

Constraining CP violation in the Higgs–fermion interactions

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THE UNIVERSITY OF
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Talk based on

- **2007.08542:**

Indirect CP probes of the Higgs-top-quark interaction: current LHC constraints and future opportunities;

in collaboration with P. Bechtle, S. Heinemeyer, J. Katzy, T. Klingl, K. Peters, M. Saimpert, T. Stefaniak, G. Weiglein.

- **2110.10177:**

Constraining CP-violation in the Higgs-top-quark interaction using machine-learning-based inference;

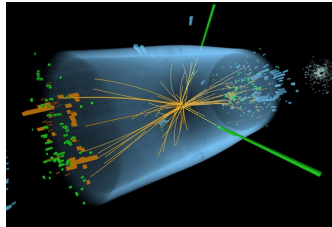
in collaboration with S. Brass.

- **2202.11753:**

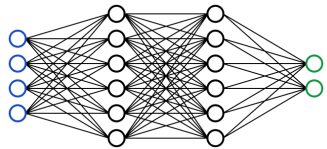
Constraining the CP structure of Higgs-fermion couplings with a global LHC fit, the electron EDM and baryogenesis;

in collaboration with E. Fuchs, S. Heinemeyer, J. Katzy, M. Menen, K. Peters, M. Saimpert, G. Weiglein.

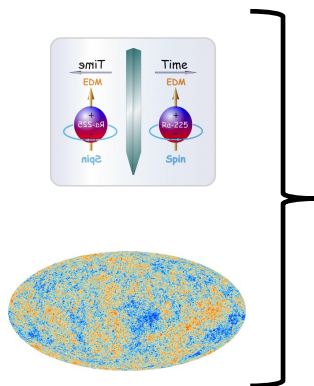
Outline of the talk



Global LHC fit



Constraining CP violation using ML-based inference



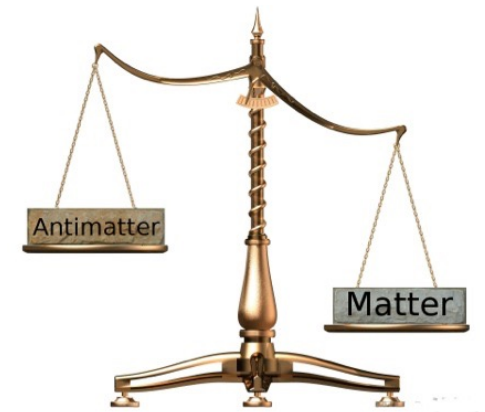
Complementarity with EDM and baryogenesis constraints

Introduction

Why should we care about CP violation in the Higgs–fermion couplings?

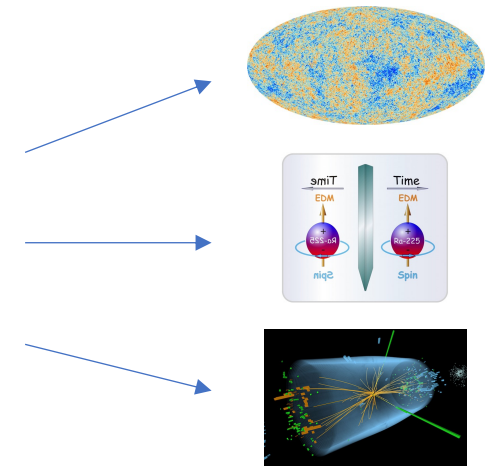
CP violation in the Higgs sector

- New sources of CP violation are necessary to explain the baryon asymmetry of the Universe.
- One possibility: CP violation in the Higgs sector.



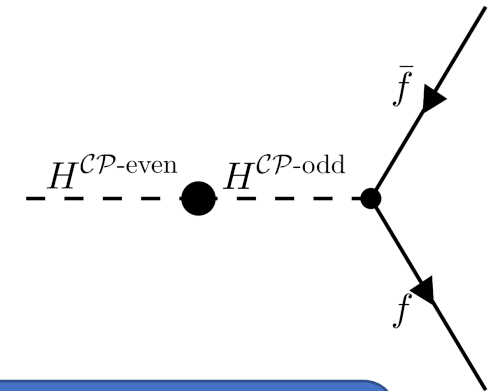
Is the SM-like Higgs boson a CP-admixed state?

- CP violation in the Higgs sector can be constrained by
 - demanding significant contribution to the baryon asymmetry (BAU)
 - electric dipole measurements,
 - collider measurements.



The CP nature of the Higgs boson

- CP violation in HVV couplings already tightly constrained via VBF and $pp \rightarrow VH$ production as well as $H \rightarrow 4l$ decay. [ATLAS,CMS:...,2002.05315, 2104.12152,2109.13808,2202.06923,2205.05120]
- CP-violating HVV coupling can only be induced at the loop level \rightarrow expected to be small in most BSM theories.
- CP violation in Higgs–fermion couplings can be induced at the tree level.

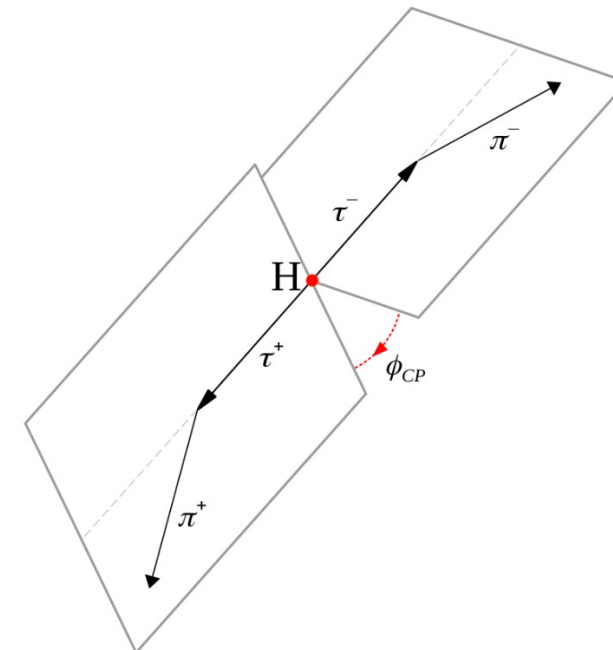
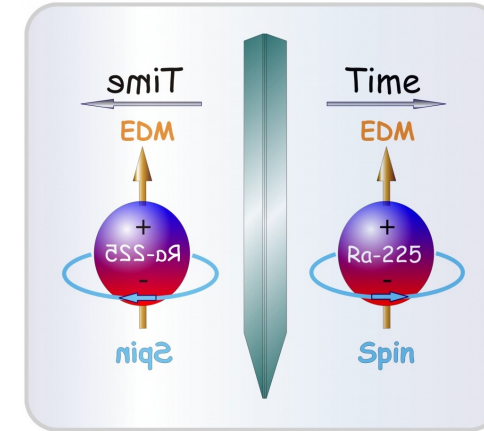


Focus of this talk: Constraining CP violation in the Higgs–fermion interactions.

