Probes of CP-violating Higgs couplings and their impact on baryogenesis

Marco Menen (Leibniz University Hanover / PTB Braunschweig)

24.05.2023

Based on: Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein [2202.11753]

And: Bahl, Fuchs, Hannig, MM (in preparation)

Leibniz Universität Hannover

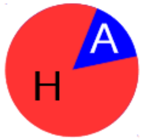
PTB

LHCPhysics
Belgrade, 22 - 26 May 2023

QuantumFrontiers
Cluster of Excellence

Outline & Motivation

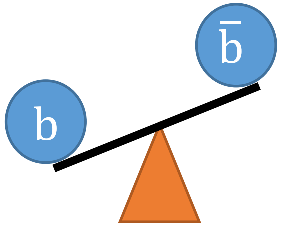
The road so far:



- CP structure of the discovered Higgs boson still subject of investigation
- Most stringent constraints on CP violation for the HVV couplings ATLAS ´21, ATLAS ´22
- CP Yukawa couplings comparably unconstrained $\left(\alpha \lesssim 45^{\circ} @ 95\% \,\mathrm{C.L.}\right)$ CMS ´21

Importance of CP violation:

- BSM CP violation needed to explain observed baryon asymmetry of the universe



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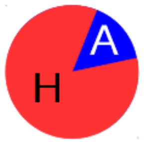

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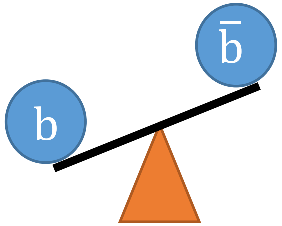

- Genuine CP-odd observables
- Total rate information
- Kinematic distributions

→ High-energy physics

- Electric dipole moments

→ Low-energy physics

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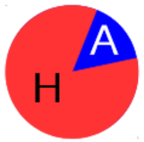

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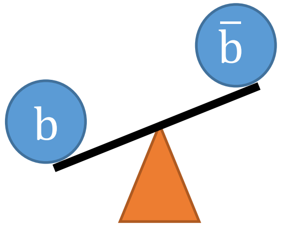
Part I



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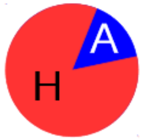

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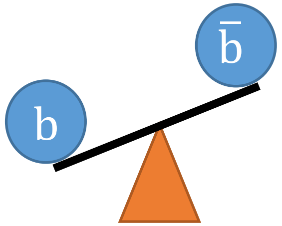
Part II



- Genuine CP-odd observables
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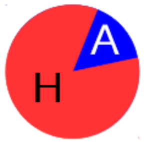
BSM framework

Part I

Free parameters:

- "Higgs characterisation model": Higgs H assumed to be mixed CP state
- Yukawa coupling: $\mathcal{L}_{\text{Yuk}} = -\sum_f \frac{g_f}{\sqrt{2}} \bar{\psi}_f \left(c_f + i\gamma_5 \tilde{c}_f \right) \psi_f \phi$
- SM obtained for $c_f = 1, \tilde{c}_f = 0$
- Effective couplings for Hgg and $H\gamma\gamma$ possible (Part II)

Artoisenet et al. ´13



Effects on signal rates:

- Higgs decay into fermions: $\mu_{Hff} = \frac{\Gamma(\phi \to f\bar{f})}{\Gamma^{SM}(H^{SM} \to f\bar{f})} \sim c_f^2 + \tilde{c}_f^2$
- Higgs-top coupling mainly constrained by μ_{ggH} and $\mu_{H\gamma\gamma}$ Bahl et al. ´20

Constraints from LHC data

Part I

Higgs rate measurements:

- HiggsSignals2 used for analysing rate measurements vs BSM models Bechtle et al. ´20
- Data: Combined Run 1 measurement, 31 measurements from Run 2
- Additionally: Latest $H \to c\bar{c}$ and $H \to \mu\bar{\mu}$ measurements ..., CMS ´20, ATLAS ´22

Note: Code has been updated
to HiggsTools Bahl et al. ´22

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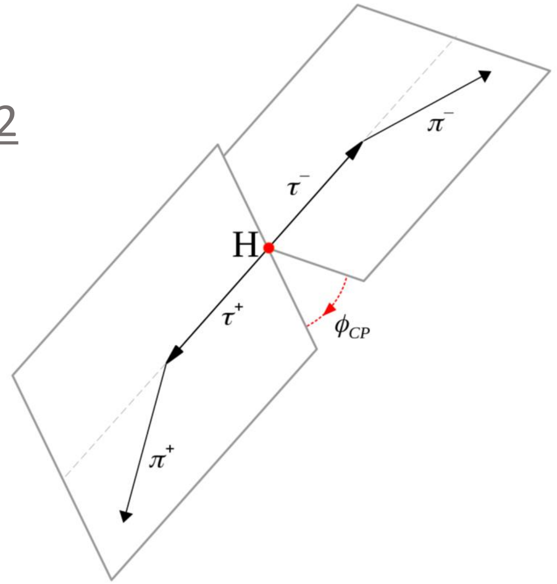
CP-odd measurements:

- Dedicated CP-analysis in $H \to \tau\bar{\tau}$ by CMS & ATLAS CMS ´21, ATLAS ´22
- Angular distribution of τ decay products as CP-odd observable



Kinematic distributions:

- Can be used to propose new observables (Part II)

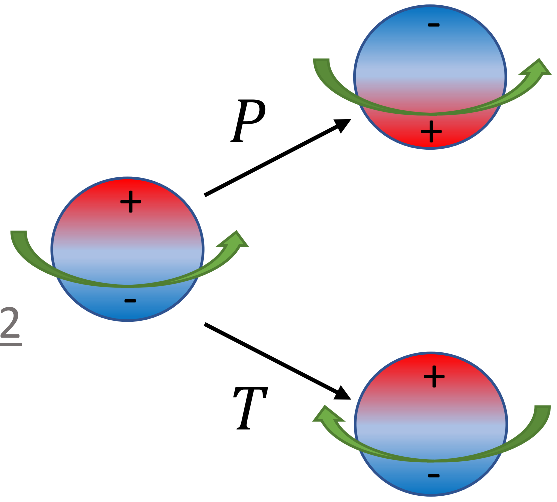
Electron Electric Dipole Moment (eEDM)

Part I

Testing BSM theories with EDMs

- BSM theories with additional CP violation predict large EDMs
- EDM measurements set complementary constraints

Review: Pospelov, Ritz ´05 See also: Brod et al. ´22



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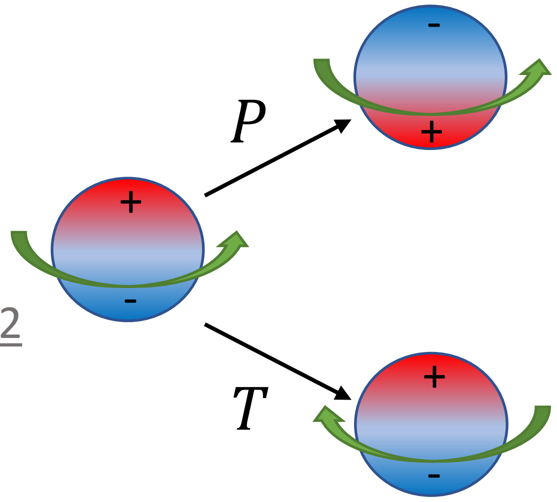

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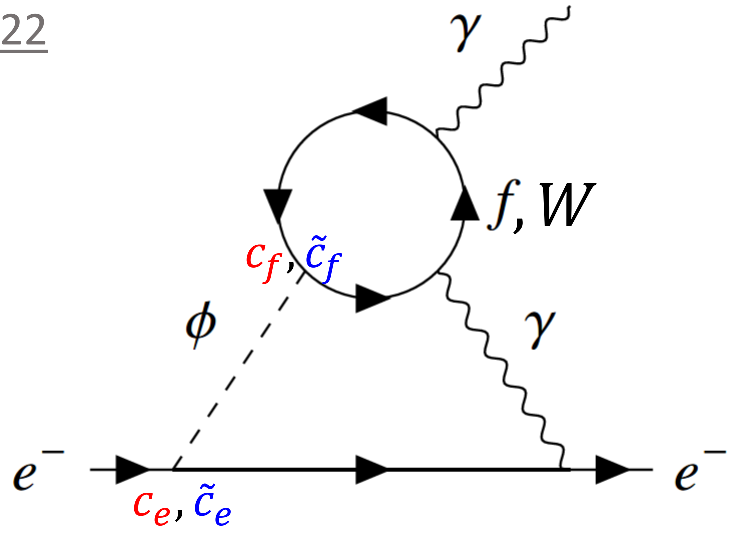
Impact of the eEDM:

- EDM with the lowest theoretical uncertainty
- Upper limit: $|d_e| < 1.1 \times 10^{-29}\, e$ cm (90% CL)
- Leading contribution from 2-loop Barr-Zee diagrams:

ACME ´18
Update (2022):
JILA ´22

$$\left|{d_e}/{d_e^{\mathrm{ACME}}}\right| = \boldsymbol{c_e}(\mathbf{870.0}\boldsymbol{\tilde{c}_t} + 3.9\tilde{c}_b + 3.4\tilde{c}_\tau + \cdots)$$
$$+\boldsymbol{\tilde{c}_e}(\mathbf{610.1}\boldsymbol{c_t} + 3.1c_b + 2.8c_\tau + \cdots - \mathbf{1082.6}\boldsymbol{c_V})$$

Brod et al. ´13, Altmannshofer et al. ´15,
Panico et al. ´18, Altmannshofer et al. ´20



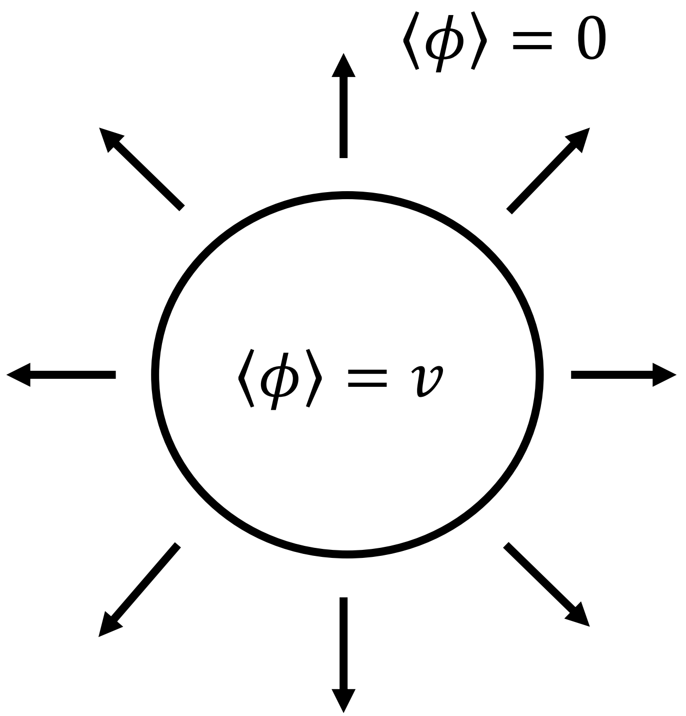
Electroweak baryogenesis (EWBG)

Part I

Process of baryogenesis:

- Expanding bubbles of broken symmetry start to form
- CP violation at bubble wall leads to baryon asymmetry in the broken phase

Reviews: Krauss et al. ´99, Cline ´06, Morrissey et al. ´12, Bödeker et al. ´20



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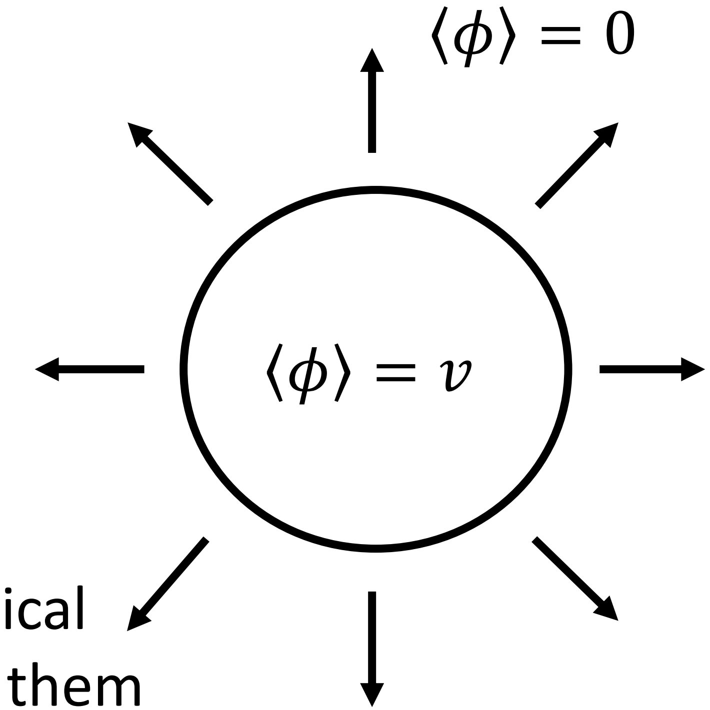


Current status:

Riotto ´98, Kainulainen et al. ´02

- Competing approches: perturbative (VIA) and semi-classical
- Large theoretical uncertainties and differences between them
- Choose most optimistic benchmark for upper limit of BAU: Cline, Laurent ´21, Postma et al. ´22

