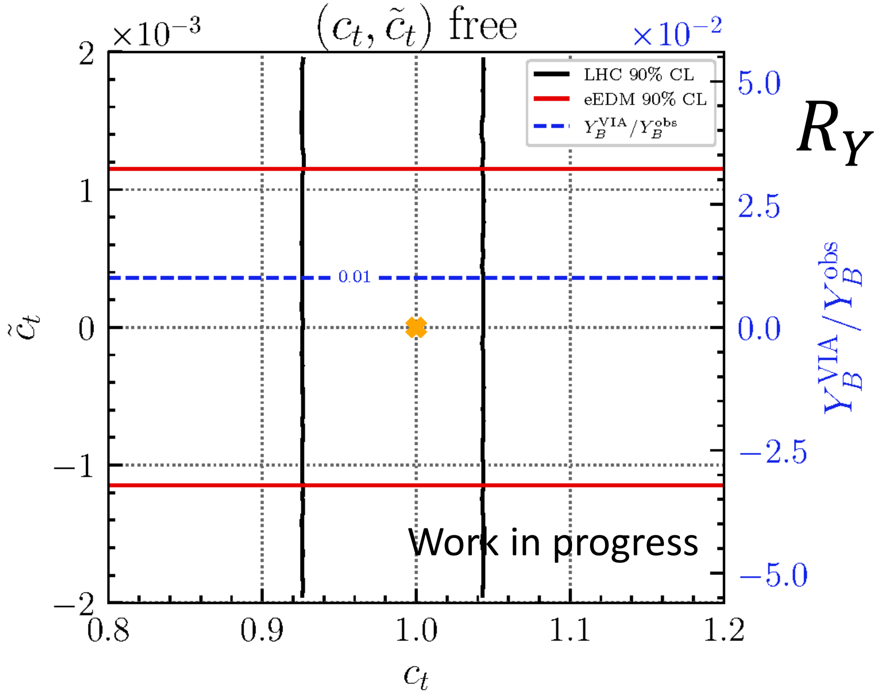
$R_Y \leq 5\%$

eEDM is limiting factor for CP-odd Yukawa structure

→

Only small amounts of Y_B realizable in these models

t,b-Yukawa CP structure: LHC, eEDM, BAU



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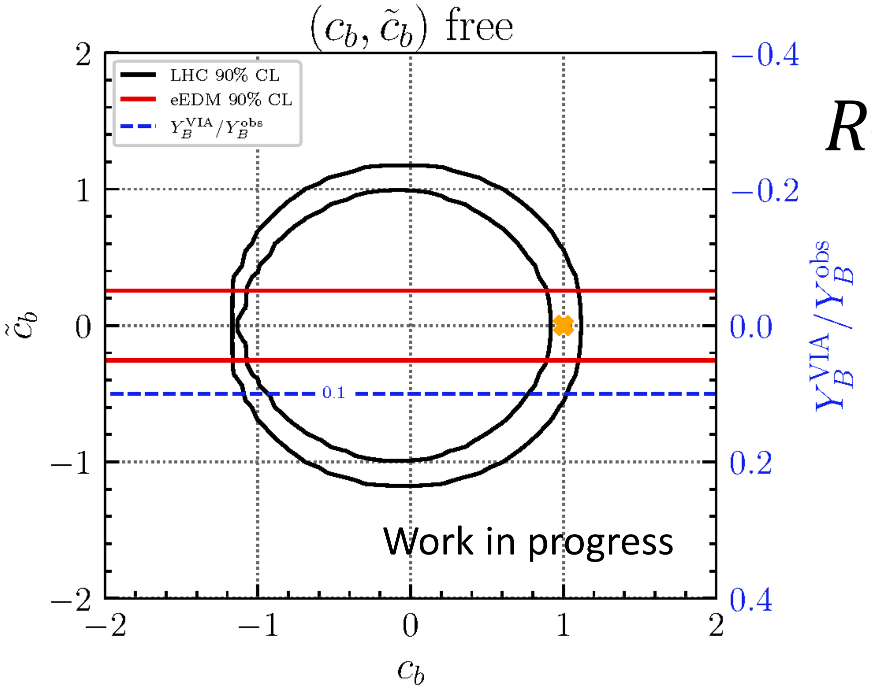
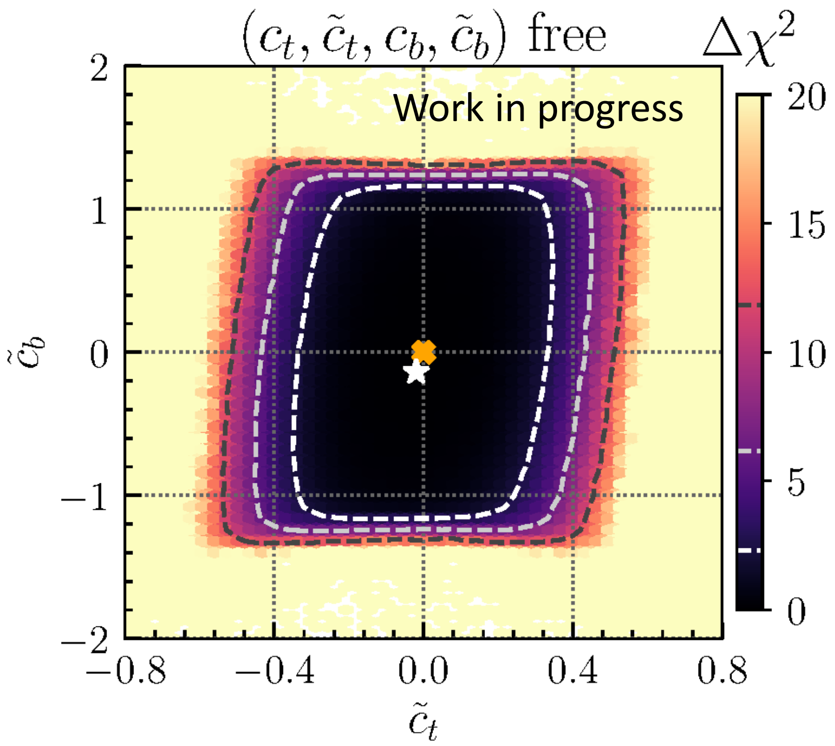


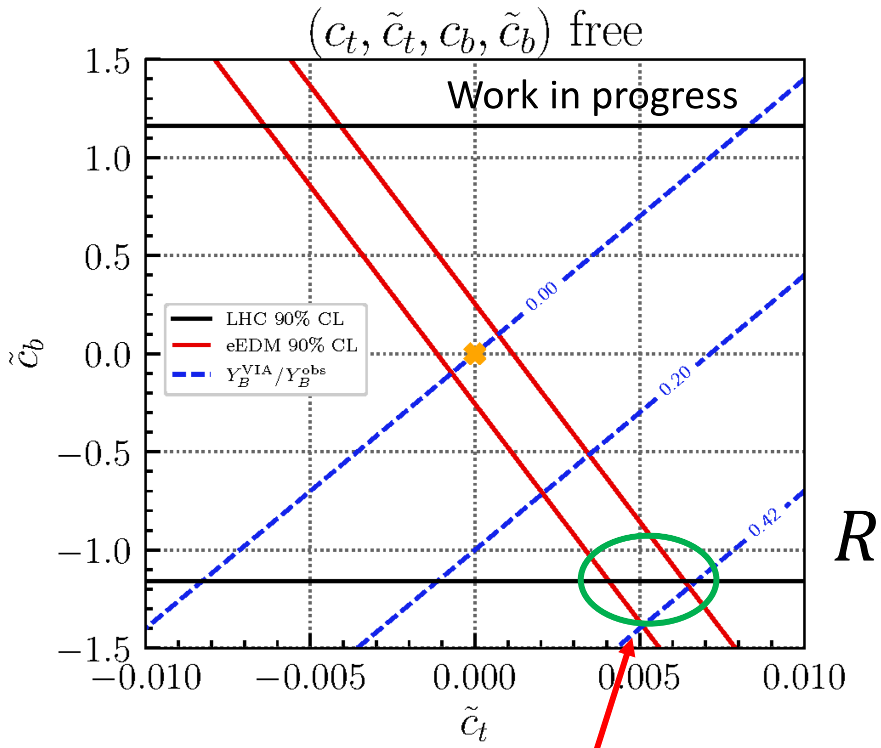
$R_Y \leq 5\%$

eEDM is limiting factor for CP-odd Yukawa structure → Only small amounts of Y_B realizable in these models

What about cancellations from multiple free couplings?