Constraining CP violation

CP violation in the Higgs sector can be constrained using:

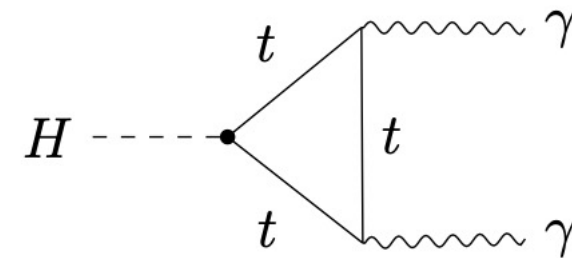
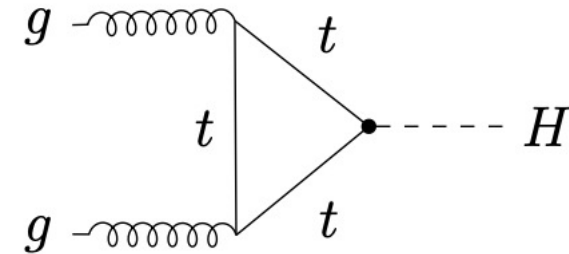
- **Pure CP-odd observables:**
 - Unambiguous markers for CP violation: e.g.
 - EDM measurements,
 - decay angle in $H \rightarrow \tau^+ \tau^-$.
 - Experimentally difficult for some processes (i.e., top-associated Higgs production).



Constraining CP violation

CP violation in the Higgs sector can be constrained using:

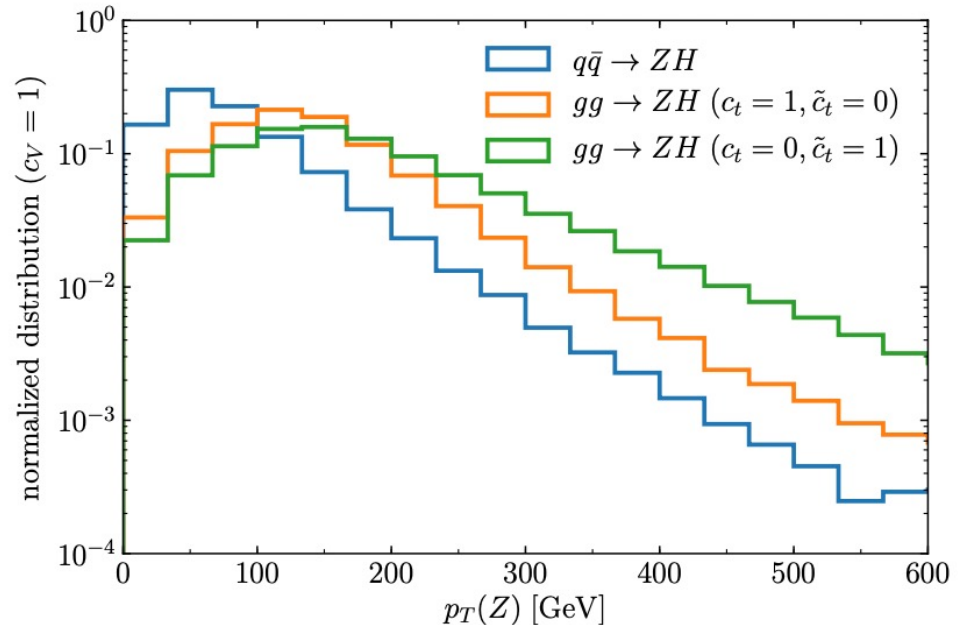
- **Pure CP-even observables:**
 - Many rate measurements are indirectly sensitive: e.g.
 - Higgs production via gluon fusion,
 - $H \rightarrow \gamma\gamma$.
 - Deviations from SM need not be due to CP violation.



Constraining CP violation

CP violation in the Higgs sector can be constrained using:

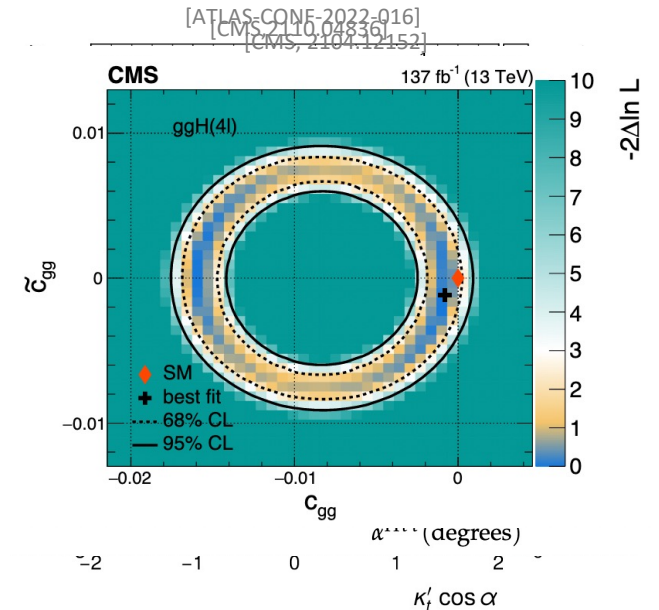
- **Kinematic information:**
 - Effectively mixes CP-even and CP-odd observables.
 - High sensitivity expected since all available information is used.
 - Can be difficult to reinterpret if multivariate analysis is used.



Exploit all three complementary approaches to learn as much as possible!

Why should we look for CP-violating $Hf\bar{f}$ couplings now?

- More and more experimental CP measurements:
 - Htt coupling: $t\bar{t}H$, tH , tWH production (with $H \rightarrow \gamma\gamma, \bar{b}b$) using kinematic analysis,
 - $H\tau\tau$ coupling: $H \rightarrow \tau\tau$ using CP-odd observable,
 - ggH coupling: $H + 2j$ production using CP-odd observable.
- Increased precision on indirectly sensitive channels.
 - E.g., ggH , $H \rightarrow \gamma\gamma$, etc.
- Much more luminosity to be collected at HL-LHC.
- Tighter upper bounds on CP violation from EDM measurements.



- Combine LHC measurements in global fit.
- Propose ways to improve measurements in the future.
- Compare LHC measurements with EDM bounds and baryogenesis constraints.