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

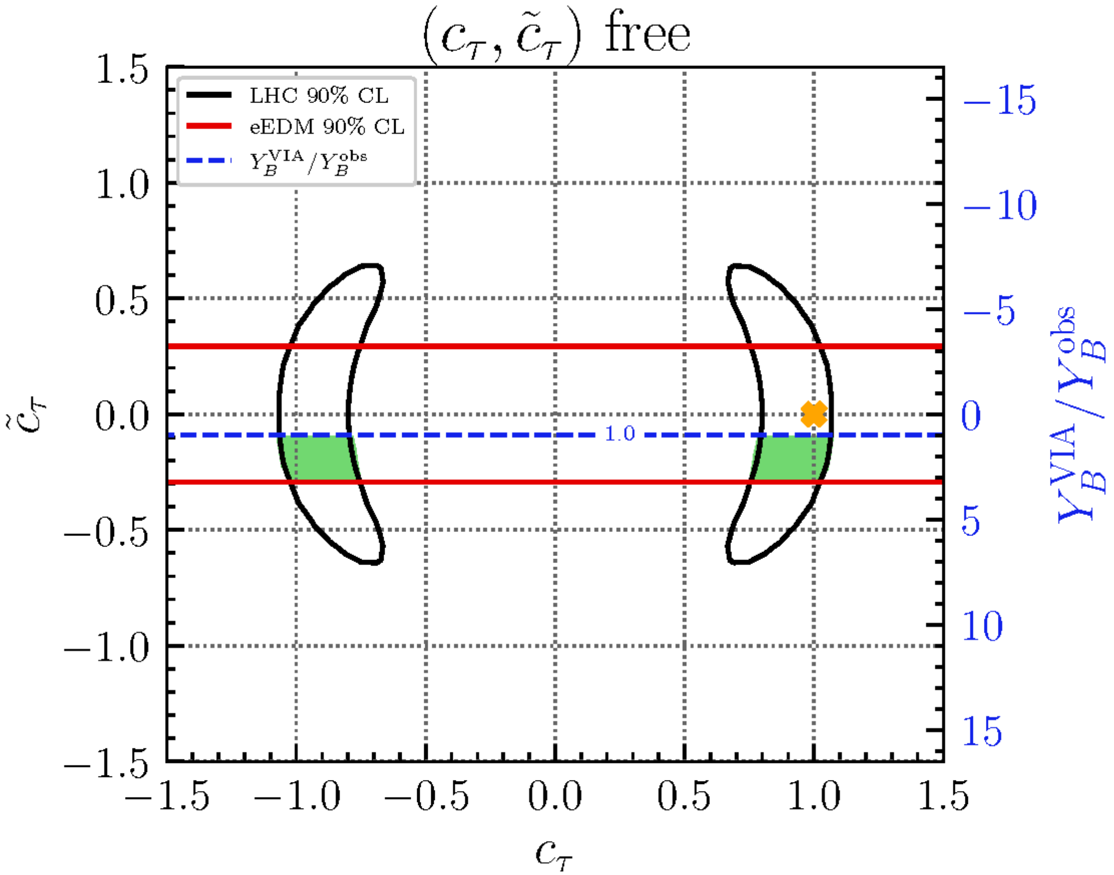
Fuchs et al. ´20, Shapira ´21

τ-Yukawa CP structure: LHC, eEDM, BAU

Part I

From: MM et al. ´22

Collider bounds dominated by $H \to \tau\tau$ CP-analysis



LHC 90% CL

τ-Yukawa coupling in earlier works: de Vries et al. ´17, Fuchs et al. ´20, Shapira ´21, Alonso-Gonzalez et al. ´21

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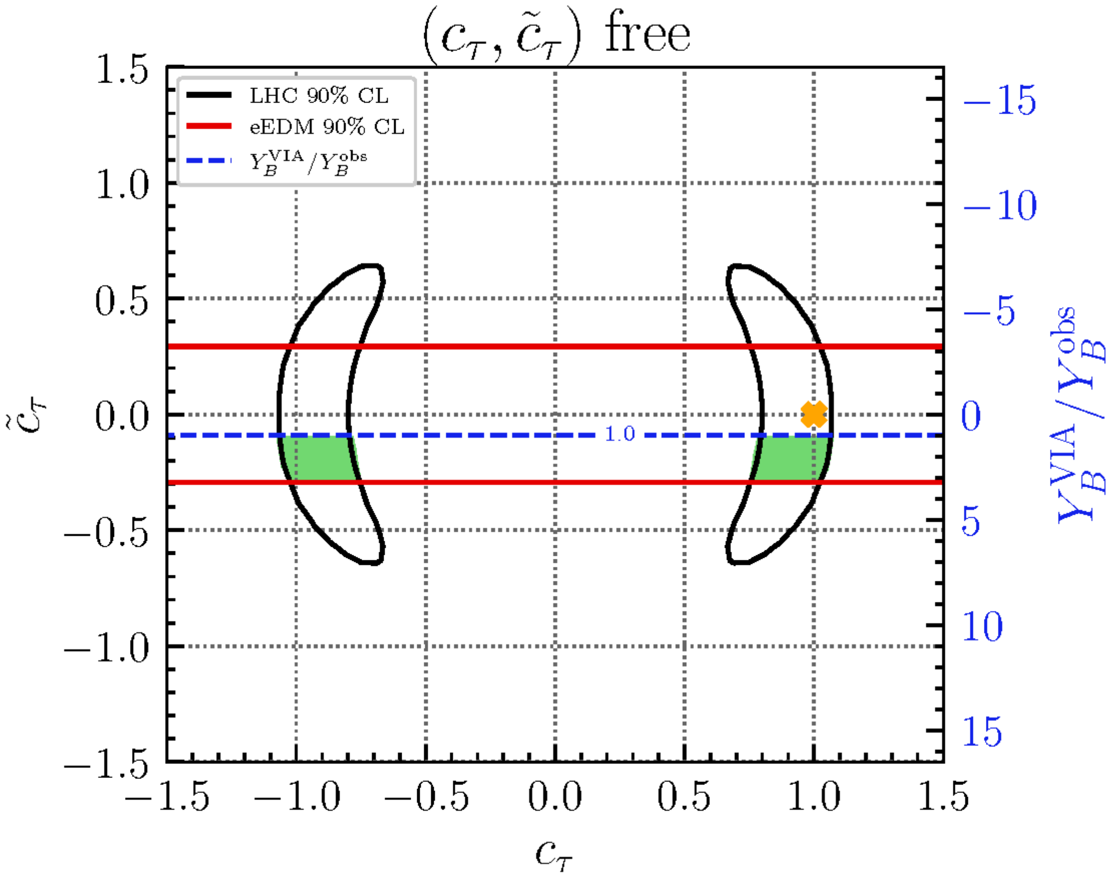

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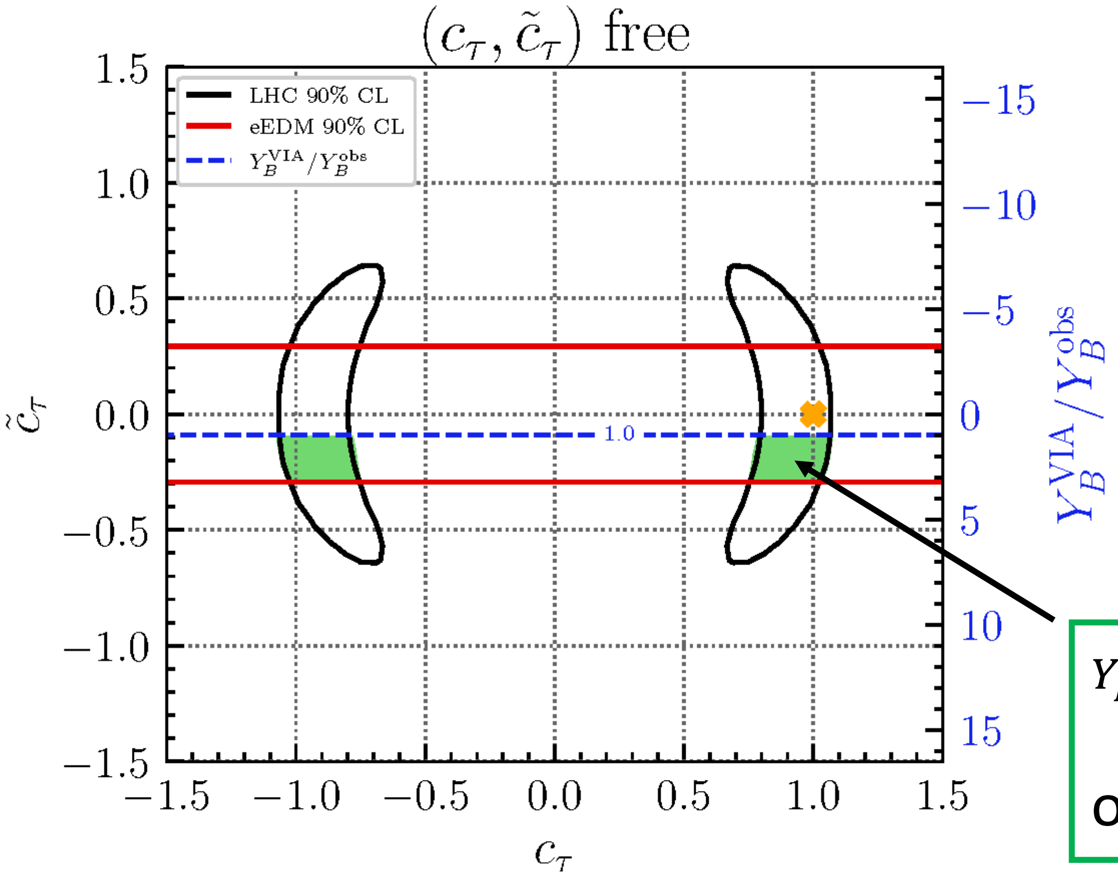

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$Y_B^{\mathrm{VIA}}/Y_B^{\mathrm{obs}}$

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

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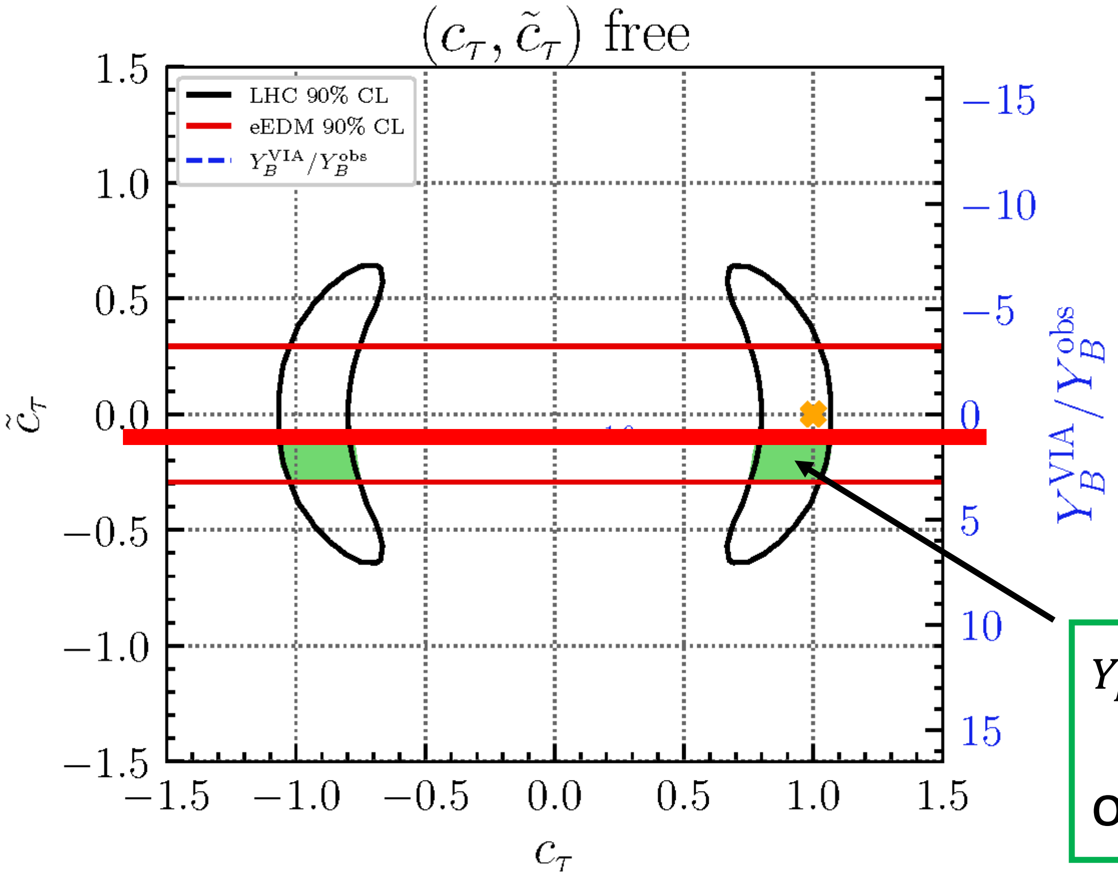

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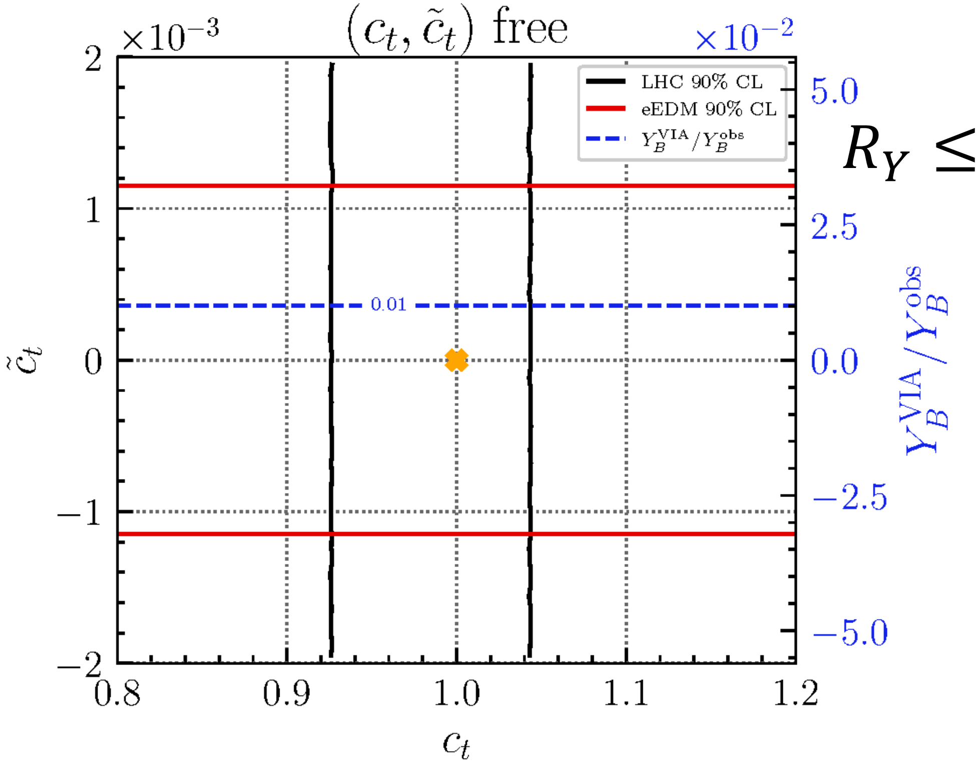
New eEDM limit: Option for τ as sole BAU source borderline

t-Yukawa CP structure: LHC, eEDM, BAU

Part I

From: MM et al. ´22



$R_Y \leq 3\%$

eEDM is limiting factor for CP-odd Yukawa

Only small amounts of Y_B realizable

t-Yukawa CP structure: LHC, eEDM, BAU

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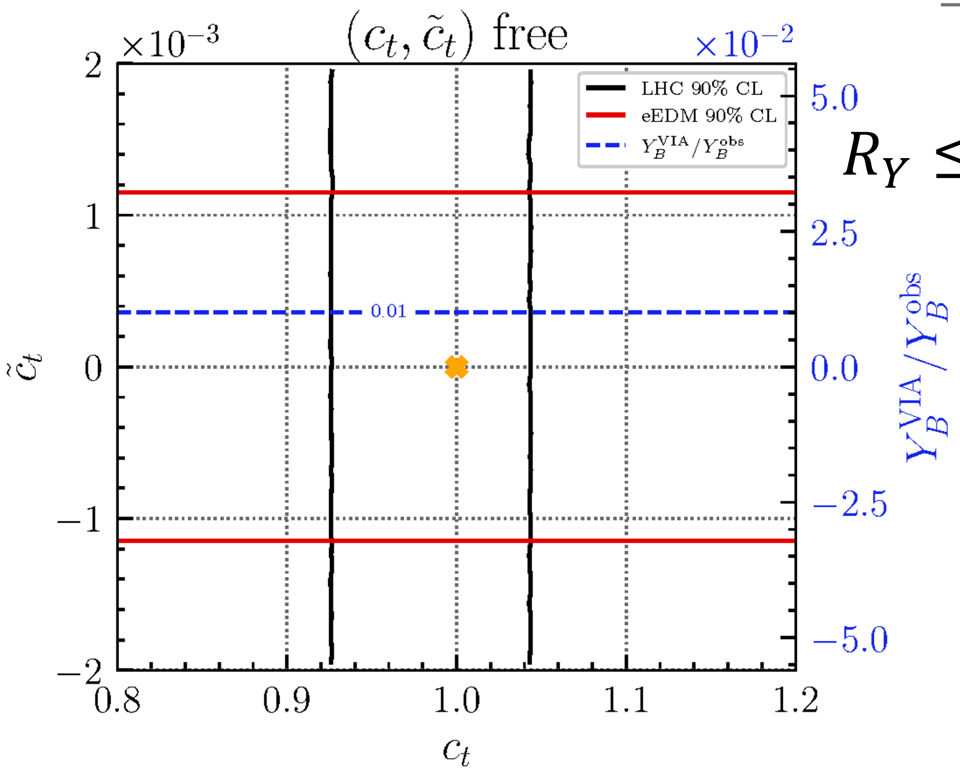