t & b complementarity





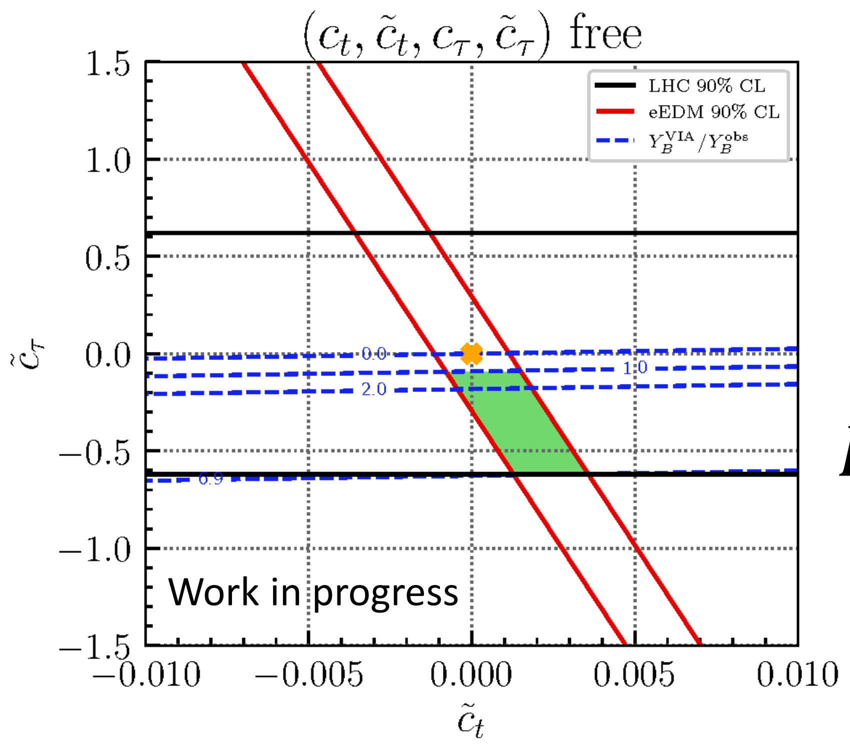
$R_Y \leq 42\%$

$ggH \propto -0.12 c_t c_b - 0.20 \tilde{c}_t \tilde{c}_b$

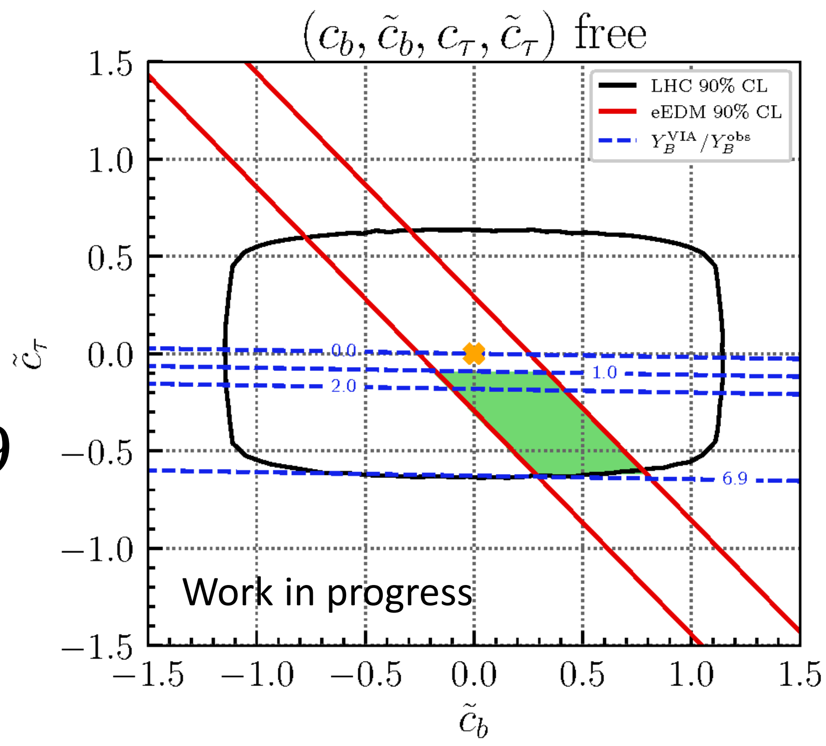
eEDM no longer limiting factor

Fuchs, Losada, Nir, Viernik (2020) found $Y_B \leq 0.12$ for SM-like CP-even parameters

τ & t / τ & b complementarity



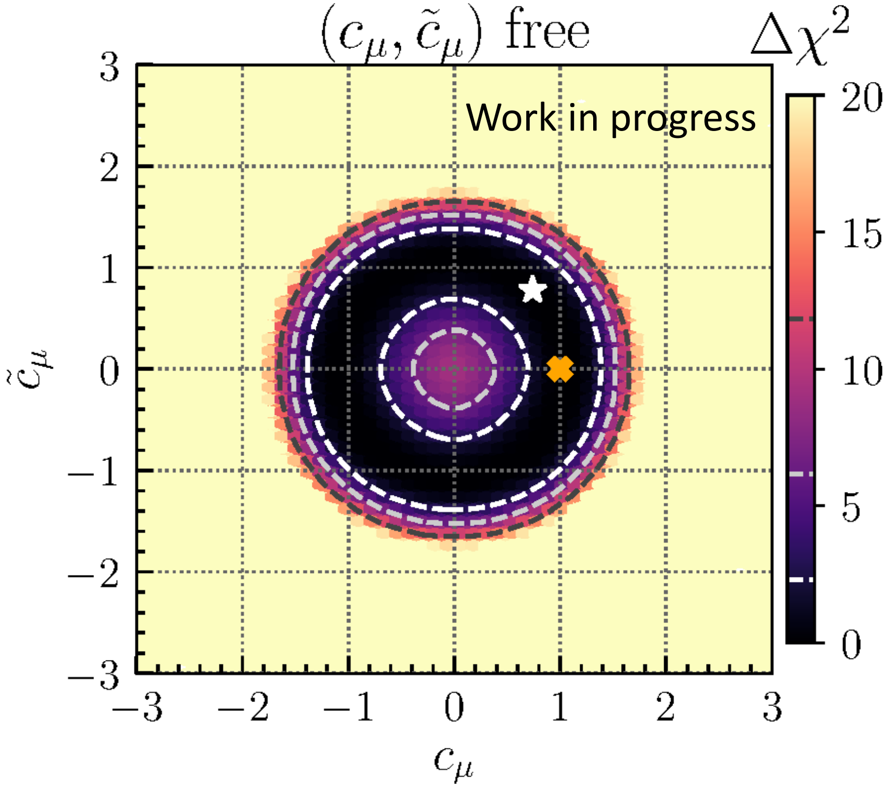
$R_Y \leq 6.9$

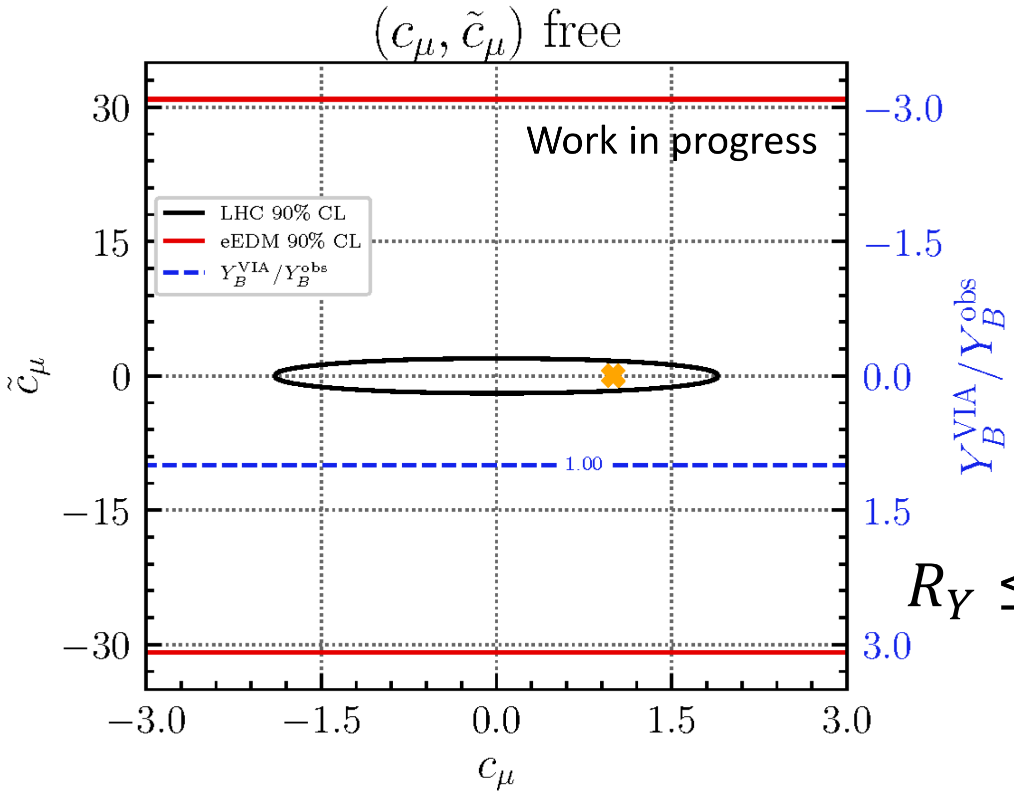


eEDM no longer limiting factor

Cancellations can enhance maximally allowed baryon asymmetry

Constraints of μ-Yukawa coupling





$R_Y \leq 0.17$

$H \to \mu\mu$ observed (3σ): ATLAS Collaboration (2021) & CMS Collaboration (2021)