Effective model

- Modify Yukawa interactions by (e.g. generated by dim-6 $(\phi^\dagger \phi) Q_L \tilde{\phi} t_R$ operator)

$$\mathcal{L}_{\text{yuk}} = - \sum_{f=u,d,c,s,t,b,e,\mu,\tau} \frac{y_f^{\text{SM}}}{\sqrt{2}} \bar{f} (c_f + i\gamma_5 \tilde{c}_f) f H,$$

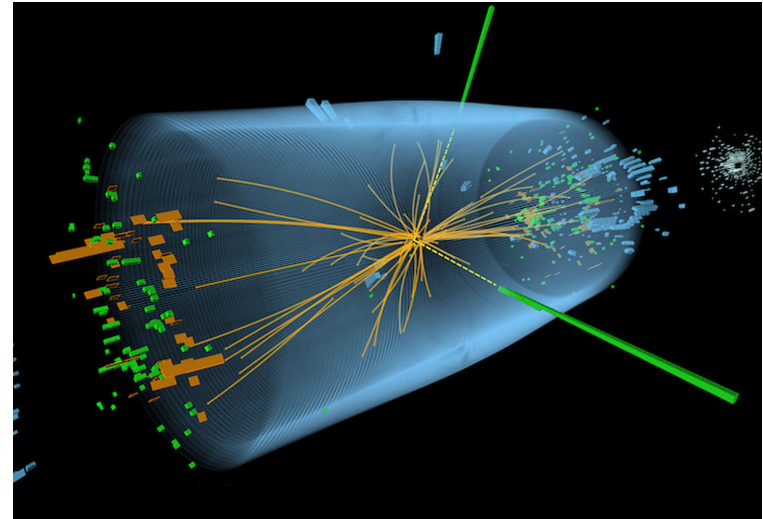
- Allow moreover for CP-conserving modification of HVV couplings

$$\mathcal{L}_V = c_V H \left(\frac{M_Z^2}{v} Z_\mu Z^\mu + 2 \frac{M_W^2}{v} W_\mu^+ W^{-\mu} \right)$$

- SM: $c_f = 1$, $\tilde{c}_f = 0$, $c_V = 1$.
- Parametrize effect of undiscovered colored and neutral BSM particles via effective Higgs–gluon and Higgs–photon interactions.

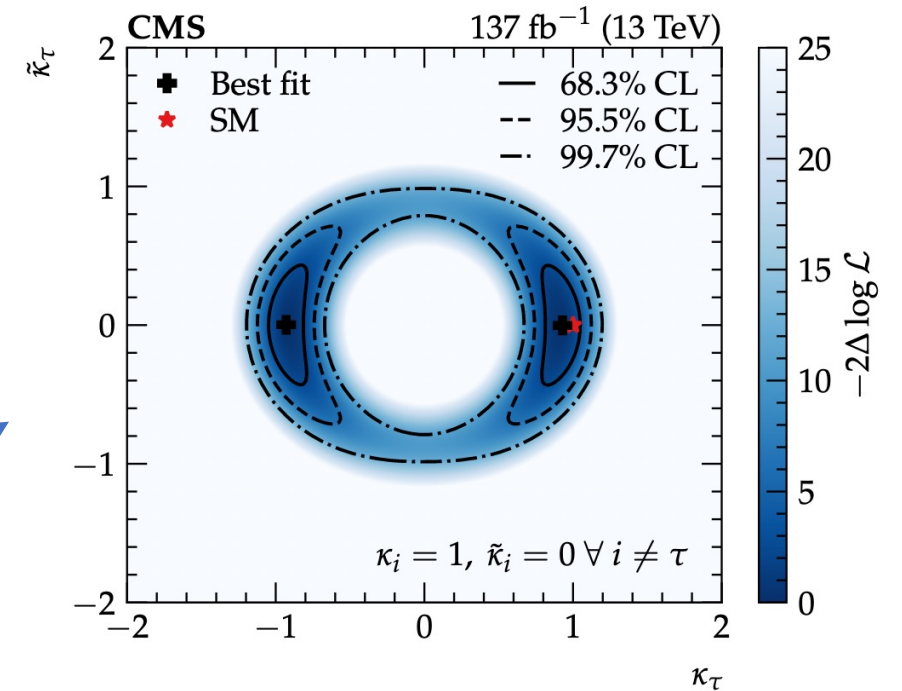
Global LHC fit

What can we learn from current LHC data?



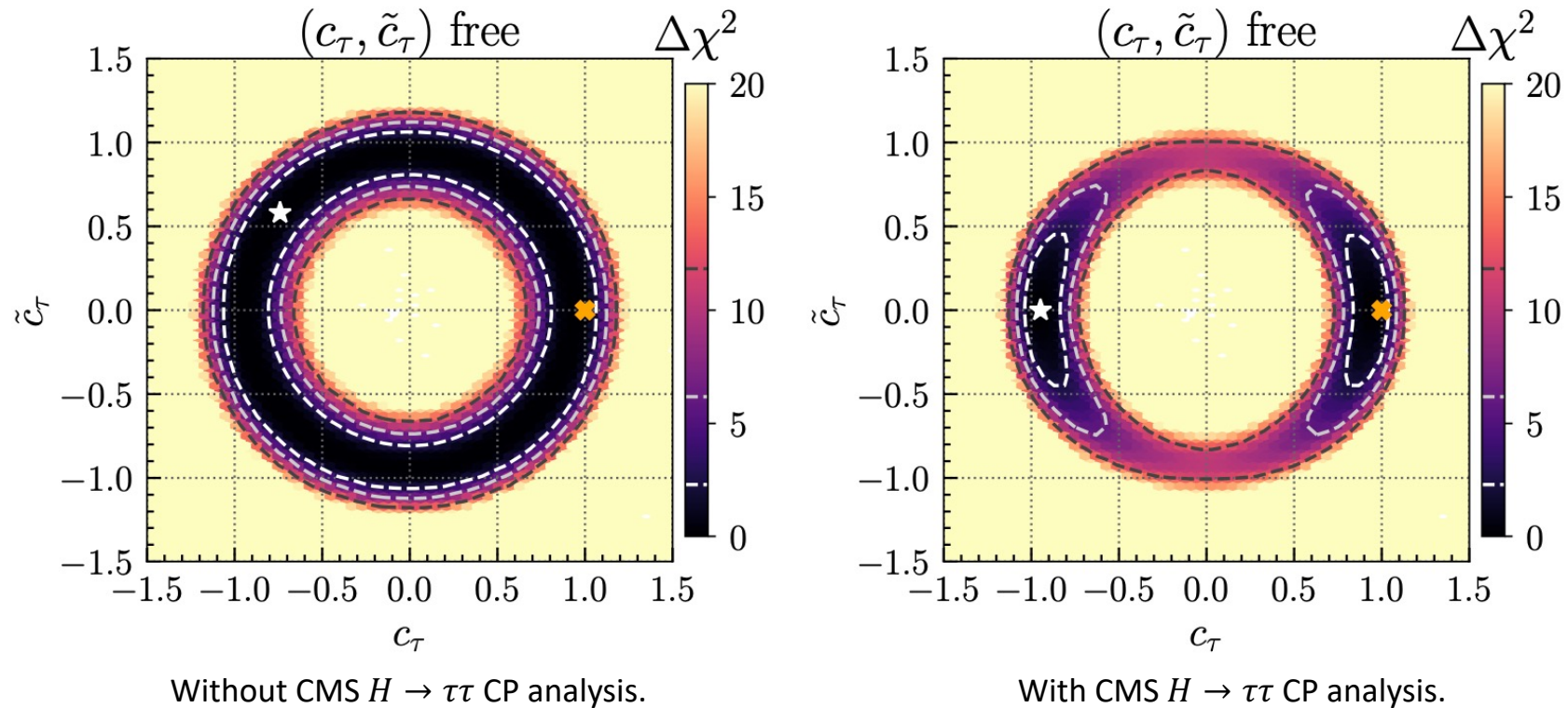
LHC constraints — setup

- Experimental input:
 - All relevant Higgs measurements:
 - Rate measurements (production + decay),
 - ZH STXS measurements (p_T shape),
 - CMS $H \rightarrow \tau\tau$ CP analysis, [2110.04836]
 - did not include dedicated experimental top-Yukawa CP analyses (difficult to reinterpret in another model).
 - If available, included all uncertainty correlations.
- Scanning using either random scan or Markov-chain algorithm,
- χ^2 fit performed using HiggsSignals including ~ 100 different measurements.