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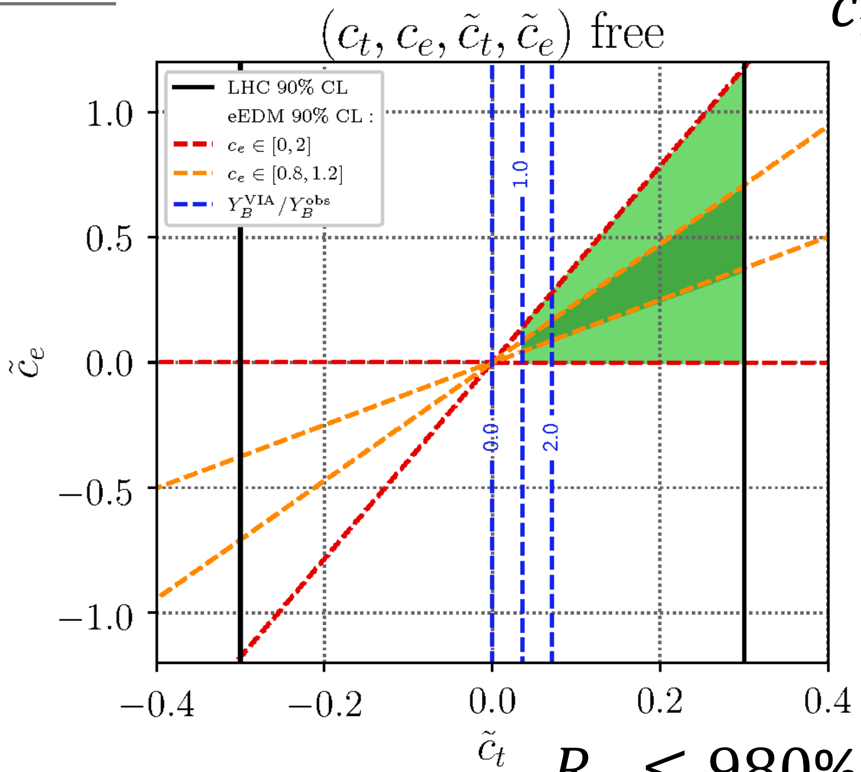


$c_t \in [0.86, 1.04]$

$c_e \in [0.8, 1.2]$

$c_e \in [0, 2]$

$R_Y \leq 980\%$

eEDM is limiting factor for CP-odd Yukawa

Only small amounts of Y_B realizable

Free e-Yukawa coupling: Bounds from eEDM completely vanish

CP observables from boosted classifiers

General strategy:

Based on: Bhardwaj et al. ´21 (CPV in HVV couplings)

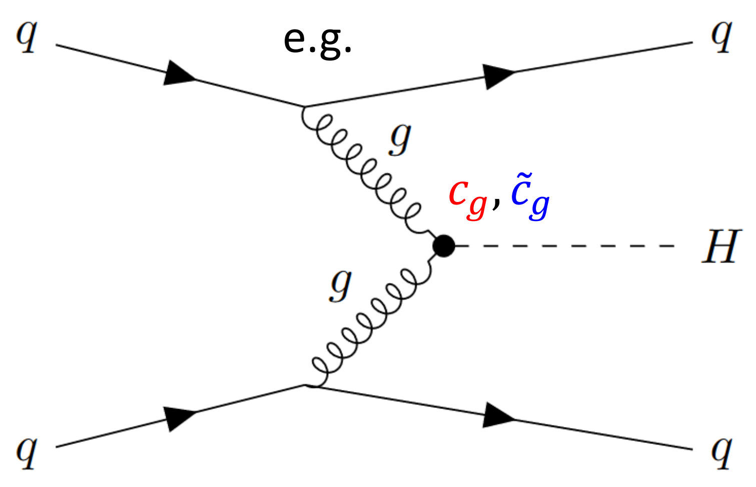
- Exploit full kinematic information by using boosted classifiers
- Identify observables with most sensitivity to CP violation
- Goals: Experimental analysis with found observable / extend STXS binning

Our approach:

Bahl, Fuchs, Hannig, MM (in preparation)

- Free effective Higgs-gluon coupling $c_g, \tilde{c}_g$
- Train on $c_g^2, \tilde{c}_g^2$ and interference events in ggF + 2 jets
- Compare classifiers to traditional CP observable $\Delta\phi_{jj}$

ATLAS ´21



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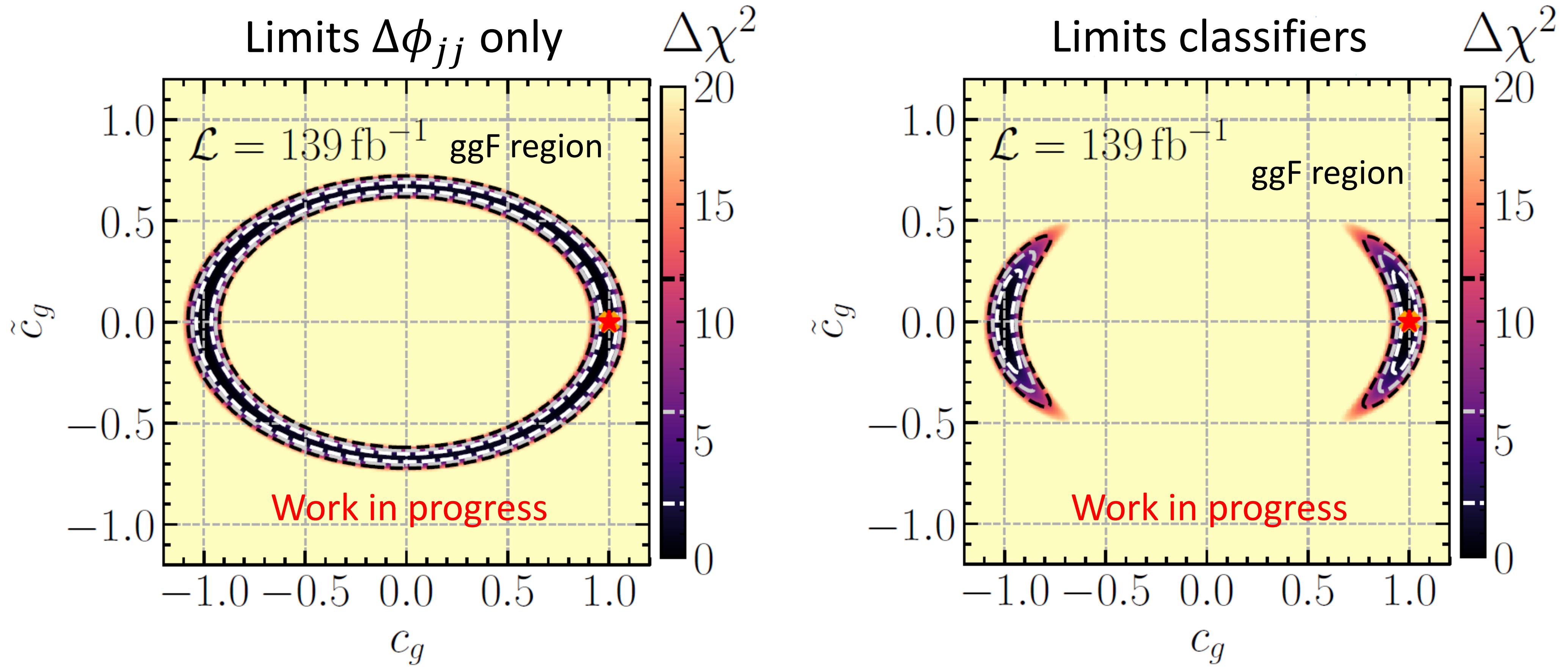


- Can constrain $\tilde{c}_g \in [-0.25, 0.25]$ @ 68% C. L. $\Rightarrow$ $\tilde{c}_t \in [-0.25, 0.25]$
- Best existing limit: $\tilde{c}_t \in [-0.4, 0.4]$ (in VBF-like region + ttH) CMS '21

Conclusions

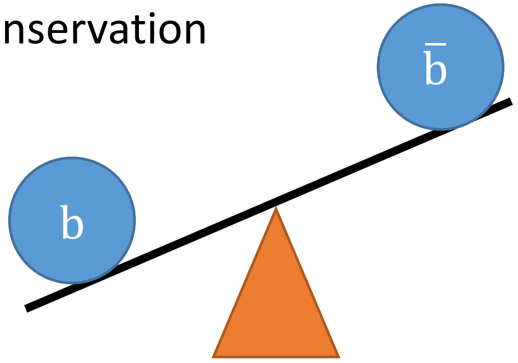
- LHC can probe CP structures of individual Higgs couplings
- Potential of τ to be sole and viable EWBG source reduced to marginal coupling range by latest eEDM results
- EDMs put strong constraints on CP-violating couplings, but the constraints can be lifted by cancellations
- Exploitation of full information needed (kinematics, channels, low-energy probes) $\rightarrow$ machine learning as powerful tool

More results: MM et al. ´22 [2202.11753]
+ stay tuned for upcoming study

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

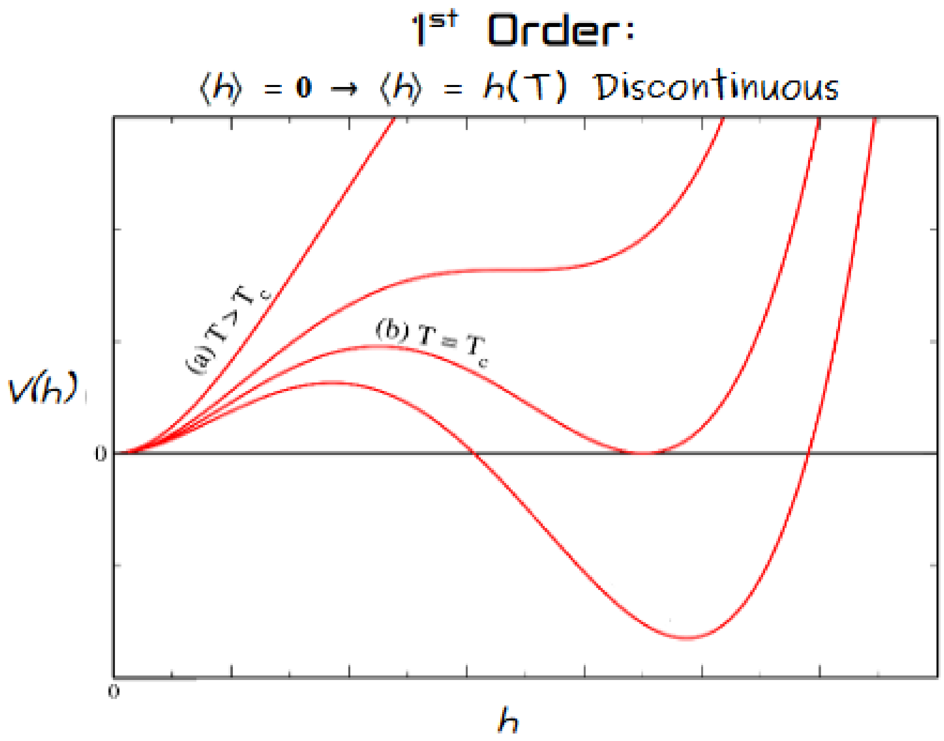
$< 10^{-10}$ of total BAU needed

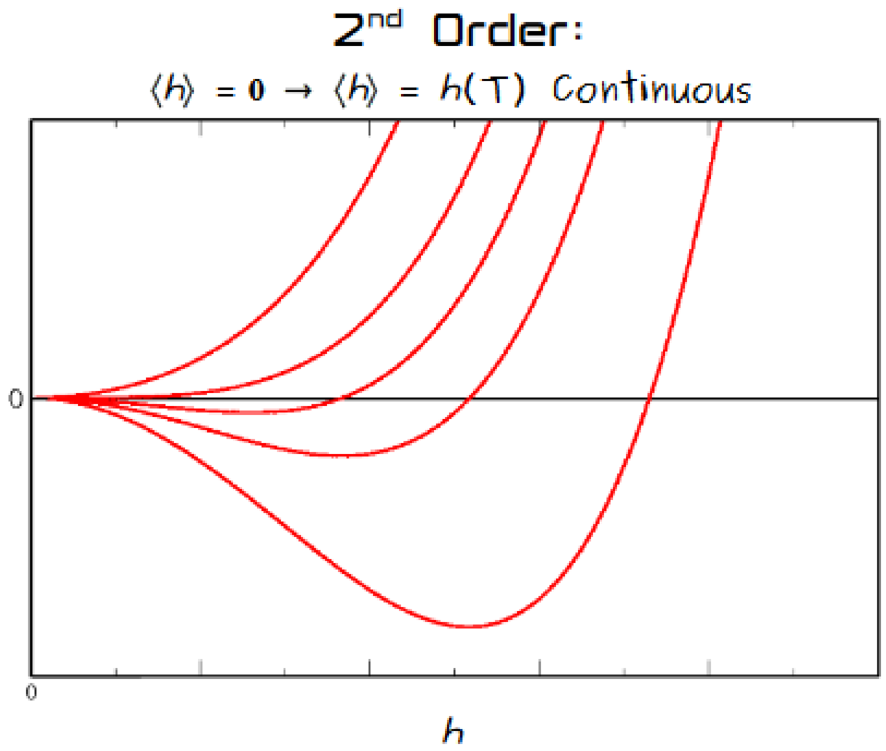
3. Deviation from thermal equilibrium

➢ Electroweak symmetry breaking (EWSB) has to be strongly first order, unfulfilled for $m_H = 125$ GeV

$m_H < 80$ GeV needed

Backup: EWSB Transition





Talk at CLIC from Jose Miguel No

Backup: SMEFT

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

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

e.g.