LHC constraints already way stronger than eEDM

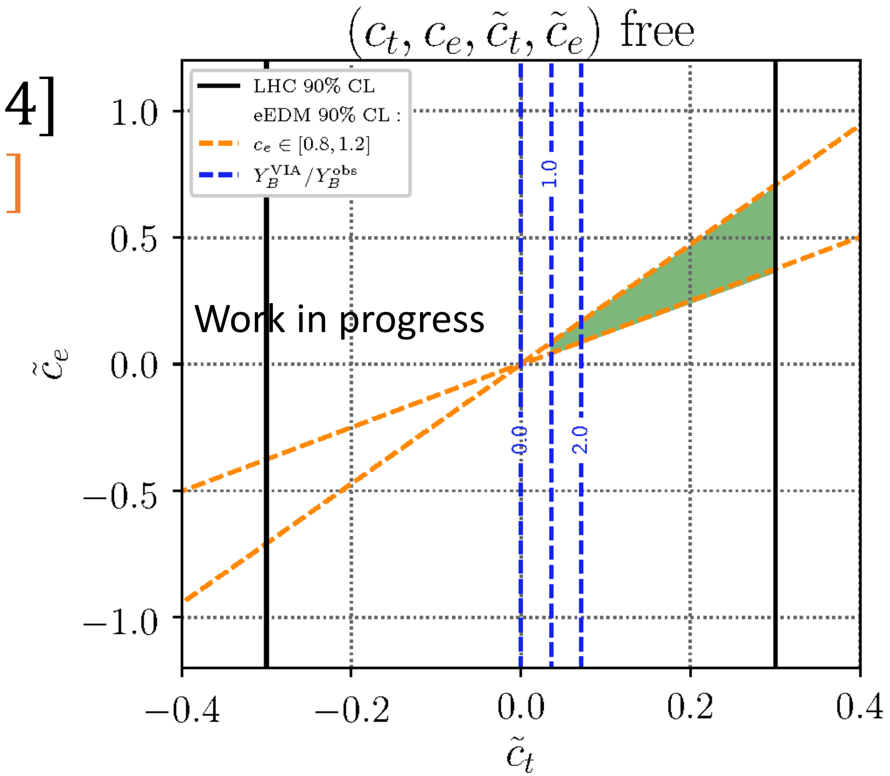
Impact of e-Yukawa coupling

Most stringent e-Yukawa bound: $g_e = \sqrt{c_e^2 + \tilde{c}_e^2} \leq 268$

- no significant collider constraints yet

ATLAS Collaboration (2020)

$c_t \in [0.86, 1.04]$
$c_e \in [0.8, 1.2]$



$$\left| {d_e}/{d_e^{\mathrm{ACME}}} \right| \propto c_e(870.0\tilde{c}_t) + \tilde{c}_e(610.1c_t - 1082.6c_V)$$

Free $c_e, \tilde{c}_e$ + other free fermion couplings: No eEDM constraints

Impact of e-Yukawa coupling

Most stringent e-Yukawa bound: $g_e = \sqrt{c_e^2 + \tilde{c}_e^2} \leq 268$

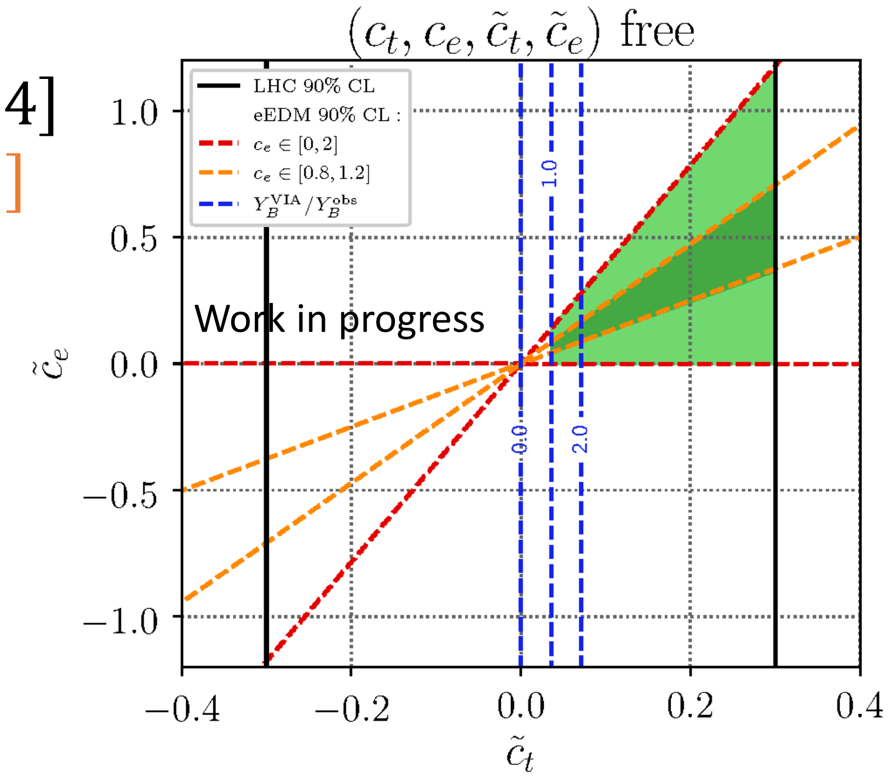
- no significant collider constraints yet

ATLAS Collaboration (2020)