Starting point — 1 flavor fits: τ

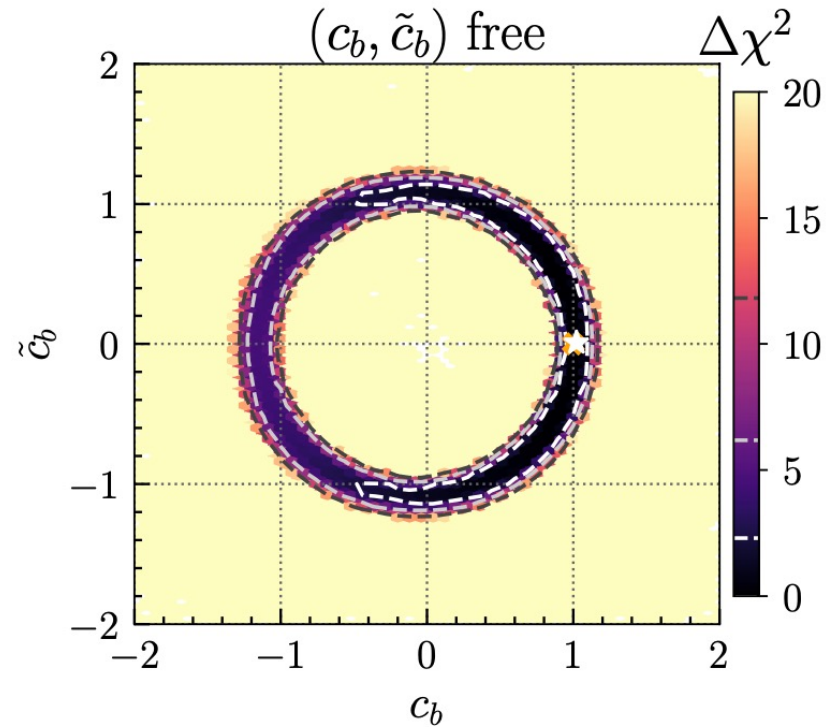
[HB et al., 2202.11753]



- Without CMS $H \rightarrow \tau\tau$ CP analysis ring-like structure since $\Gamma_{H \rightarrow \tau\tau} \propto c_\tau^2 + \tilde{c}_\tau^2$ (similar for muon-Yukawa coupling).
- With CMS $H \rightarrow \tau\tau$ CP analysis, we can differentiate between CP-even and CP-odd tau-Yukawa coupling.

1 flavor fits: b

[HB et al., 2202.11753]



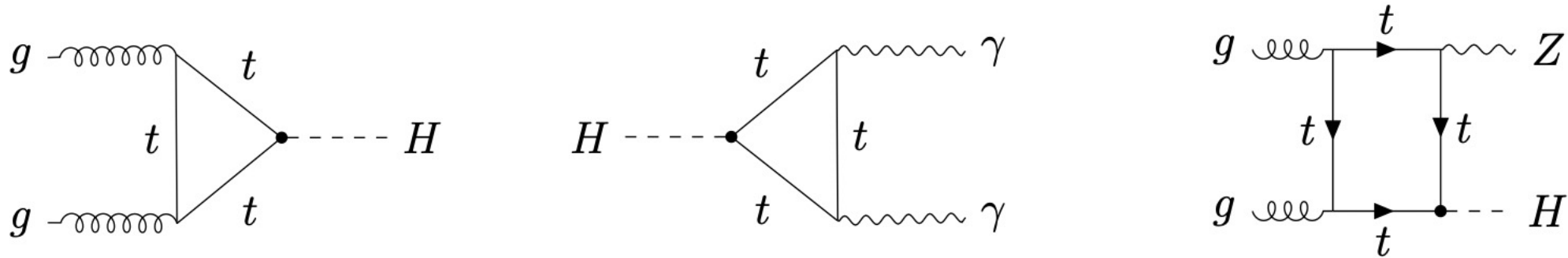
- Ring-like structure since $\Gamma_{H \rightarrow bb} \propto c_b^2 + \tilde{c}_b^2$.
- Bottom-Yukawa coupling, however, also affects ggH rate:
 - $\frac{\sigma_{gg \rightarrow H}}{\sigma_{gg \rightarrow H}^{\text{SM}}} \simeq 1.1c_t^2 + 2.6\tilde{c}_t^2 - 0.1c_t c_b + \dots$
- Negative c_b values disfavored since ggH rate is enhanced by $\sim 20\%$.
- Direct bottom CP measurements very difficult.



Indirect CP constraints will remain important for the bottom-Yukawa coupling.