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: Higgs Characterization Model

1306.6464

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

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

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

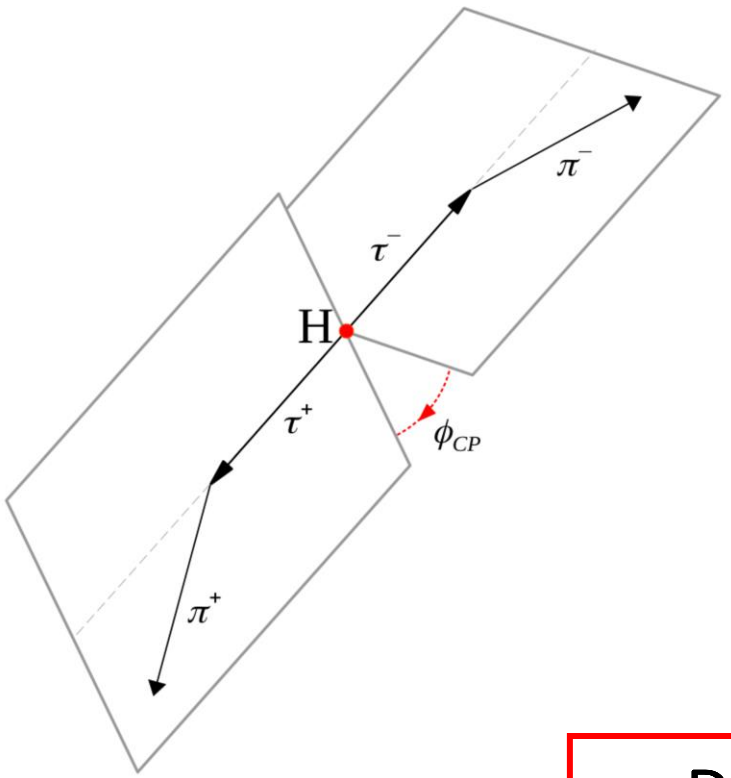
- Analogeously for associated production modes (ggZh, ttH, tH, tWH)

2007.08542

Backup: τ-Yukawa CP analysis

Dedicated CP analysis by CMS and ATLAS:

2110.04836, 2212.05833



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

Angle between τ decay planes: ϕ_{CP}

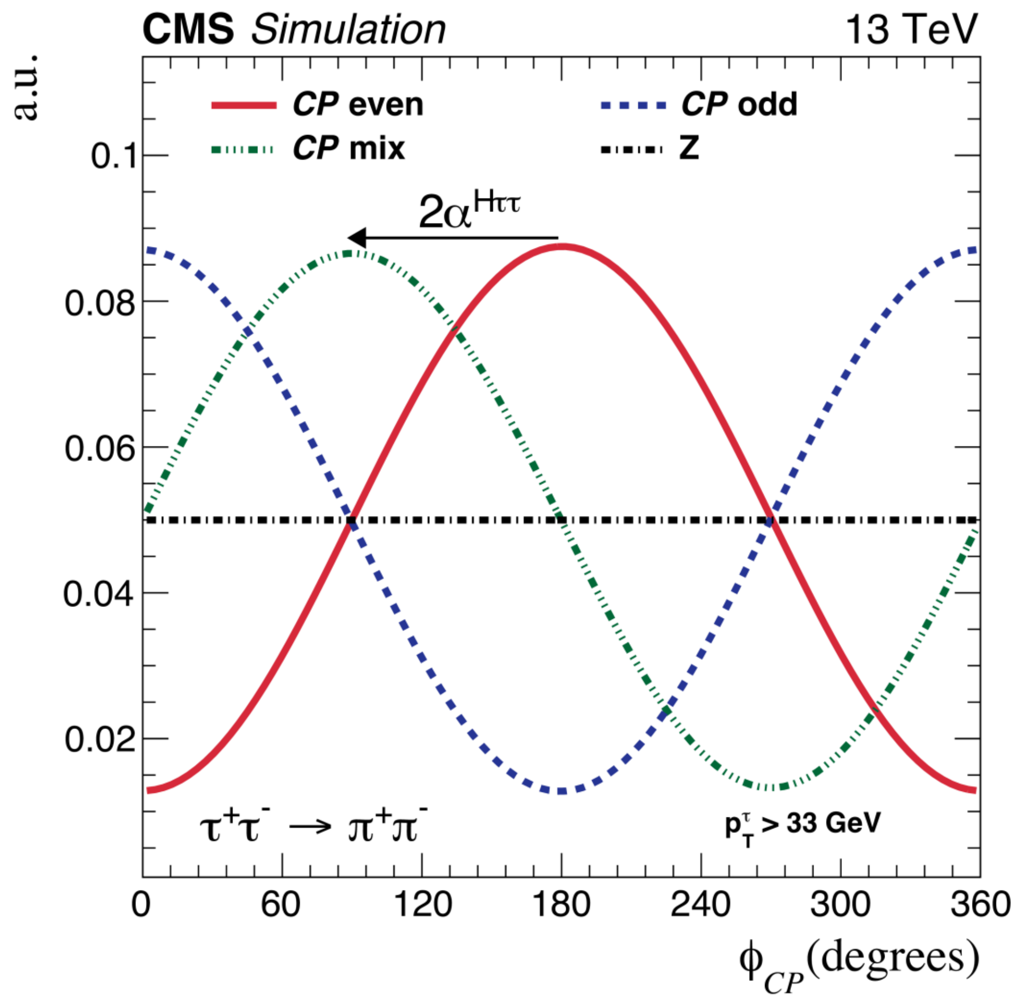
$$d\Gamma(H \to \tau^+\tau^-) \sim 1 - \cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$

1410.6362

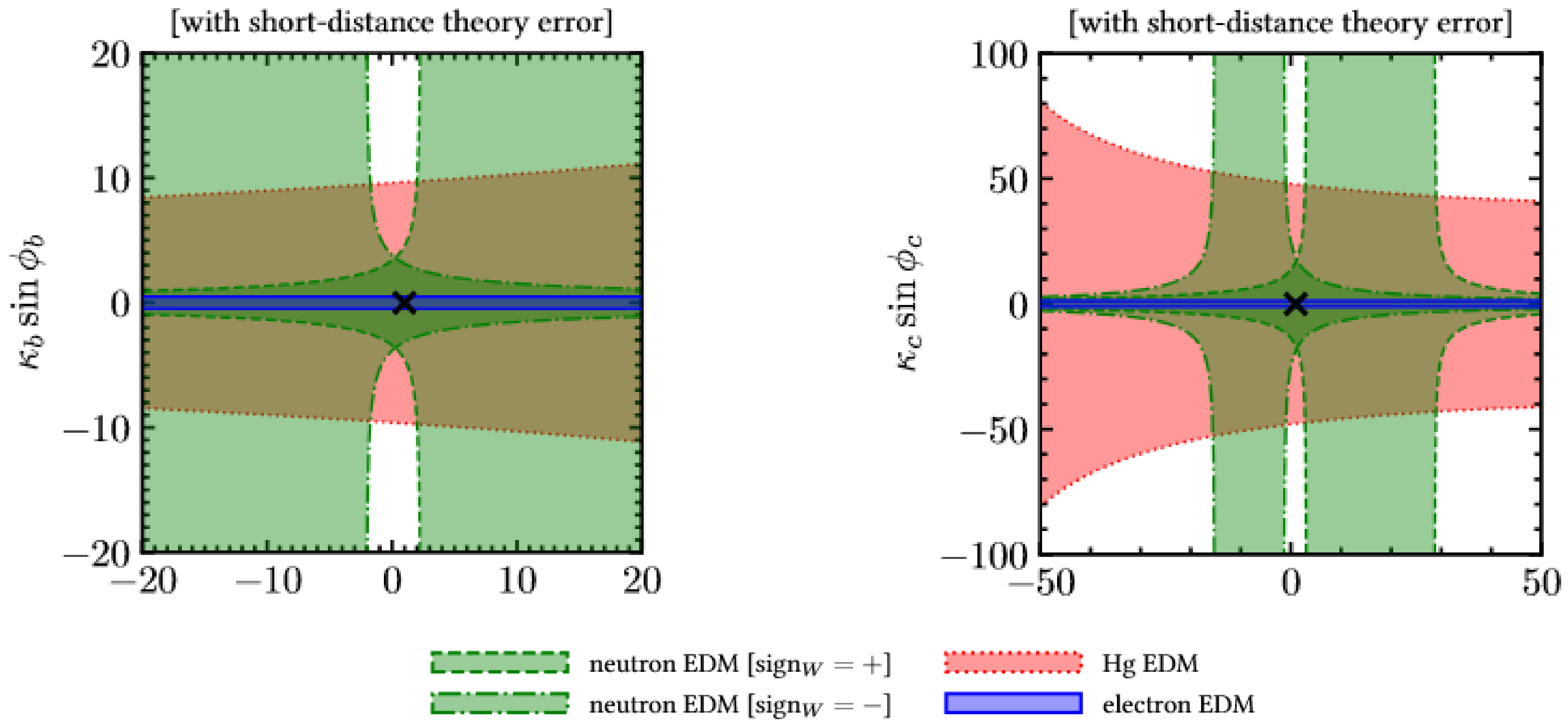
→ Direct CP constraints

Backup: τ-Yukawa CP analysis

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



Backup: EDM contributions



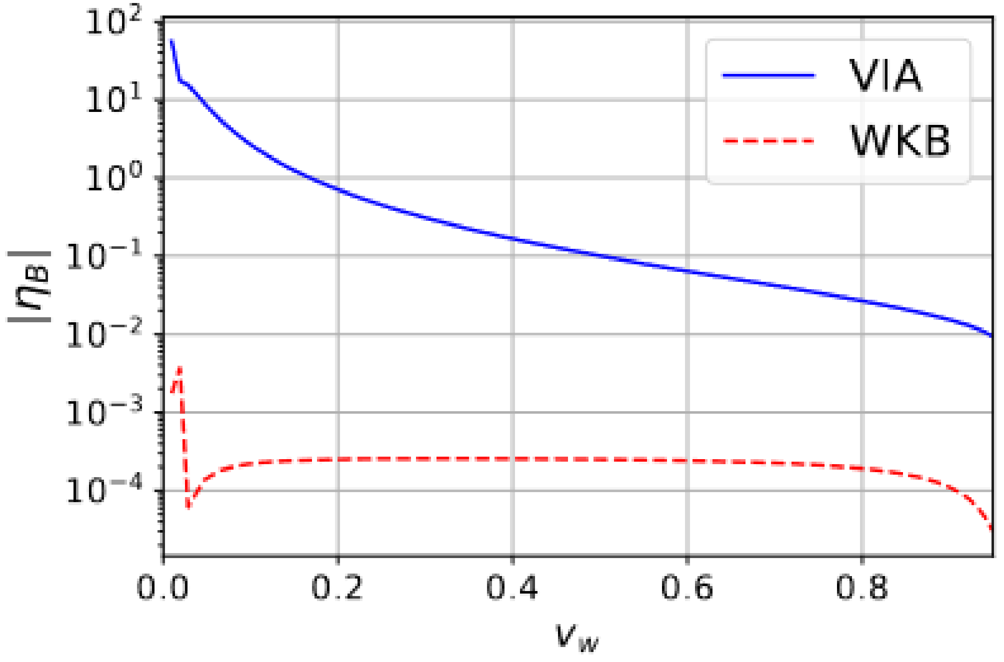
Brod, Stamou ´18

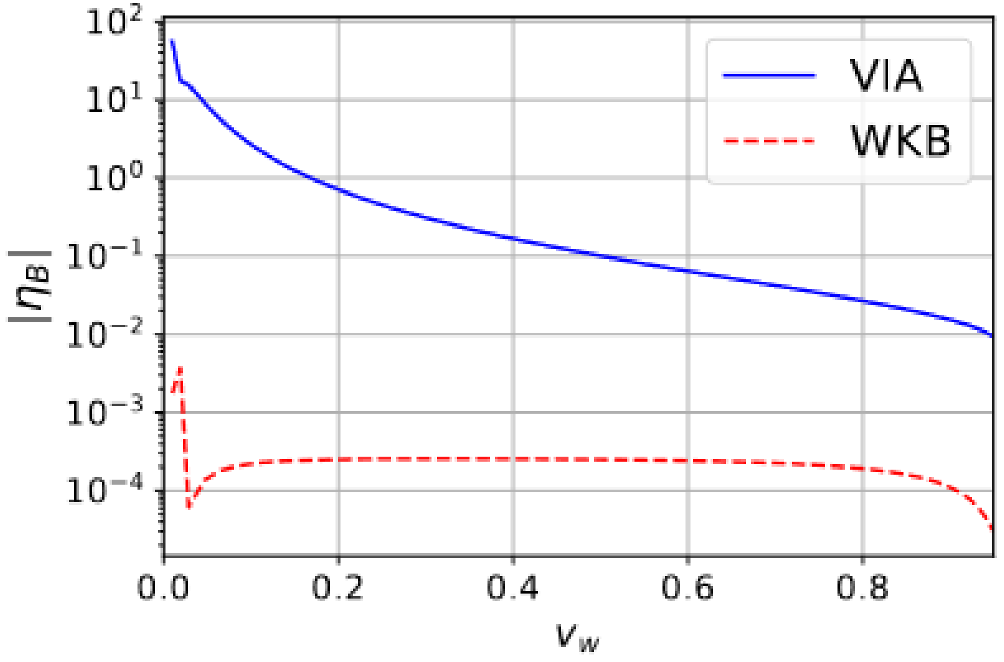
Backup: Baryogenesis

- 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: VIA vs. WKB

2108.04249





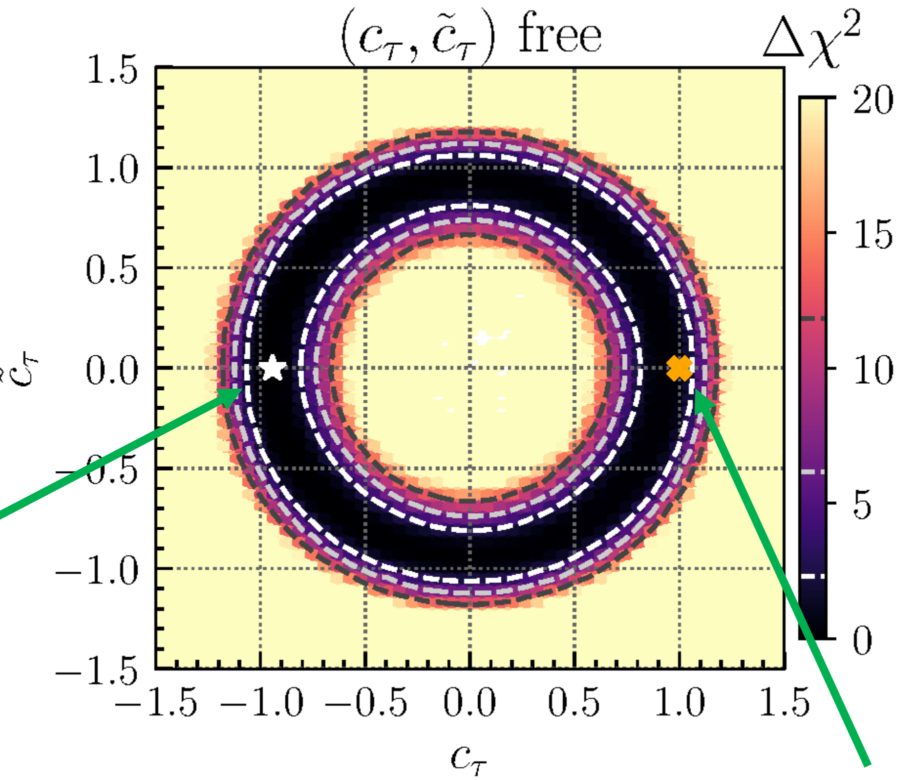
CP violating source terms vanishes in VIA at first order