$c_t \in [0.86, 1.04]$

$c_e \in [0.8, 1.2]$

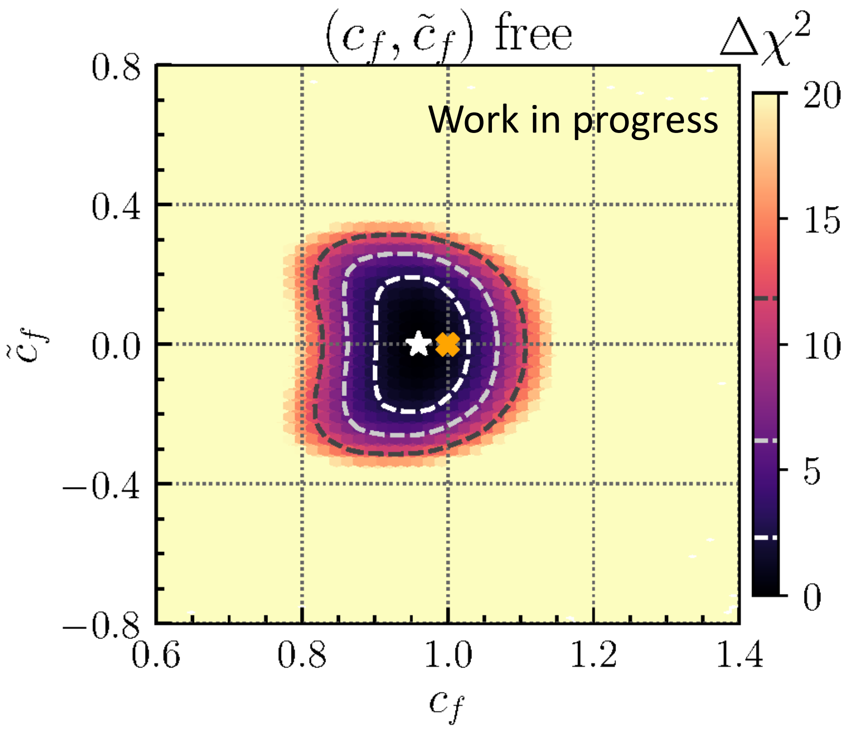
$c_e \in [0, 2]$

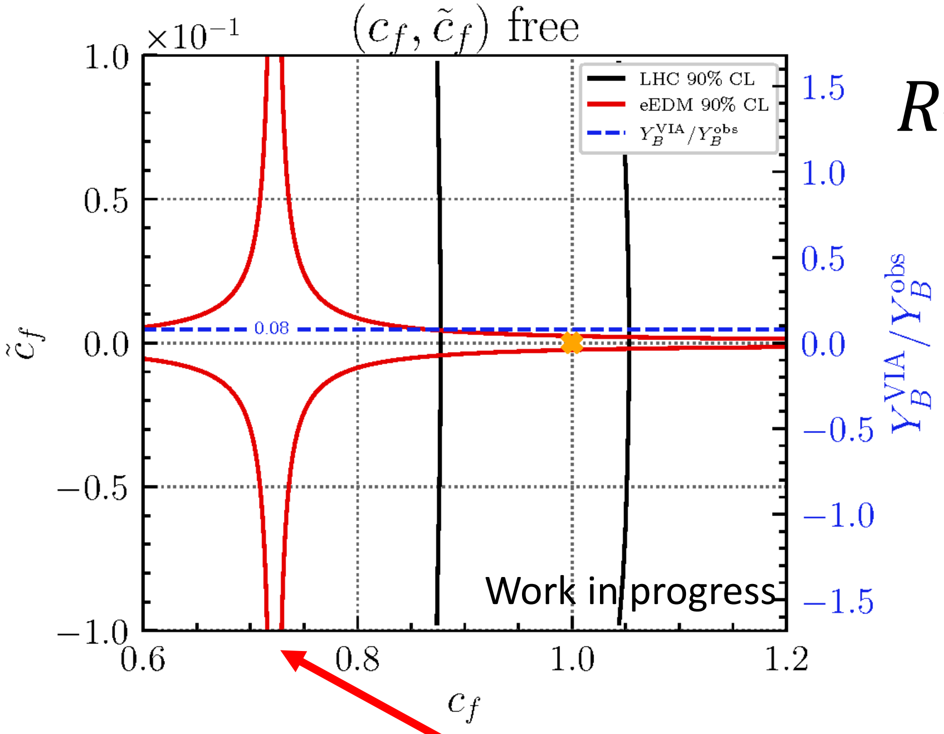


$$\left|{}^{d_e}/_{d_e^{\mathrm{ACME}}}\right| \propto c_e(870.0\tilde{c}_t) + \tilde{c}_e(610.1c_t - 1082.6c_V)$$

Free $c_e, \tilde{c}_e$ + other free fermion couplings: No eEDM constraints

Impact of e in a global fermion phase





$R_Y \leq 8\%$

Shared phase $c_f \equiv c_t = c_b = c_\tau = \cdots$

Full cancellation of eEDM

$$\left| {}^{d_e}\!/_{d_e^{\rm ACME}} \right| \propto c_e(870.0\tilde{c}_t) + \tilde{c}_e(610.1c_t - 1082.6c_V)$$

Conclusions

- τ viable EWBG source, even with latest CP analysis
- LHC constraints of 2nd gen Yukawas get more significant
- Cancellations in the eEDM allow for larger R_Y: t / b alone reach 3% / 5%, together 42%
- Heavy impact of eEDM on electron couplings → large reduction possible

	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

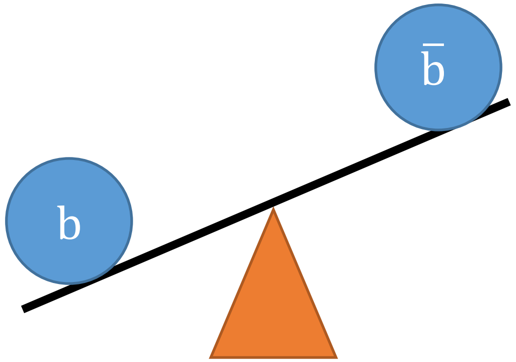
R_Y for all models with one or two free Higgs-fermion couplings


THANK YOU FOR
LISTENING TO MY
PRESENTATION

Backup

Backup: Motivation

- Observed baryon asymmetry of the universe (BAU) found to be
  $Y_B^{\text{obs}} = (8.59 \pm 0.08) * 10^{-11}$ Tanabashi et al. (2018)



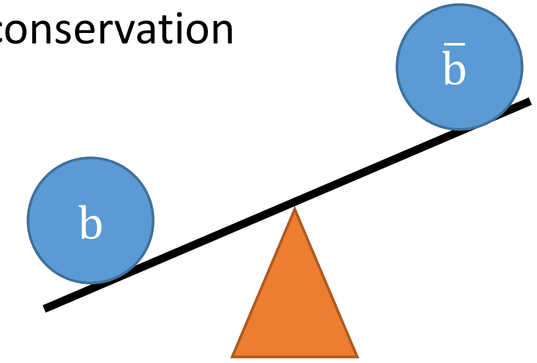
Sakharov conditions :

1. Baryon number violation ⟶ unobserved
2. Charge (C) and charge-parity (CP) violation ⟶ not enough
   Gavela, Hernandez, Orloff, Pene (1993)
3. Deviation from thermal equilibrium ⟶ not possible

$\Rightarrow$ CP violation in BSM physics

Backup: Motivation

„Accidental“ symmetry of the SM, unlike electromagnetic
Gauge invariance and lepton number conservation



1. Baryon number violation
   - Not observed, but realizable in the SM

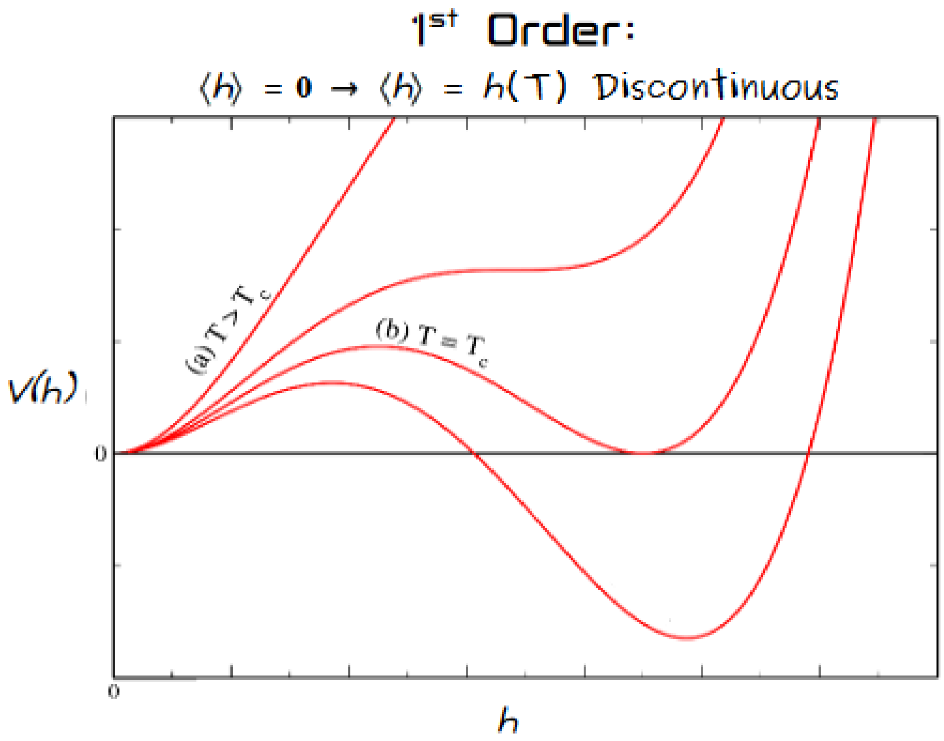
2. Charge (C) and charge-parity (CP) violation
   - Observed in the decay of neutral K-mesons in 1964 [3]
   - CP violation in the SM is not sufficient to explain BAU

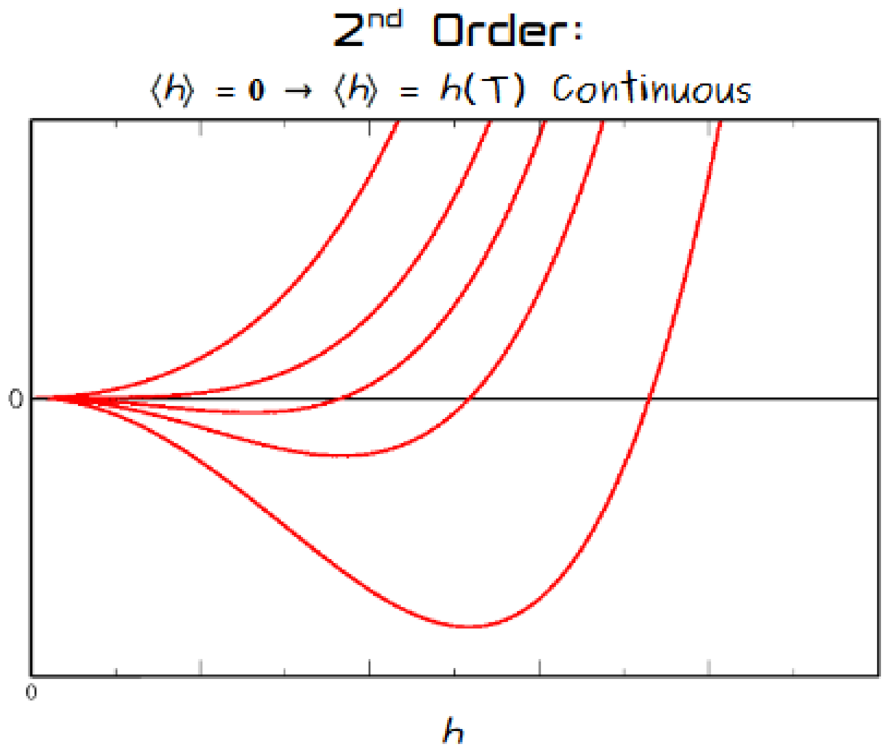
$< 10^{-10}$ of total BAU needed

3. Deviation from thermal equilibrium
   - Electroweak symmetry breaking (EWSB) has to be strongly first order, unfulfilled for $m_H = 125$ GeV [4]