Top-Yukawa coupling

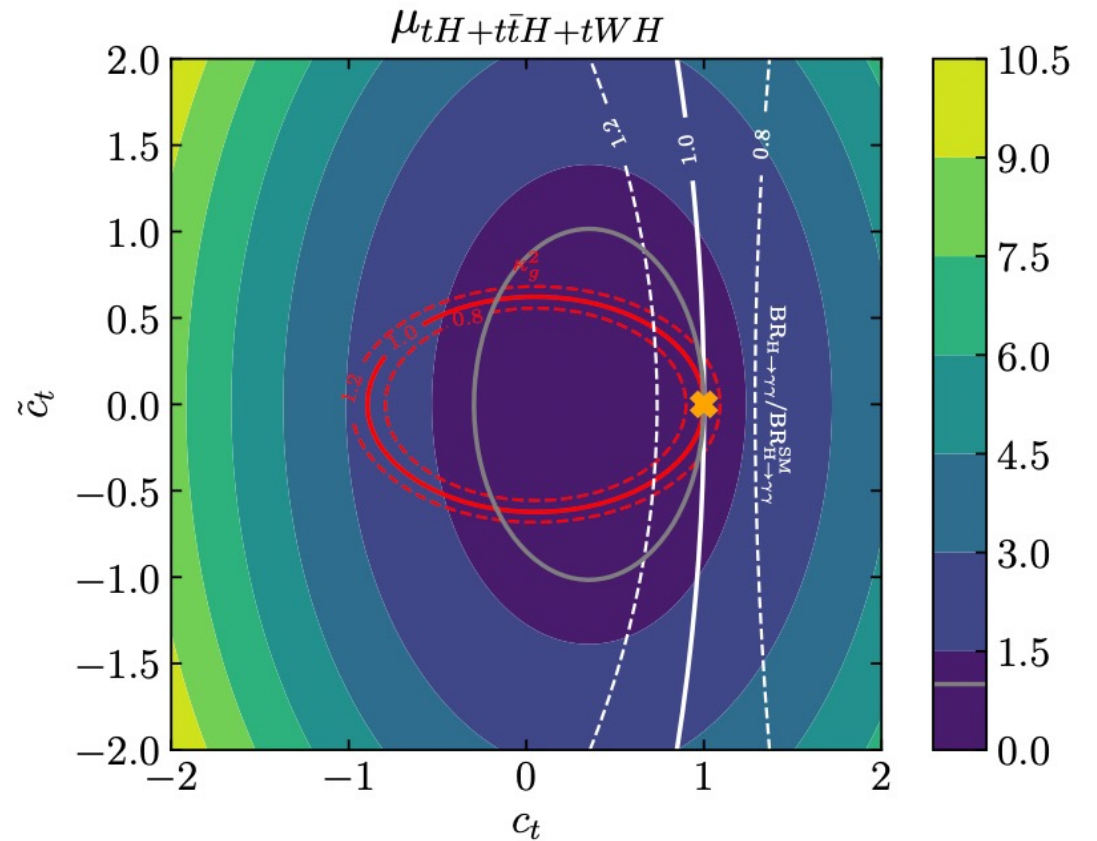
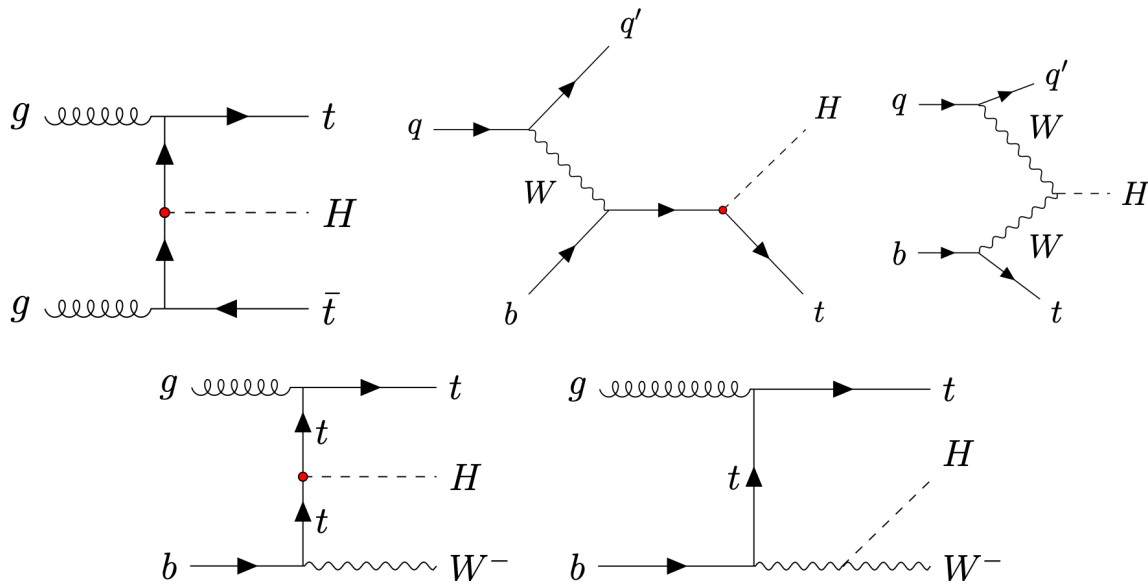
- Probe top-Yukawa coupling at the loop-level via $gg \rightarrow H$, $H \rightarrow \gamma\gamma$, $gg \rightarrow ZH$:



- $\kappa_g^2 \equiv \frac{\sigma_{gg \rightarrow H}}{\sigma_{gg \rightarrow H}^{\text{SM}}} \simeq 1.1c_t^2 + 2.6\tilde{c}_t^2 - 0.1c_t c_b - 0.2\tilde{c}_t \tilde{c}_b + \dots$, disfavors large \tilde{c}_t .
- $\kappa_\gamma^2 \equiv \frac{\Gamma_{H \rightarrow \gamma\gamma}}{\Gamma_{H \rightarrow \gamma\gamma}^{\text{SM}}} \simeq 1.6c_V^2 - 0.7c_V c_t + 0.1c_t^2 + 0.2\tilde{c}_t^2 + \dots$, disfavors negative/small c_t .
- $\frac{\sigma_{gg \rightarrow ZH}}{\sigma_{gg \rightarrow ZH}^{\text{SM}}} \simeq 0.5c_t^2 + 0.5\tilde{c}_t^2 + 2.4c_V^2 - 1.9c_V c_t \dots$, disfavors negative c_t .

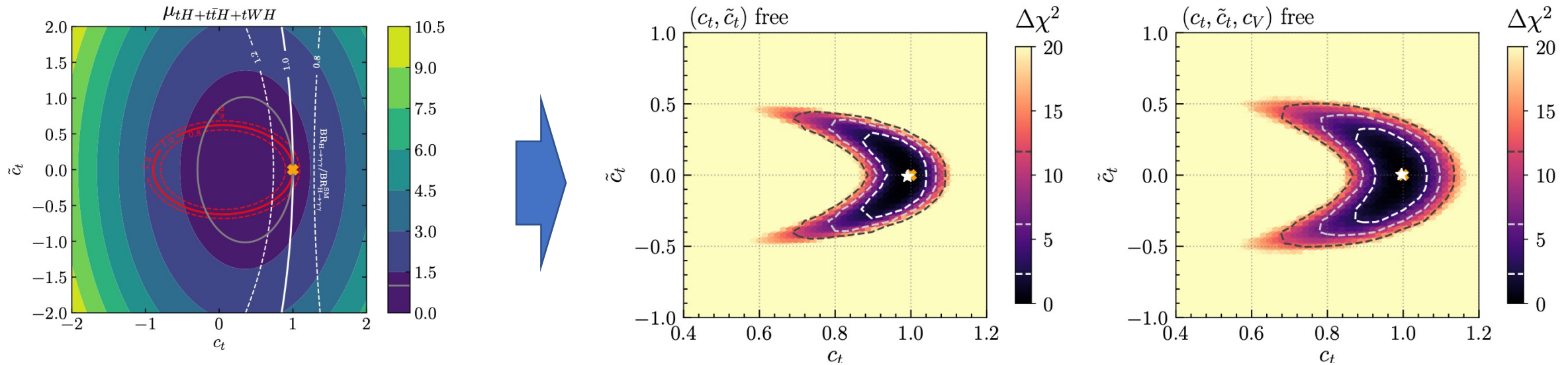
Top-Yukawa coupling

- Probe top-Yukawa coupling at the tree-level via top-associated Higgs production:
 - Three subchannels: $t\bar{t}H$, tH , tWH .
 - Difficult to disentangle experimentally.
 - Consider combined signal strength.