Effects at higher orders currently under investigation Postma et al. ´22

τ-Yukawa CP structure: LHC constraints

[Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)]

Global signal rate fit with HiggsSignals:



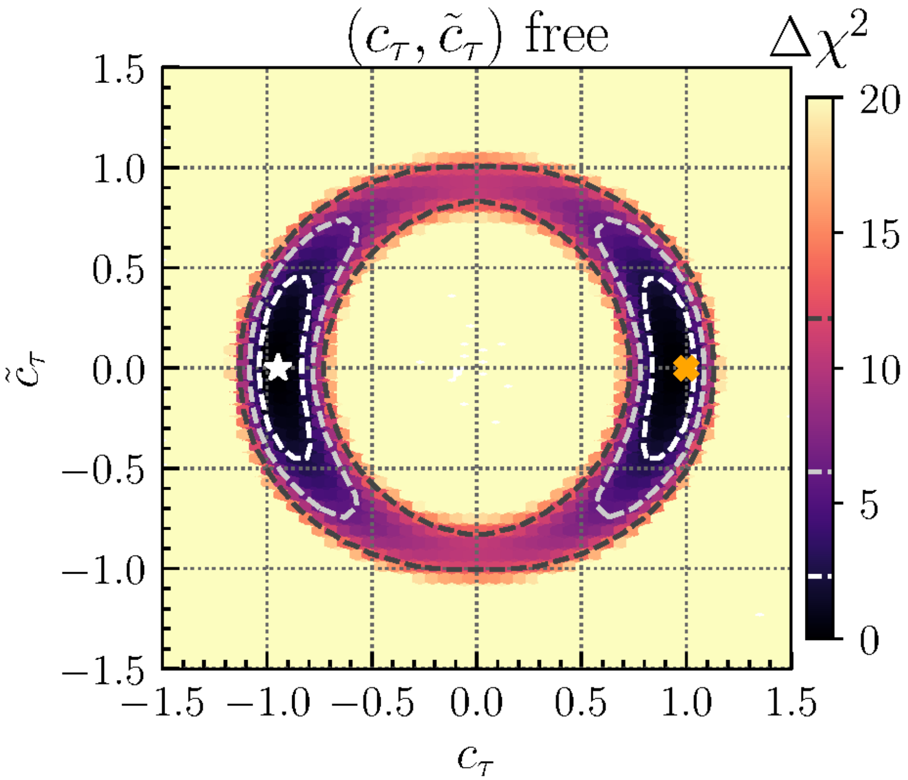
Best-fit

SM

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

➢ circle

+ CMS CP analysis:

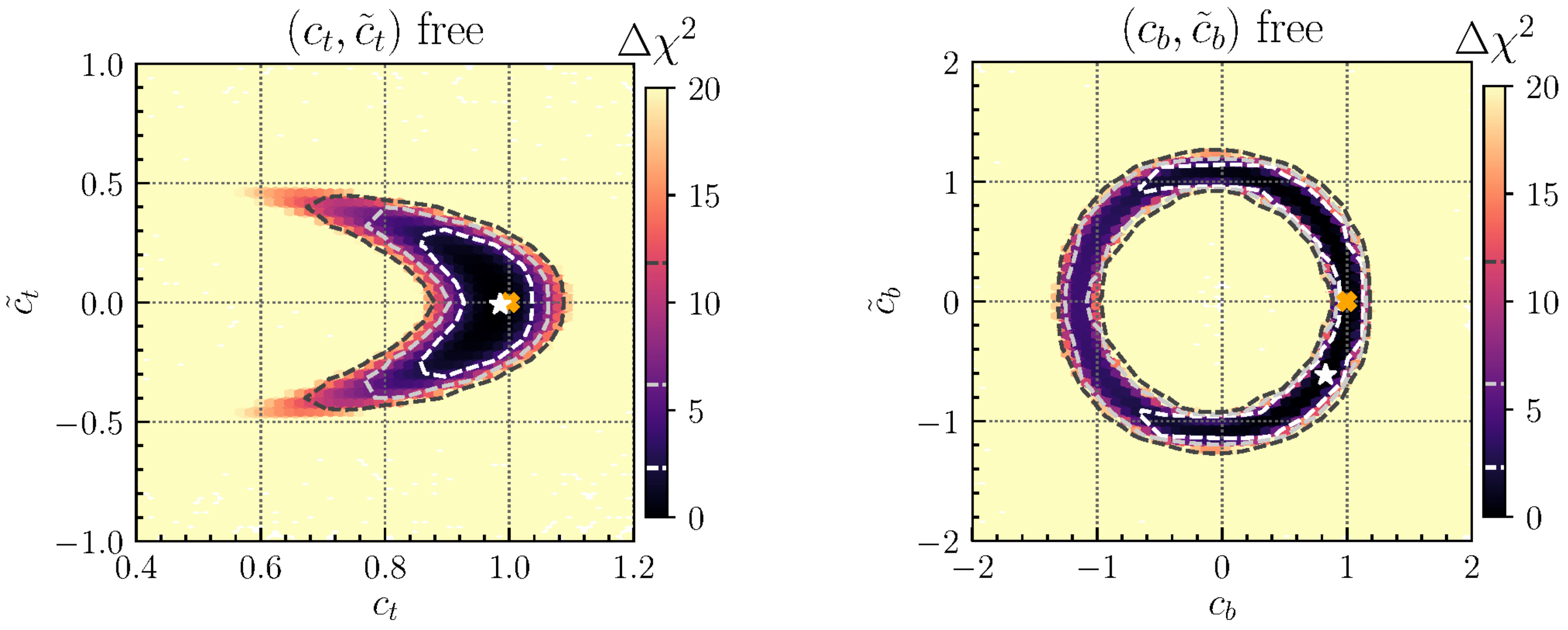


$$\alpha^{H\tau\tau} = \arctan\left(\frac{\tilde{c}_\tau}{c_\tau}\right) = (-1 \pm 19)^\circ \text{ at } 1\sigma$$

CMS ´21

t,b-Yukawa CP structure: LHC constraints

Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)



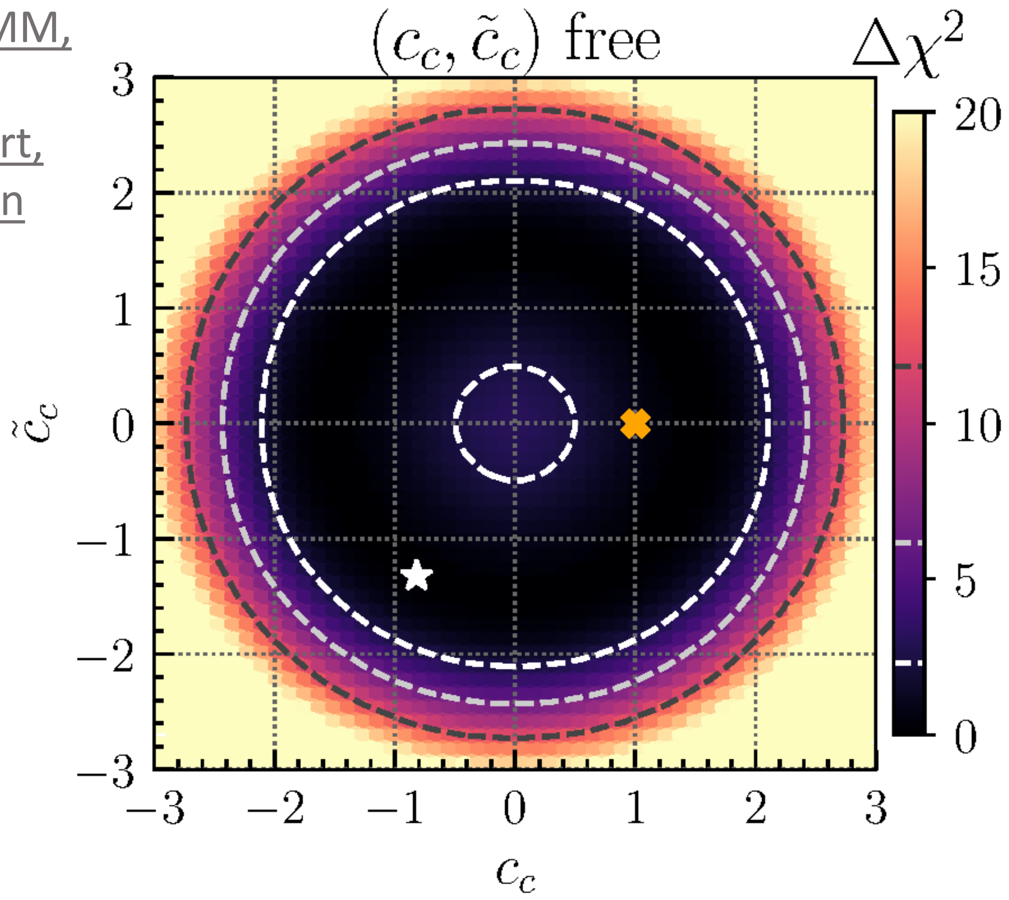
$\text{ggH} \propto 1.11 c_t^2 + 2.56 \tilde{c}_t^2$ → ellipsoid
$H\gamma\gamma \propto 1.62 c_V^2 - 0.71 c_V c_t$ → cut-off