$m_H < 80$ GeV needed

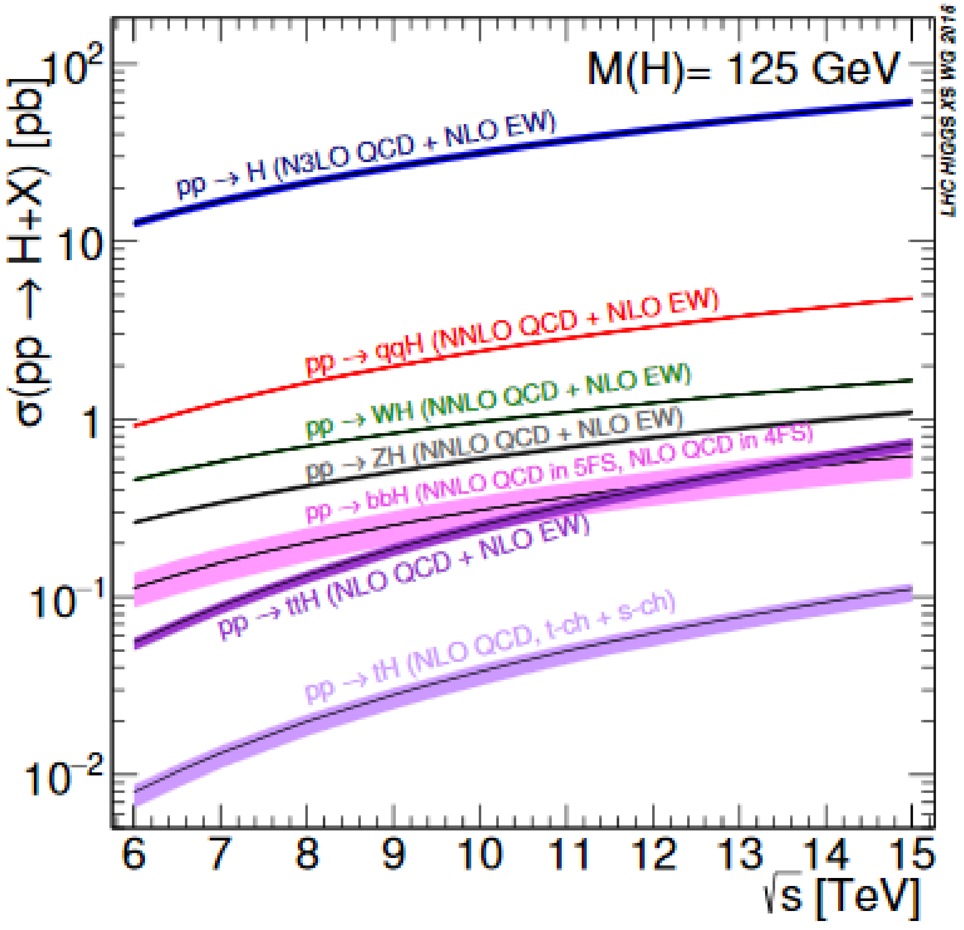
Backup: EWSB Transition

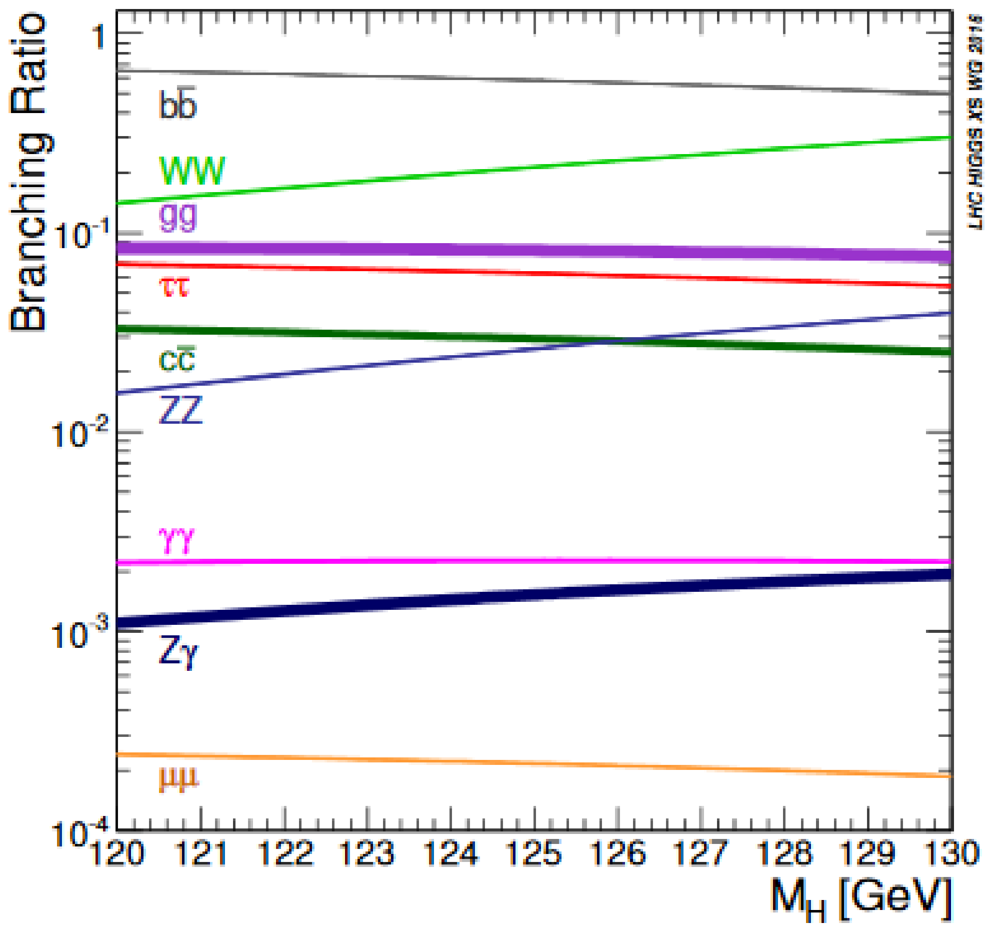




https://indico.cern.ch/event/703821/contributions/3102565/attachments/1705559/2748036/CLICdp_EWPT_JMNo.pdf

Backup: Higgs channels





Backup: SMEFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_D \frac{1}{\Lambda^{D-4}} \left(\sum\nolimits_i C_i^D \boldsymbol{O}_i^D \right)$$

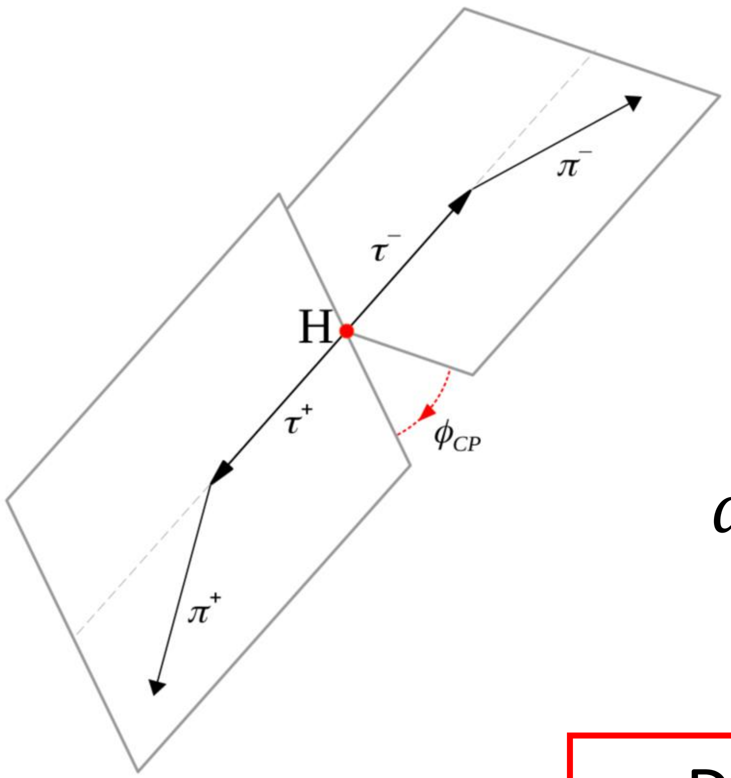
Dim 5: $O_{\nu\nu}^5 = \left(\bar{\phi}^\dagger L_p\right)^T C \left(\bar{\phi}^\dagger L_r\right) \longrightarrow$ Lepton number violation