1 flavor fits: t

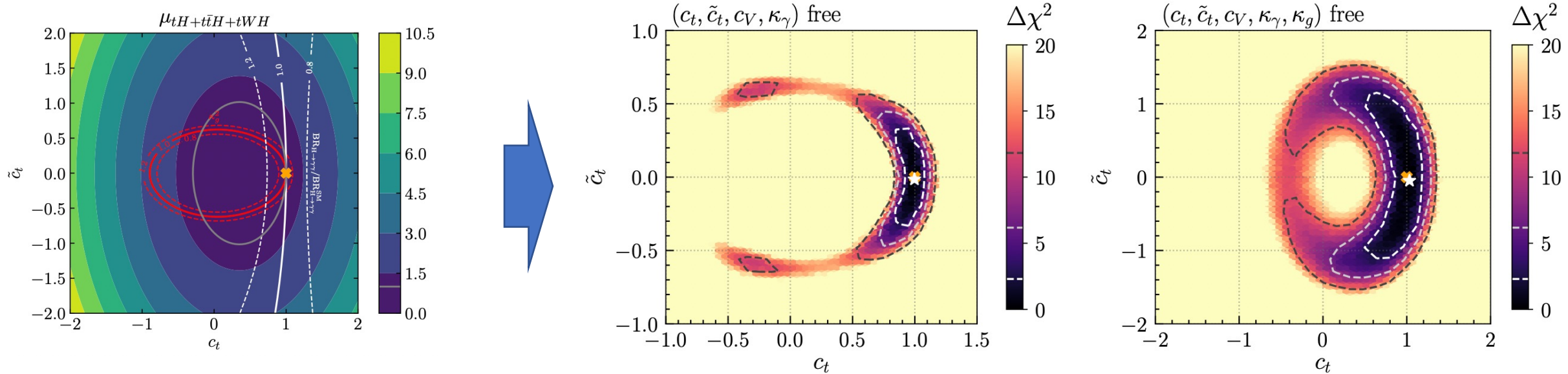
[HB et al.,2007.08542]



- ggH and $H \rightarrow \gamma\gamma$ total rates strongly constraint CP violation in top-Yukawa coupling.
- Relies on assumption that no other BSM physics affect ggH and $H \rightarrow \gamma\gamma$.
- What happens if we allow κ_γ and κ_g to float freely?

1 flavor fits: t — free κ_γ, κ_g

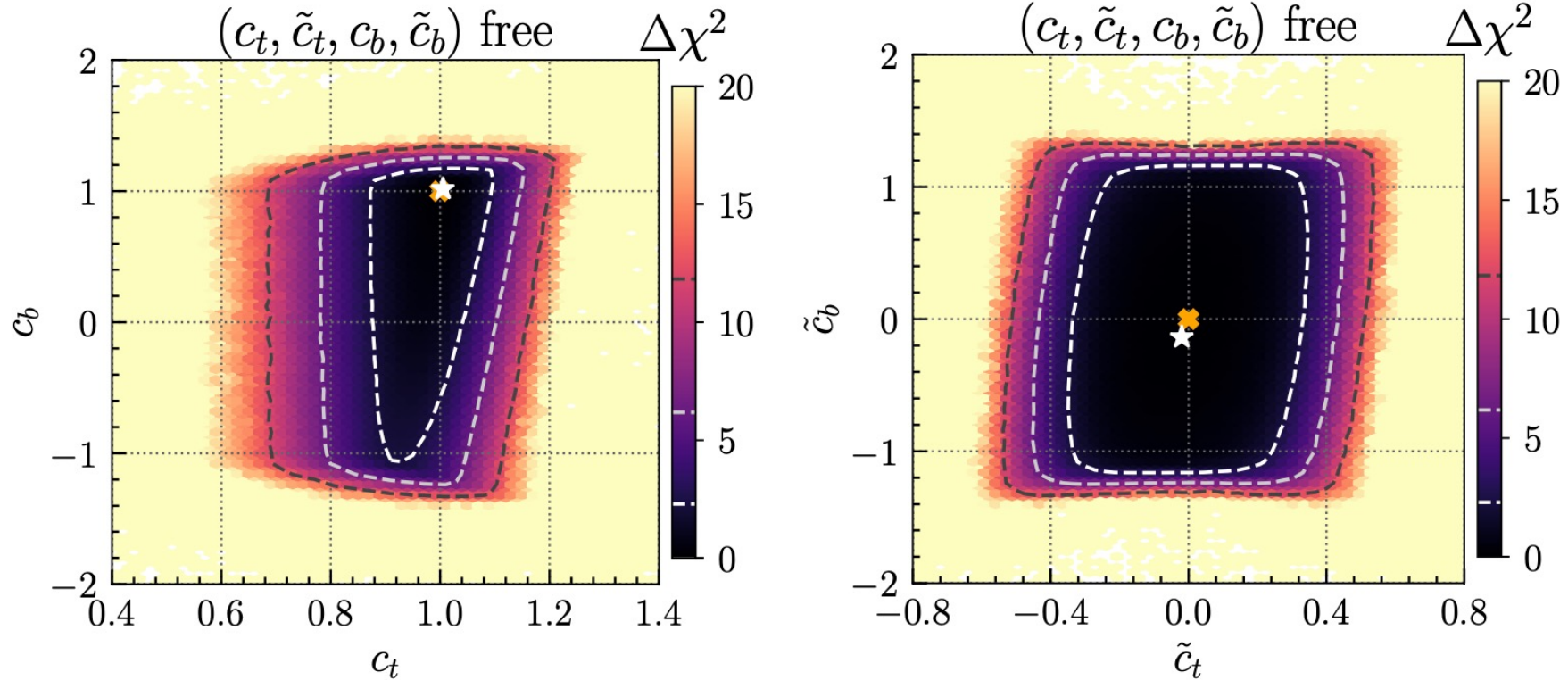
[HB et al., 2007.08542]



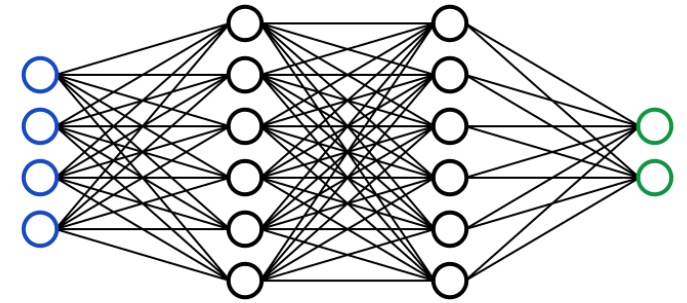
- Colored and charged BSM particles can cancel the effect of a modified top-Yukawa coupling.
- Top-associated Higgs production is a more model-independent but weaker probe.