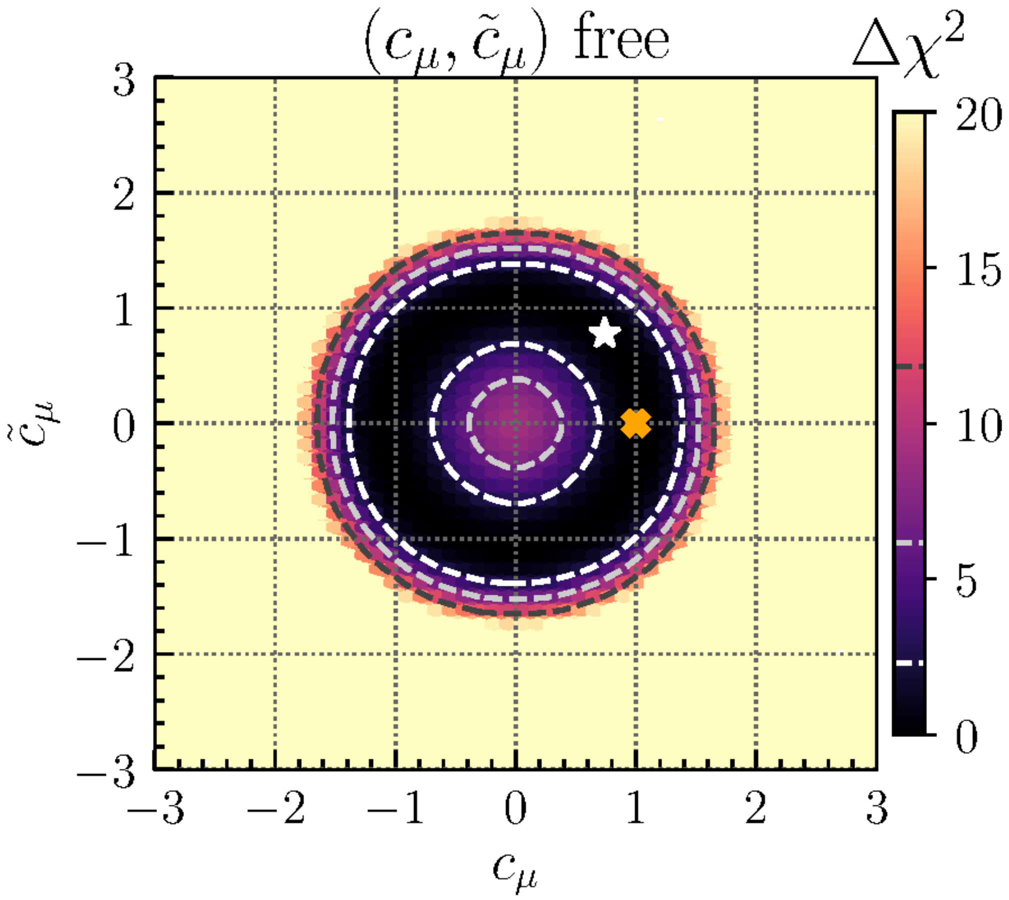
$H \to bb$: Ring
ggH: Small deformation

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

Backup: Additional results

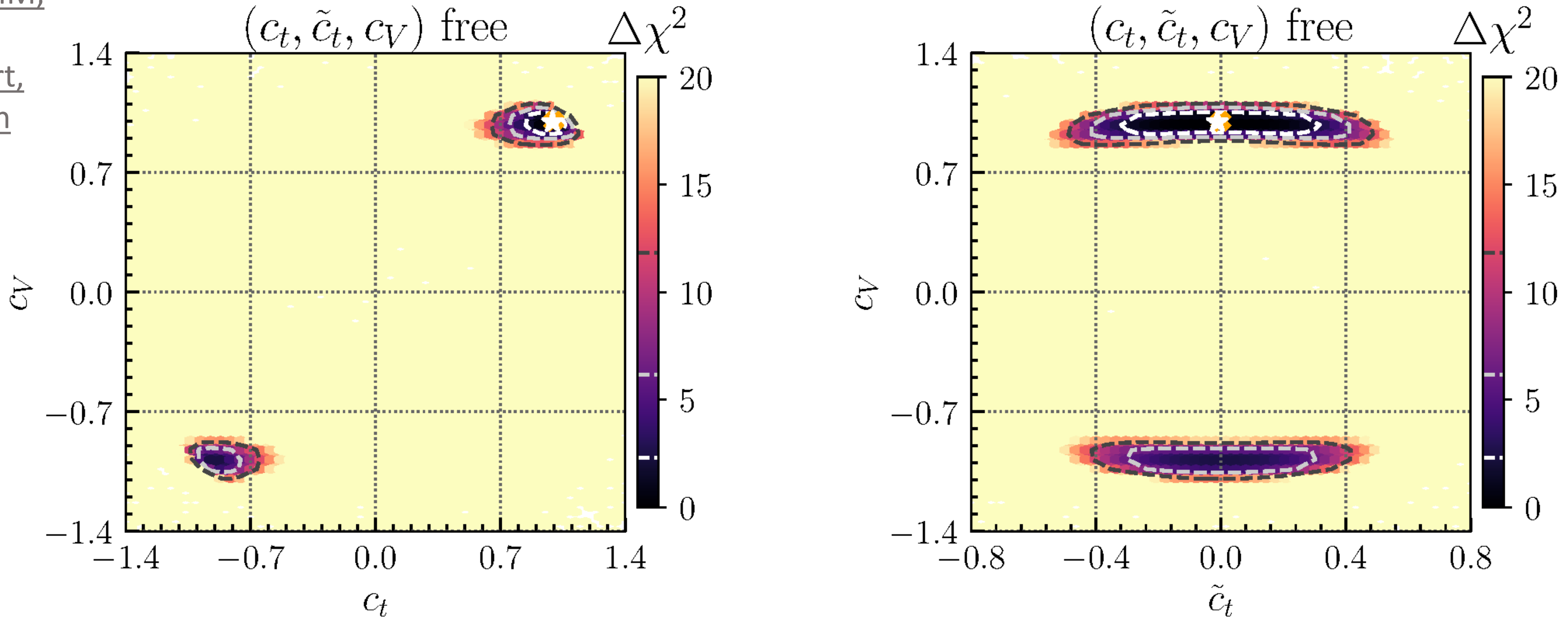
Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)



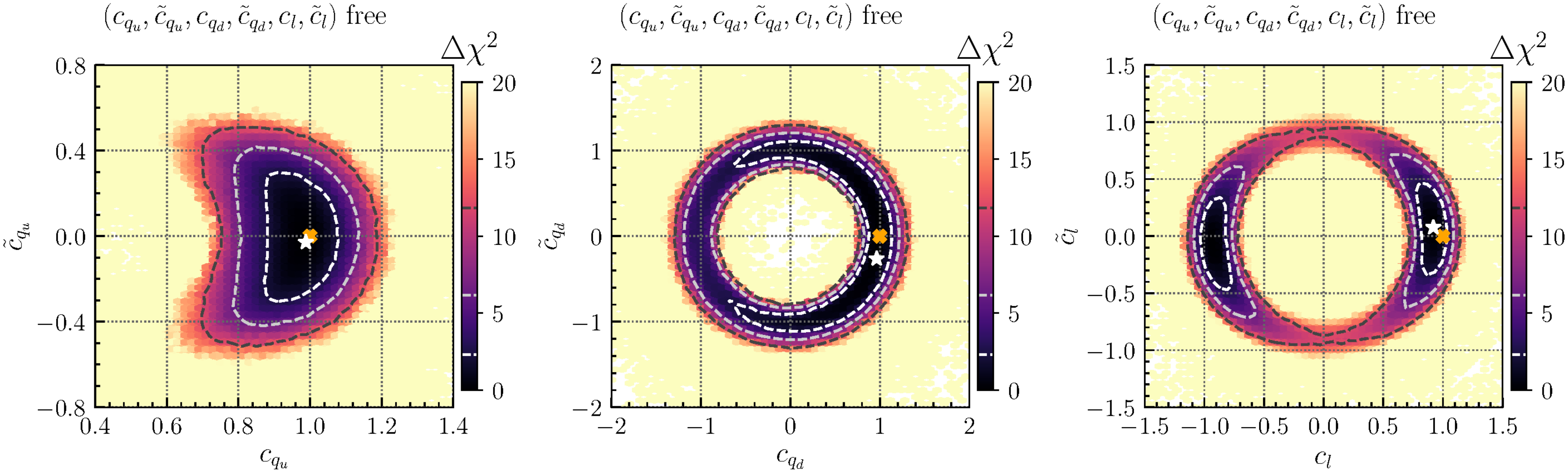


Backup: Additional results

Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)

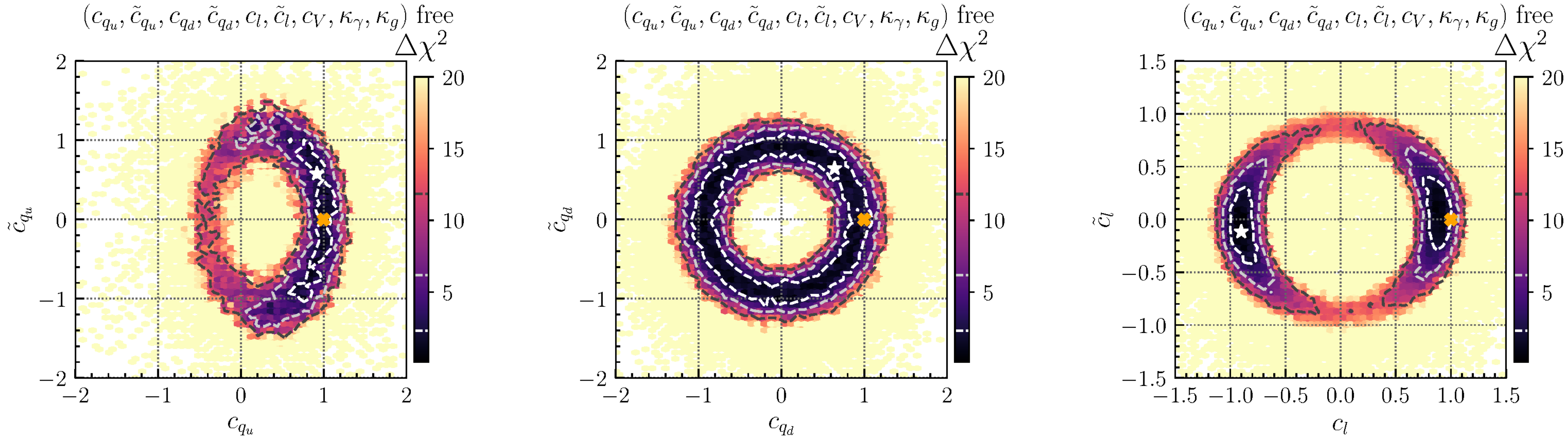


Backup: Additional results



Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)

Backup: Additional results



Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)

Backup: Additional results

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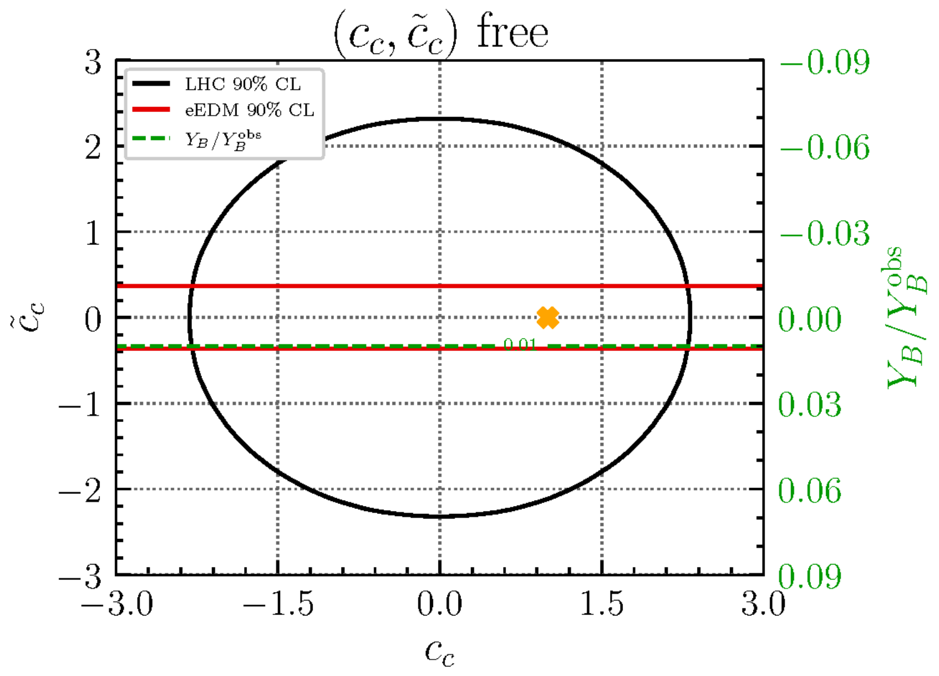
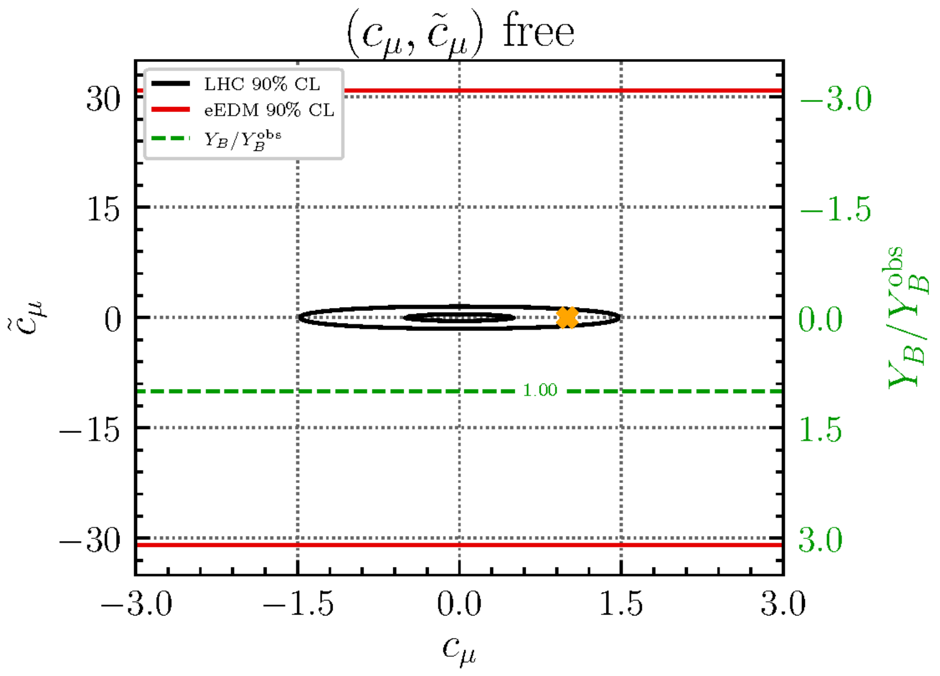
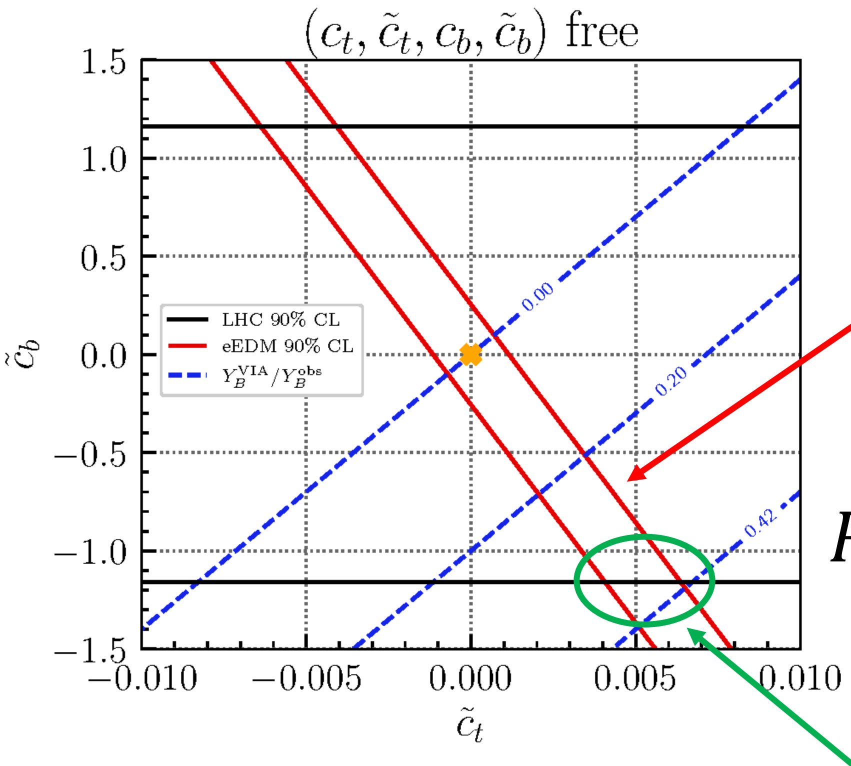




t & b complementarity

Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)



Cancellations possible:

$$\left|{}^{d_e}\!/_{d_e^{\rm ACME}}\right| \sim 870.0\tilde{c}_t + 3.9\tilde{c}_b$$