Dim 6: $O_{e\phi}^6 = \left(\phi^\dagger \phi\right)\left(\bar{L}_p e_r \phi\right) \longrightarrow$ Modified Higgs-lepton coupling

$$\Lambda \geq v = 246 \text{ GeV}$$

Backup: CMS CP analysis

Dedicated CP analysis by CMS [10] :



CP mixing angle: $\alpha^{H\tau\tau} = \arctan\left(\frac{\tilde{c}_\tau}{c_\tau}\right)$

Angle between τ decay planes: ϕ_{CP}

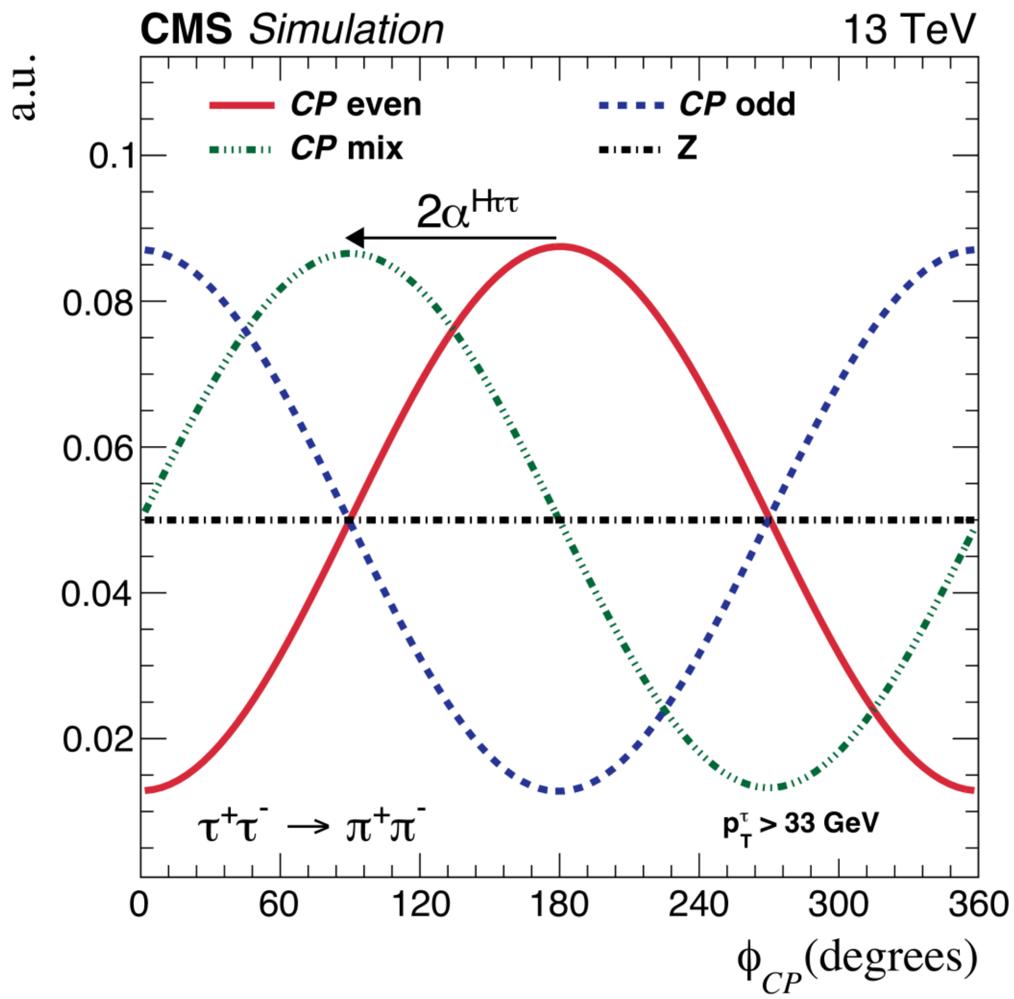
$$d\Gamma(H \to \tau^+\tau^-) \sim 1 - \cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$ [11]

→ Direct CP constraints

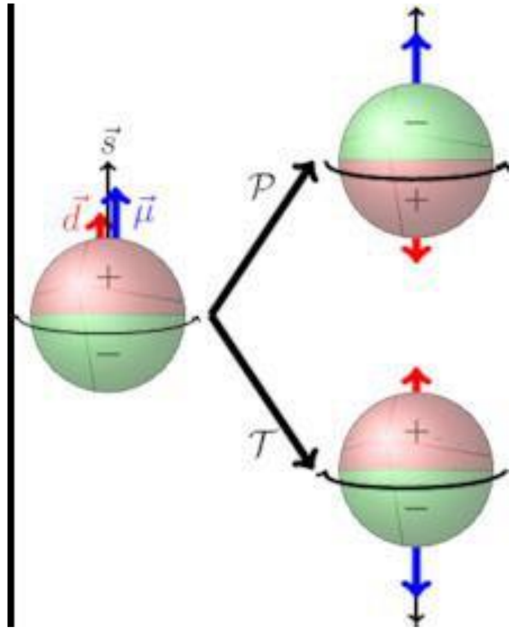
[10]: CMS Collaboration; arxiv:2110.04836 (2021)
[11]: S. Berge, W. Bernreuther, S. Kirchner; arxiv:1410.6362 (2014)

Backup: CMS CP analysis

CMS CP analysis: Determination of CP mixing angle $\alpha^{H\tau\tau}$



Backup: CMS CP analysis

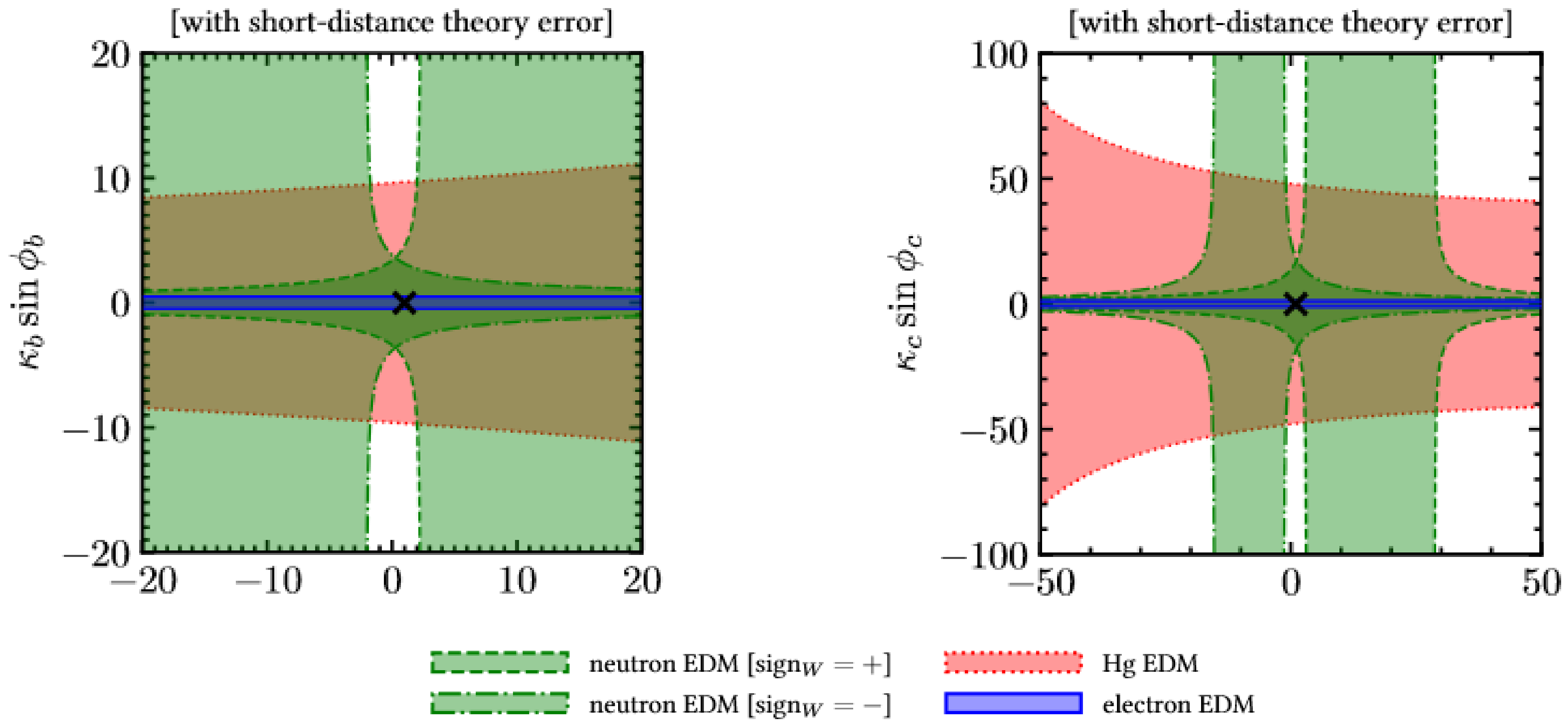


Electric dipole moments of particles with non-zero spin violate T and P symmetry

➢ CP violation

J. Pretz; https://www.institut3b.physik.rwth-aachen.de/cms/ParticlePhysics3B/Forschung/~gbve/Elektrisches-Dipolmoment/?lidx=1