2 flavor fits: t and b

[HB et al., 2202.11753]



- ggH rate correlates top and bottom Yukawa couplings: $\kappa_g^2 \simeq 1.1c_t^2 + 2.6\tilde{c}_t^2 - 0.1c_t c_b - 0.2\tilde{c}_t \tilde{c}_b$.
- Correlation of CP-odd coupling modifiers weaker since bounds on \tilde{c}_t are stronger.

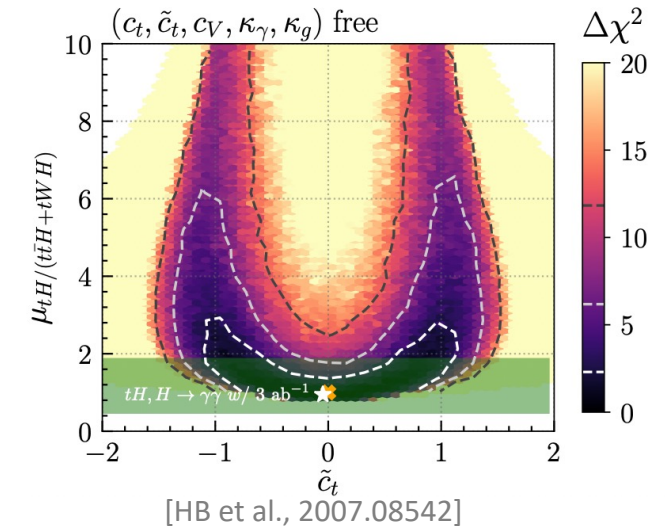


Constraining CP-violation using ML-based inference

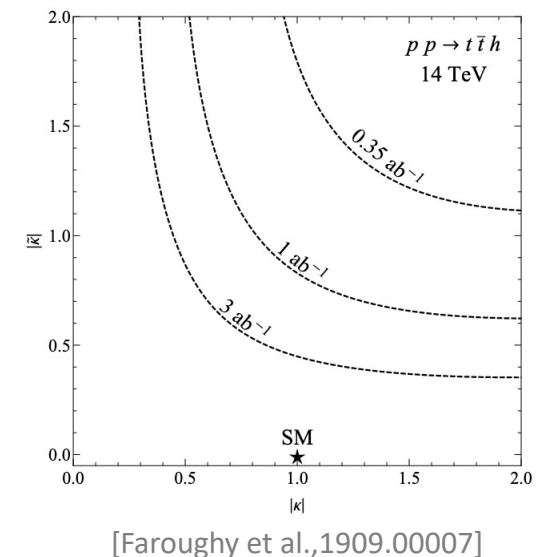
How can we improve the LHC bounds on the top-Yukawa coupling in the future?

Future probes of the top-Yukawa interaction

- Future rates measurements:
 - Need to disentangle $t\bar{t}H$ and tH to improve sensitivity on \tilde{c}_t .
[HB et al., 2007.08542]
 - Possible alternative channels: $t\bar{t}$, $t\bar{t}t\bar{t}$.
[Cao et al.,1901.04567;Martini et al.,2104.04277]
 - Even at HL-LHC comparably weak bounds expected.

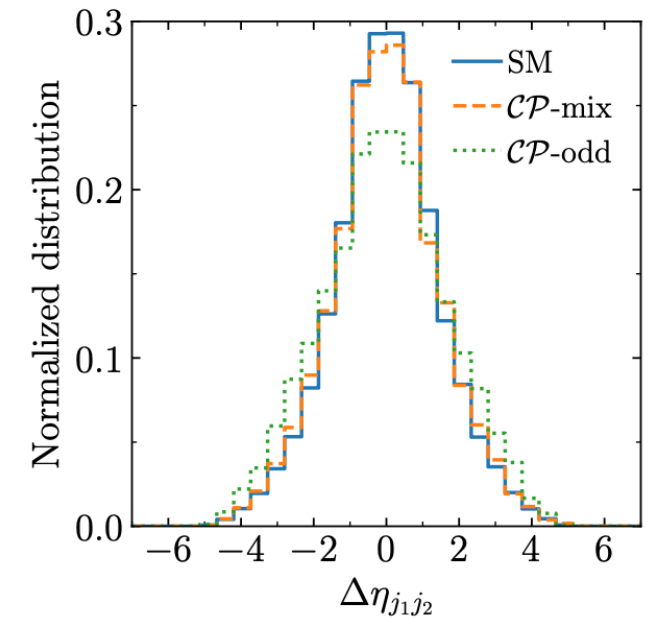
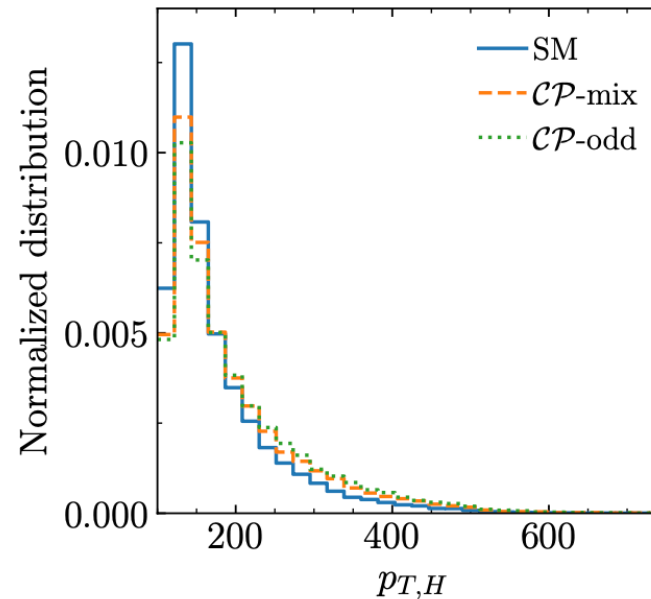


- Future measurements of CP-odd observables:
 - [e.g. Faroughy et al.,1909.00007; Bortolato et al.,2006.13110;Barman et al.,2110.07635]
 - Difficult since top quarks need to be reconstructed.
 - Resulting projected limits are relatively weak.