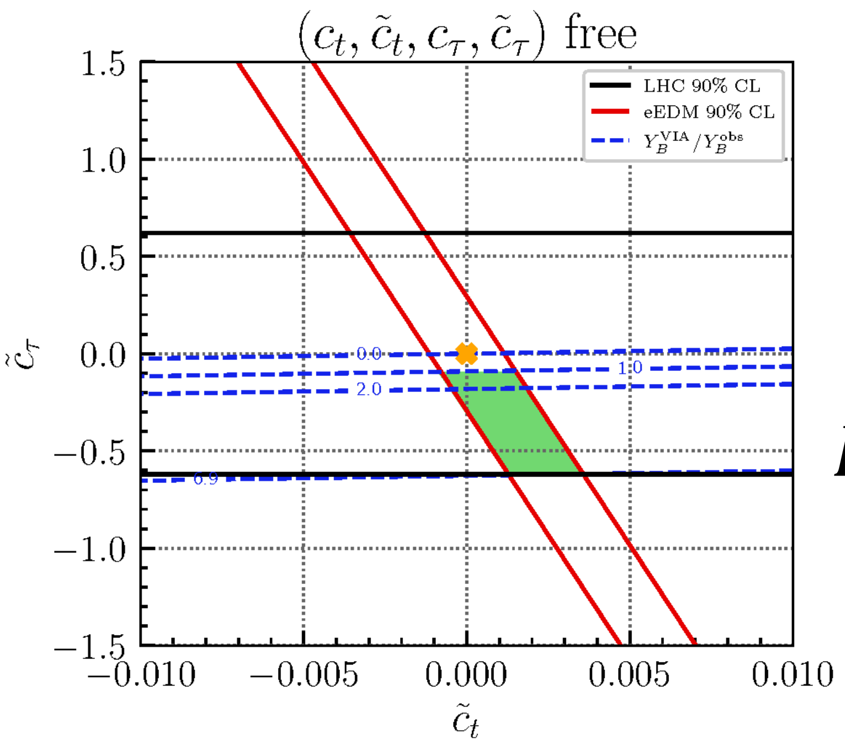
$R_Y \leq 42\%$

eEDM no longer limiting factor

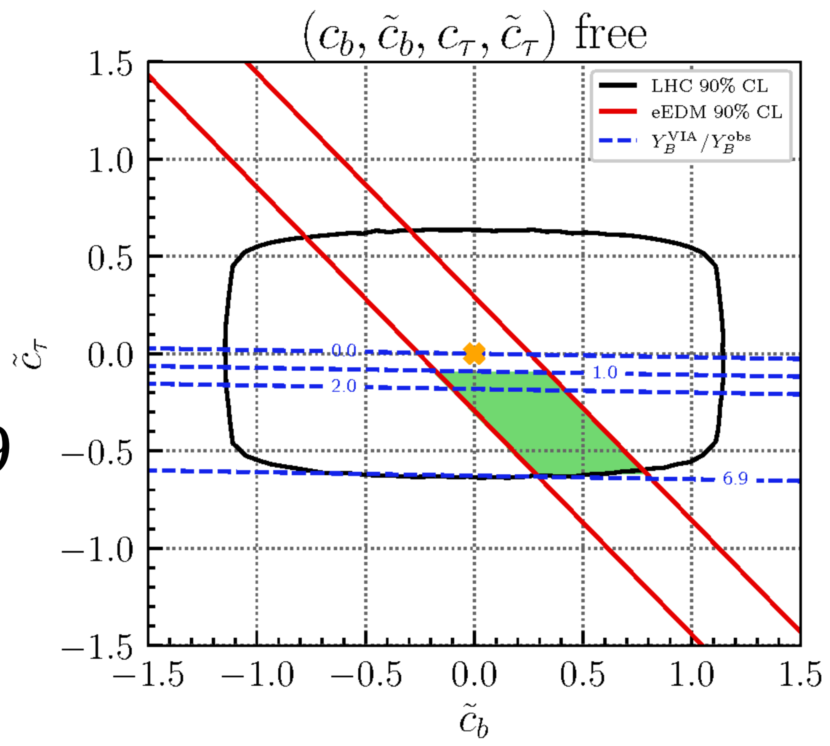
Fuchs, Losada, Nir, Viernik (2020) found $R_Y \leq 0.12$ for SM-like CP-even parameters

τ & t / τ & b complementarity

Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)



$R_Y \leq 6.9$

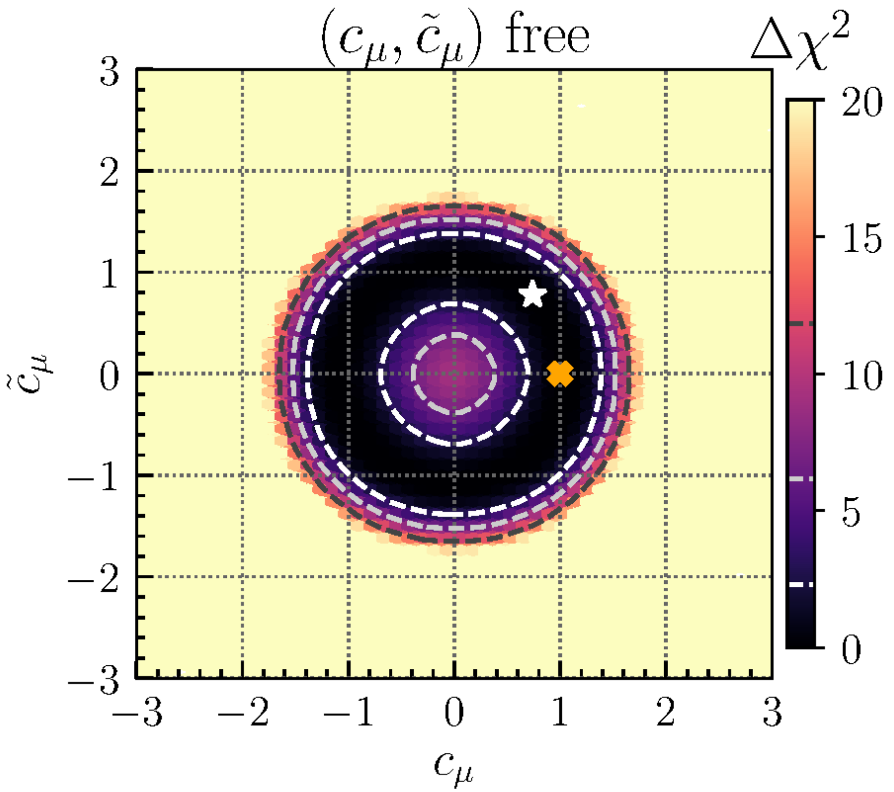


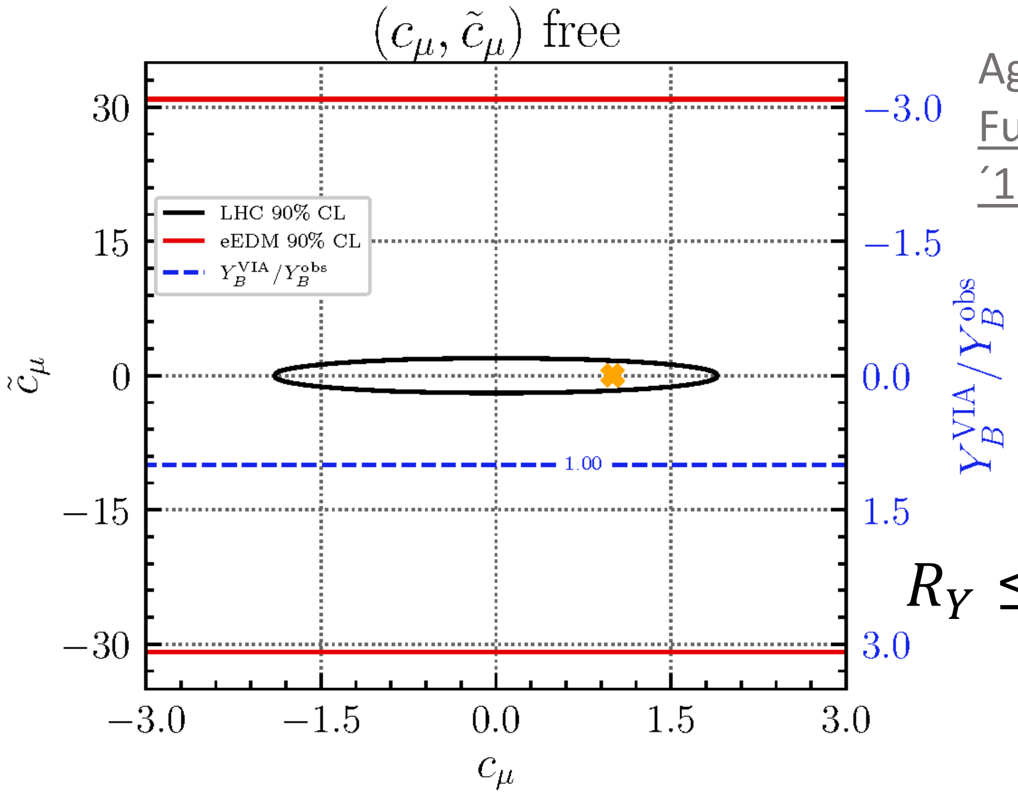
eEDM no longer limiting factor

Cancellations can enhance maximally allowed baryon asymmetry

Constraints of μ-Yukawa coupling

Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)





Agrees with Fuchs et al. ´19

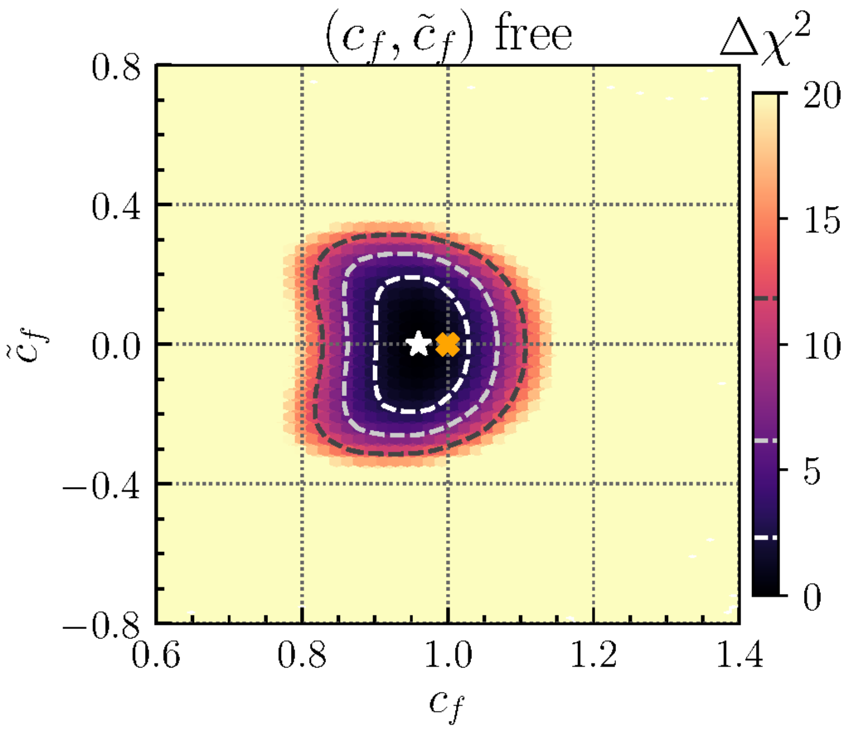
$R_Y \leq 0.17$

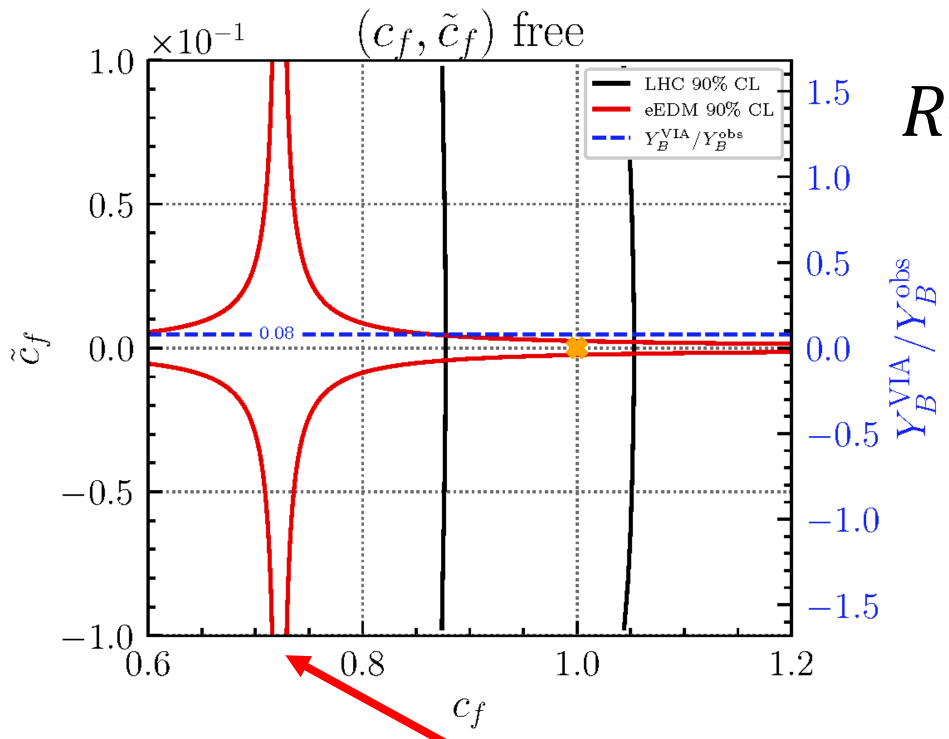
$H \to \mu\mu$ observed (3σ): ATLAS Collaboration (2021) & CMS Collaboration (2021)

LHC constraints already way stronger than eEDM

Impact of e in a global fermion phase

Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein (2022)





$R_Y \leq 8\%$

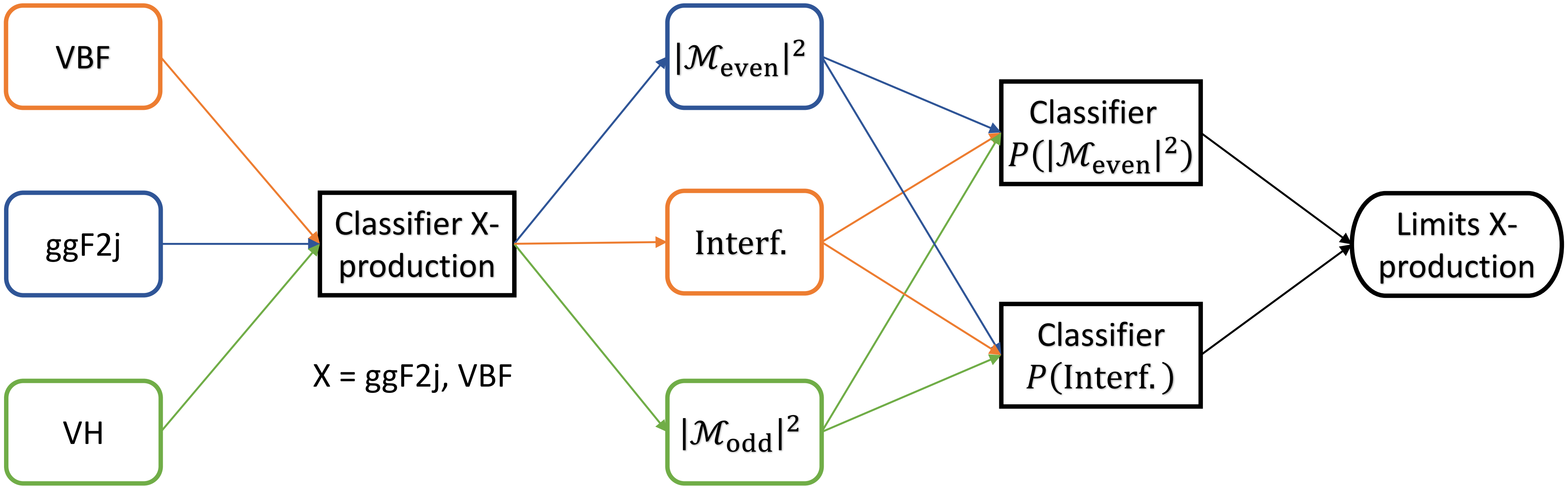
Shared phase $c_f \equiv c_t = c_b = c_\tau = \cdots$