Backup: EDM contributions



Brod, Stamou (2018)

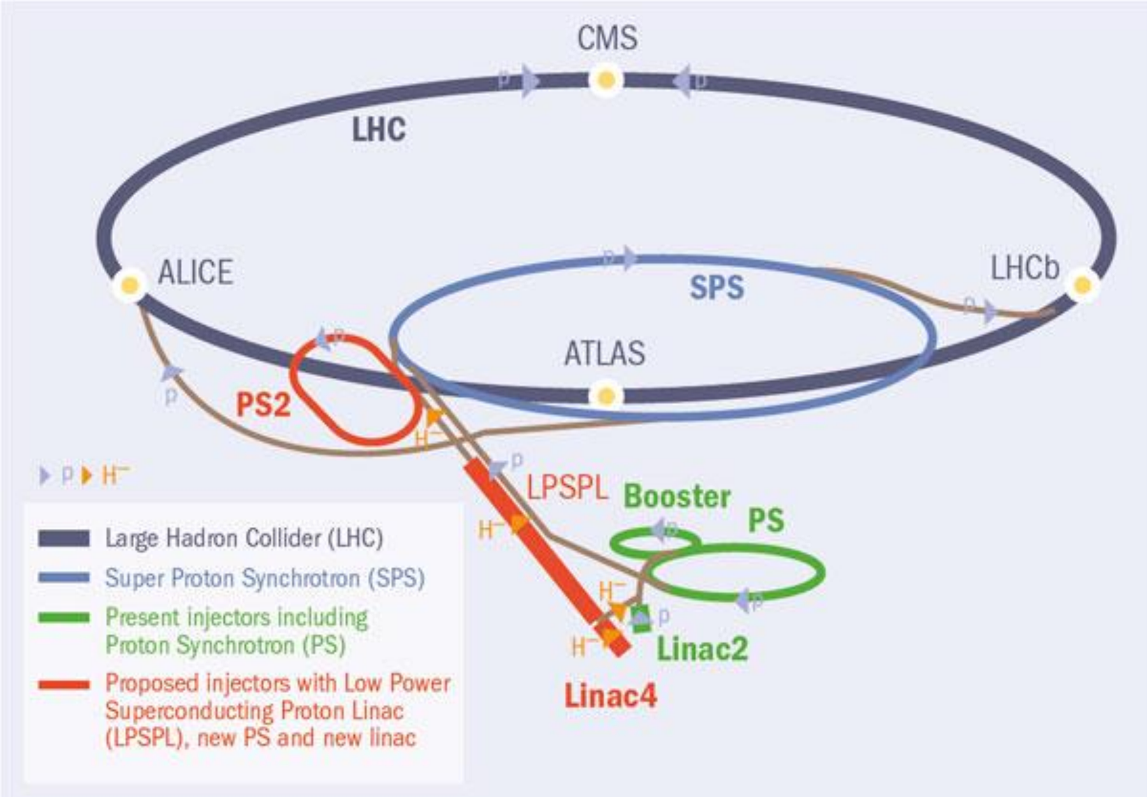
Backup: Baryogenesis

- CP violating interactions at bubble wall lead to chiral asymmetry
- Strong sphaleron process: Washout in quark sector
- Chiral asymmetry diffuses to symmetric phase, more efficient for leptons
- Weak sphaleron process: Baryon number violation from symmetric phase
- Baryon number violation frozen in by bubble wall

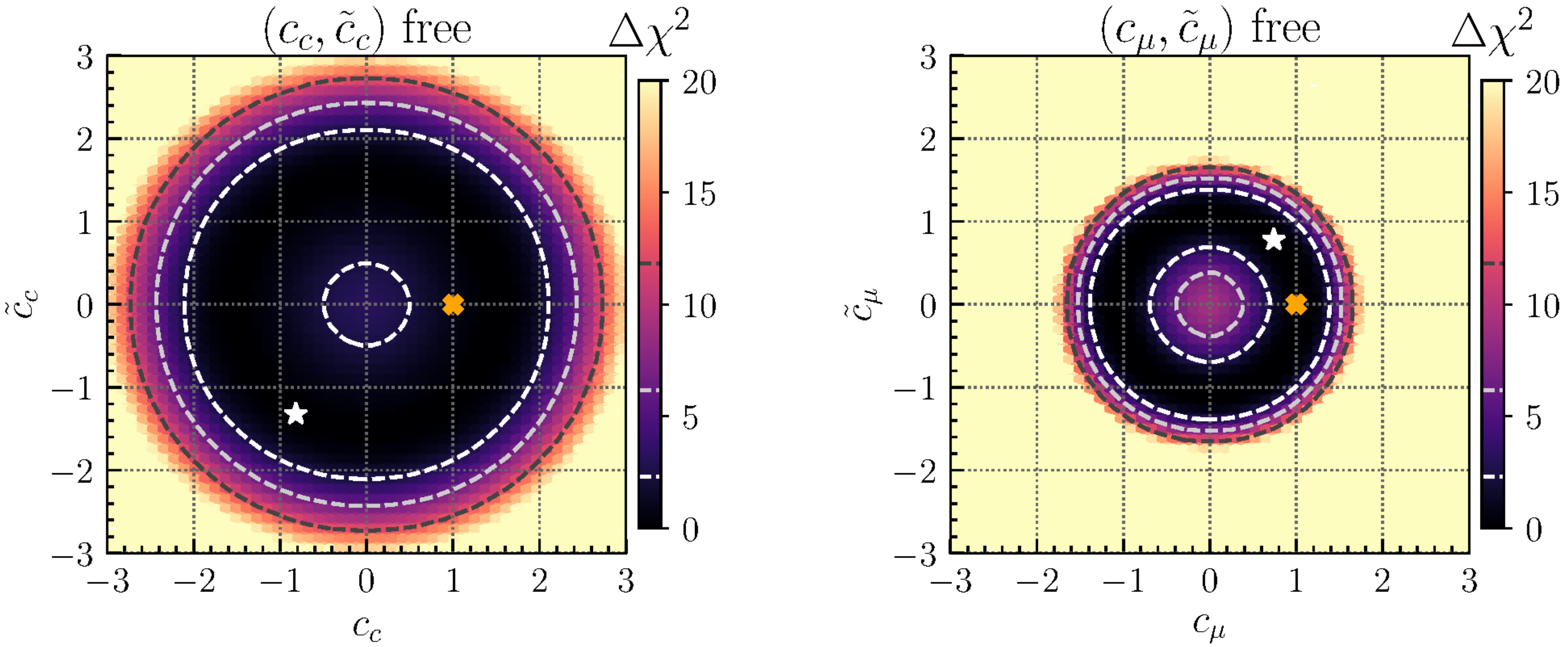
Backup: The LHC

The Large Hadron Collider (LHC)

- Worlds largest accelerator with a length of 27km
- Proton-proton (pp) collider
- CMS energies up to 14 TeV
- Multiple experiments: ATLAS, CMS, ALICE, LHCb …



Backup: Additional results



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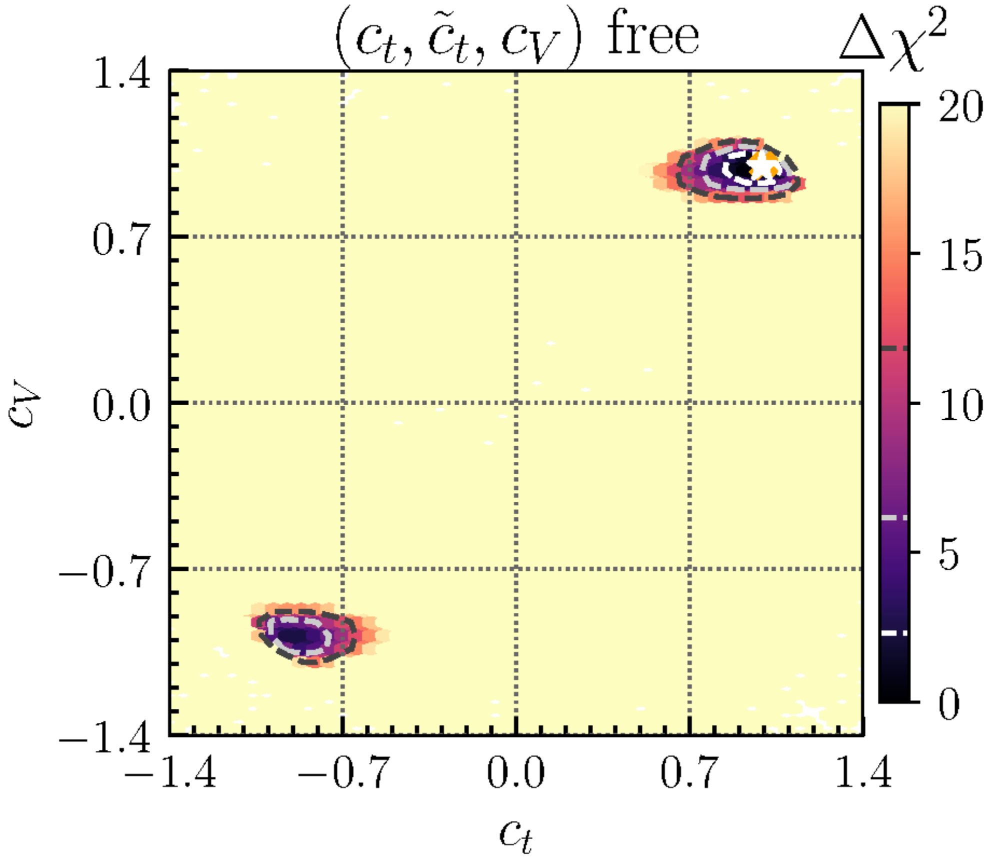

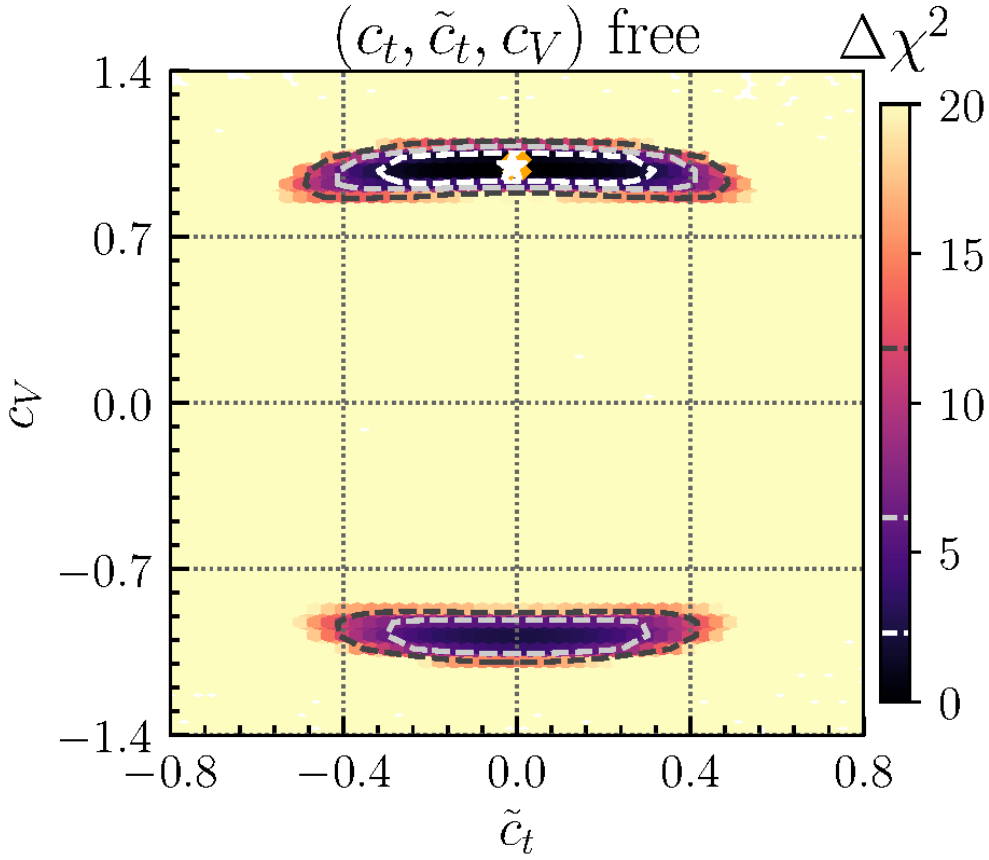

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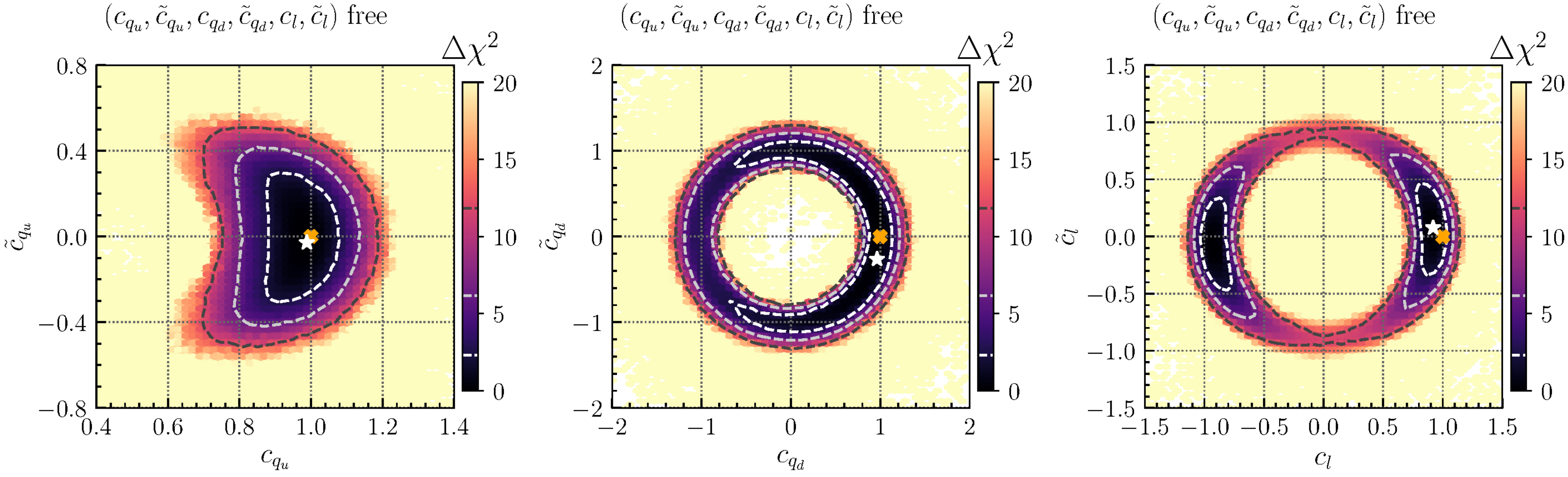

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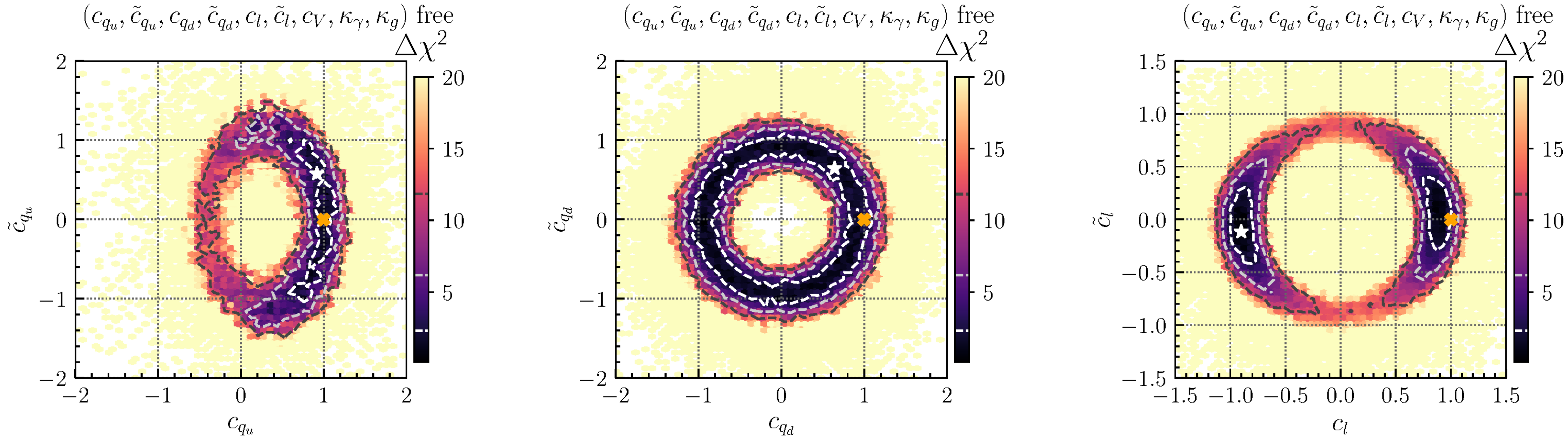

Backup: Additional results