Full cancellation of eEDM

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

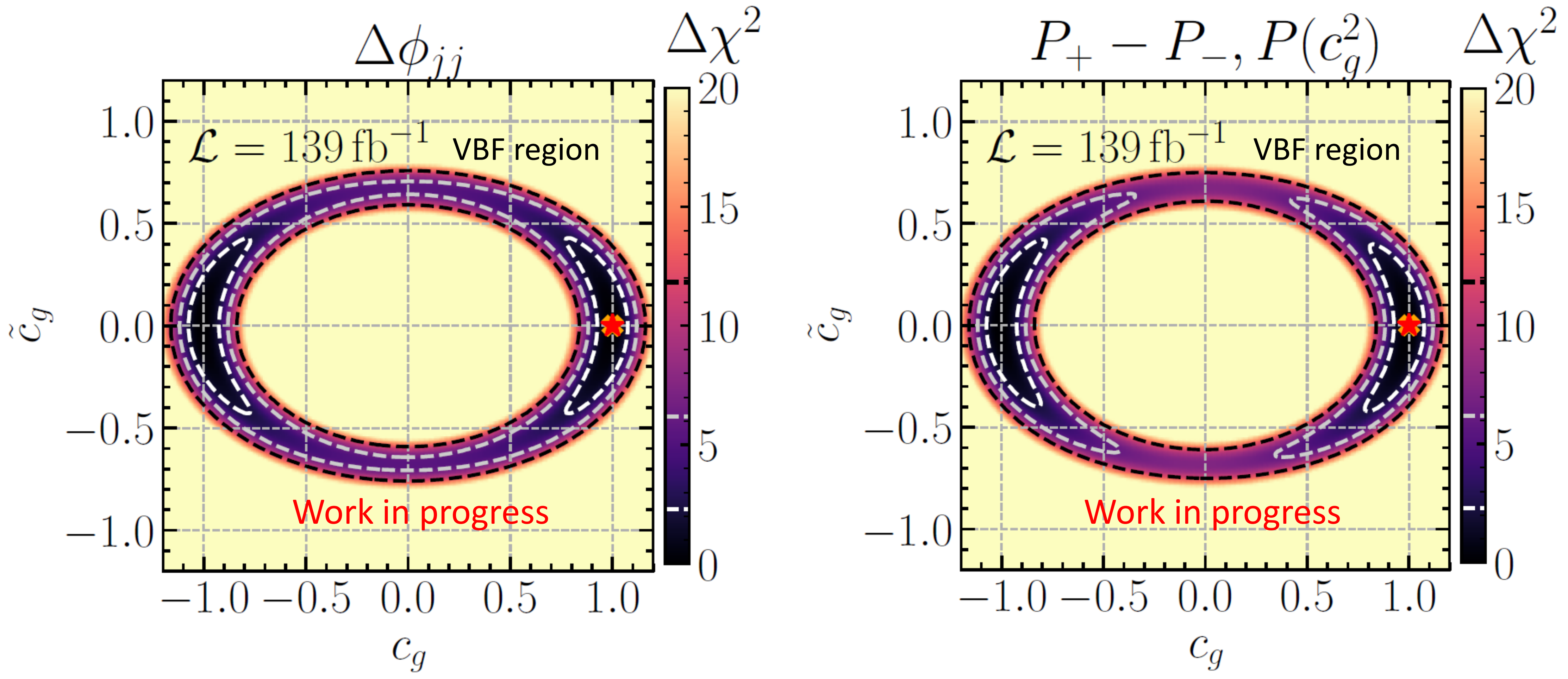
Flowchart ggF2j study

Bahl, Fuchs, Hannig, MM (in preparation)



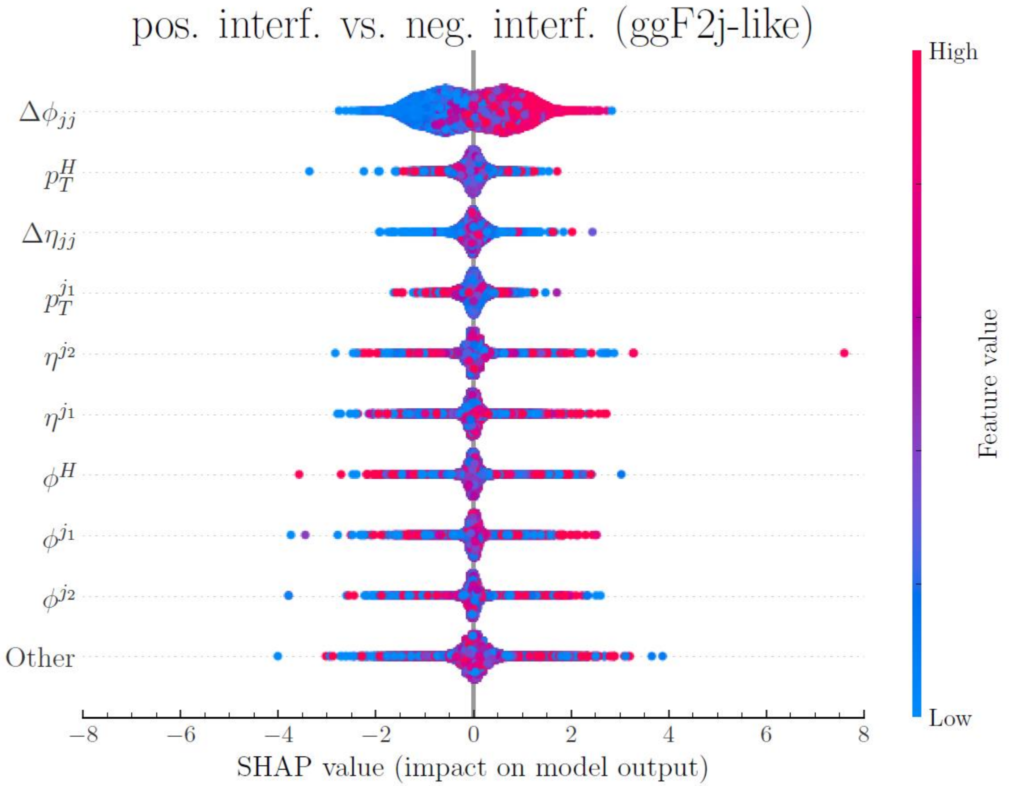
Limits ggF2j study – VBF region

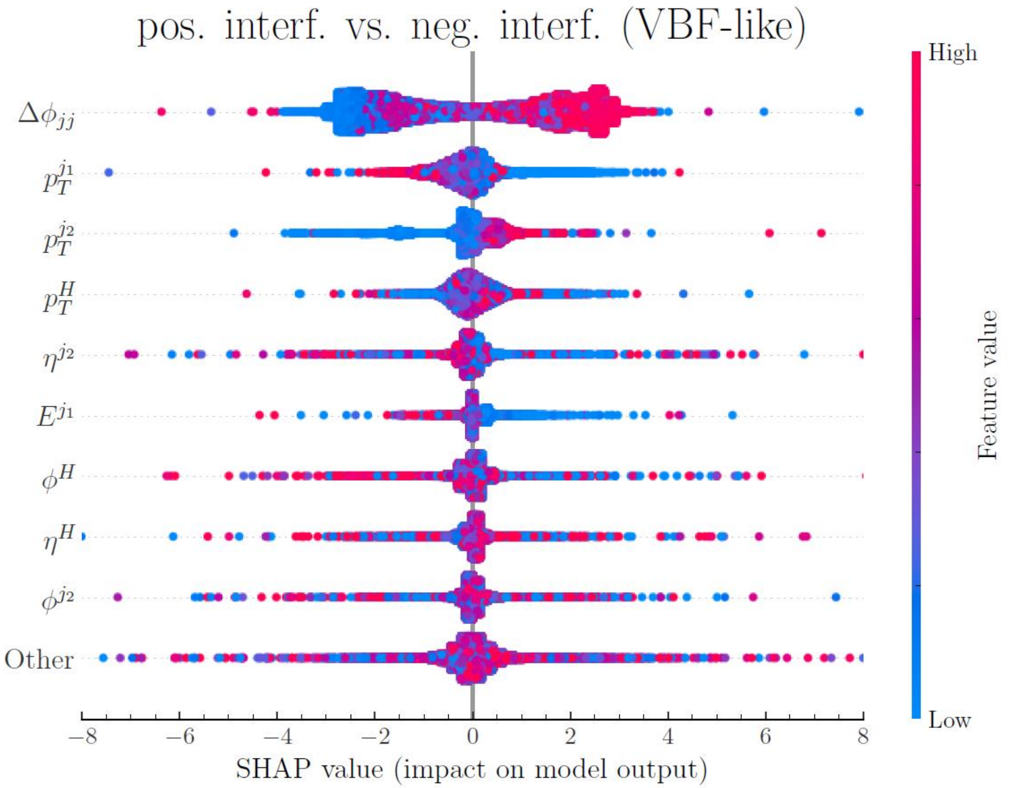
Bahl, Fuchs, Hannig, MM (in preparation)



Variable importance interf. ggF2j study

Bahl, Fuchs, Hannig, MM (in preparation)

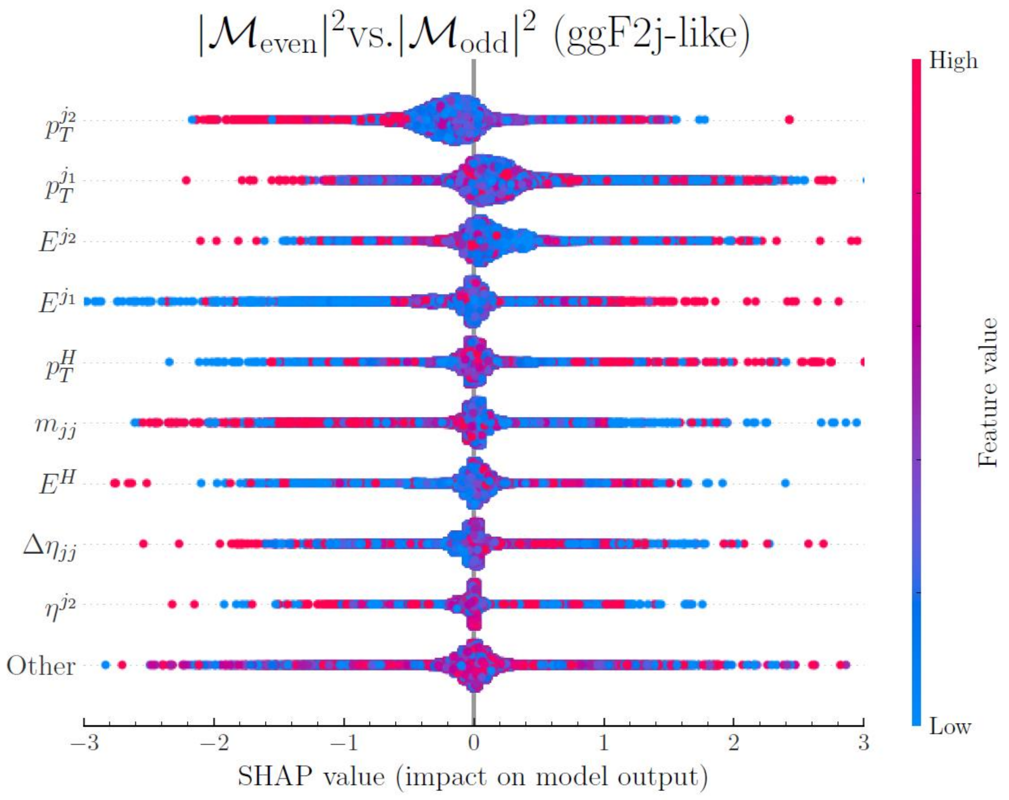


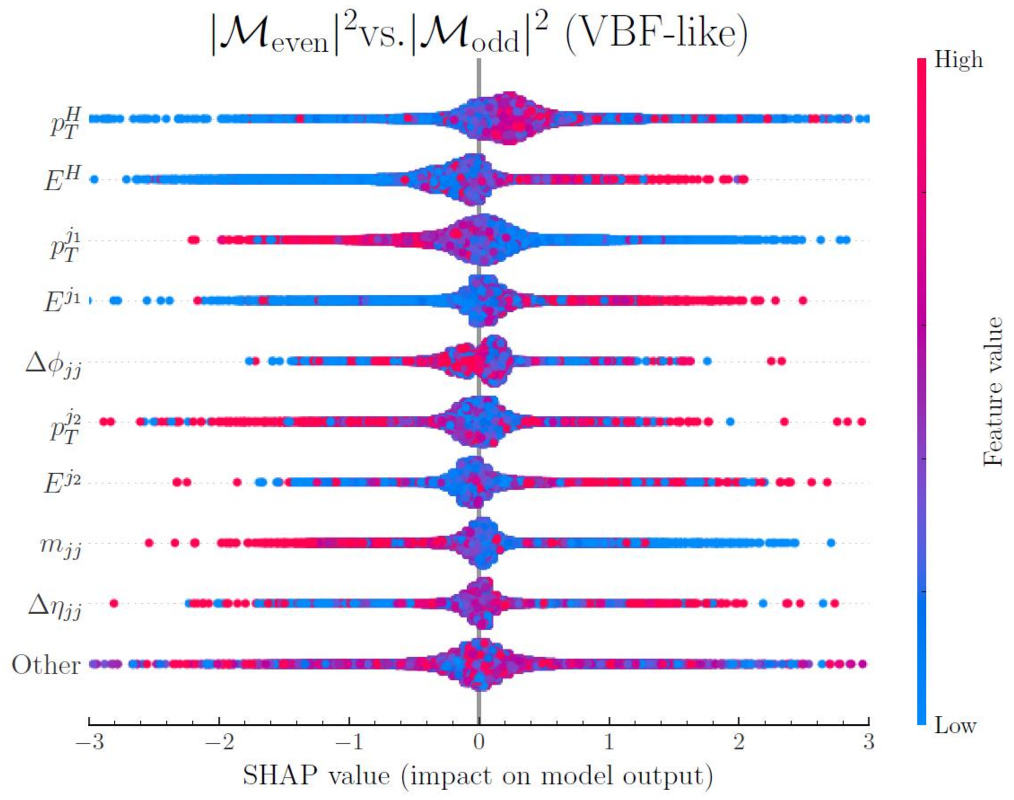


Plots made with: Shapley

Variable importance interf. ggF2j study

Bahl, Fuchs, Hannig, MM (in preparation)





Plots made with: Shapley