Alternative approach: kinematic analysis

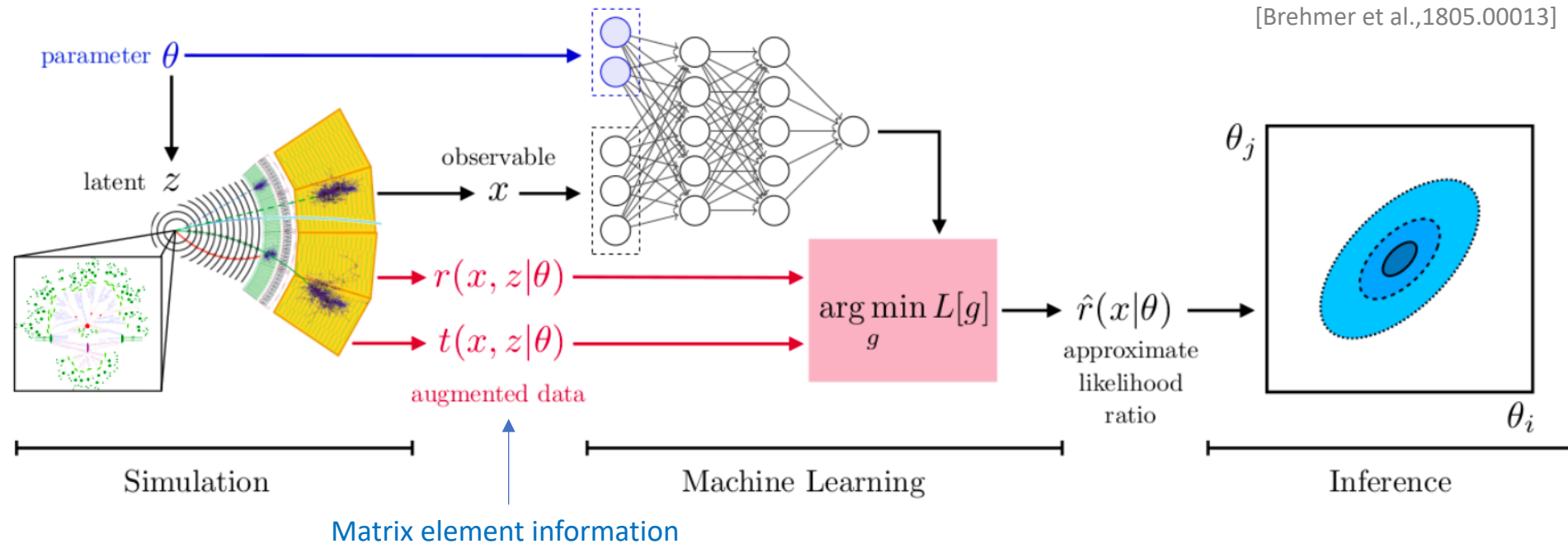
- Multivariate analyses exploiting kinematic information:
 - BDT analysis,
[CMS,2003.10866;ATLAS,2004.04545]
 - matrix-element approach,
[e.g. Goncalves et al,1804.05874;Kraus et al.,1908.09100]
 - High sensitivity expected.



How to best exploit the full available information to constraint top-Yukawa interaction?

Machine-learning based inference

[Brehmer et al.,1906.01578,1805.12244,1805.00013,1805.00020,1808.00973]



- Allows to extract the full available information (maximal sensitivity).
- No information loss due to binning (as for BDT analysis).
- No approximation of shower and detector effects (as for matrix-element approach).
- Use implementation in public code MadMiner designed to work with MadGraph + Pythia + Delphes.

[Brehmer,Kling,Espejo,Cranmer,1907.10621]

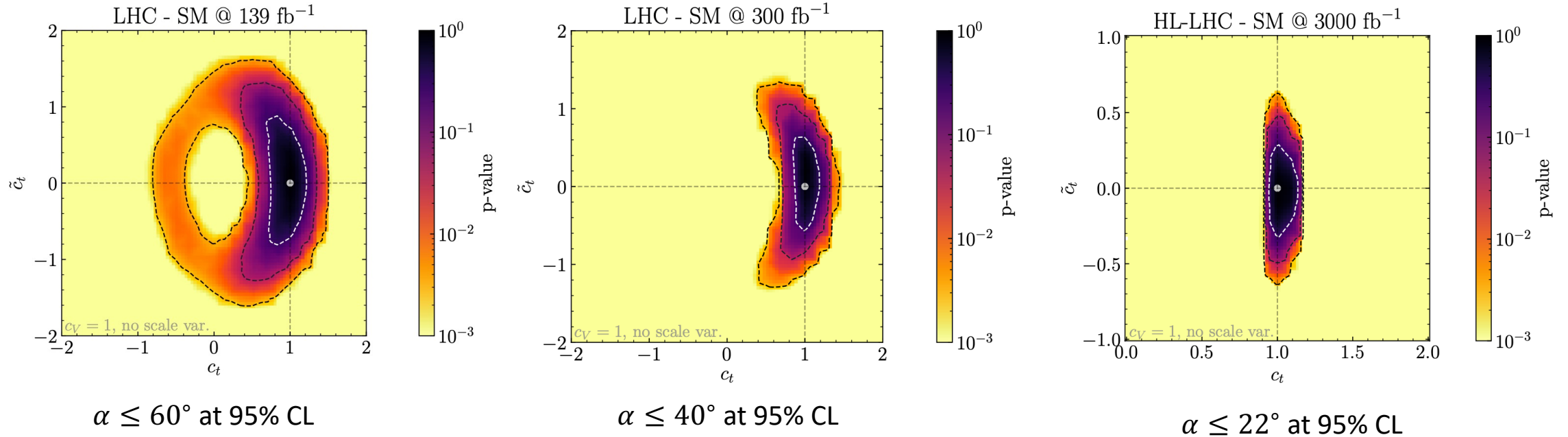
ML-based inference: setup

- Focus on top-associated Higgs production ($t\bar{t}H, tH, tWH$) with $H \rightarrow \gamma\gamma$.
- We require at least one lepton \rightarrow consider ZH, WH as backgrounds.
- Non-Higgs backgrounds are assumed to be subtracted by fit to smoothly falling $m_{\gamma\gamma}$ distribution.
- Free parameters: c_t, \tilde{c}_t , and c_V (+ renormalization scale μ_R).
- Defined 47 observables used by neural network (photon, jet, lepton momenta, Higgs p_T , etc.).
- Averaged over ensemble of six neural networks to minimize ML uncertainty.

\Rightarrow Evaluate likelihoods for different luminosities at the LHC + HL-LHC.

Expected limits at the (HL-)LHC

[HB&Brass,2110.10177]



- Can also interpret result in terms of mixing angle $\tan \alpha = \tilde{c}_t/c_t$.
- Additional variation of c_V (and of the renormalization scale) only slightly weakens bounds ($\sim 5^\circ$ for 300 fb⁻¹).

Which observables drive these constraints?

- Use Fisher matrix to evaluate information for different observables

$$I_{ij}(\theta) = \mathbb{E} \left[\frac{\partial \log p_{\text{full}}(\{x\}|\theta)}{\partial \theta_i} \frac{\partial \log p_{\text{full}}(\{x\}|\theta)}{\partial \theta_j} \middle| \theta \right], \quad \text{with} \quad \text{cov}(\hat{\theta}|\theta)_{ij} \geq I_{ij}^{-1}(\theta),$$

→ *The higher the information, the more precise we can measure a parameter.*

- E.g., for SM point we have

$$I_{ij}^{\text{full}}(\text{SM}) \simeq \begin{pmatrix} \boxed{91.4} & 13.7 & 0.1 \\ 13.7 & \boxed{108.2} & -0.1 \\ 0.1 & -0.1 & \boxed{0.004} \end{pmatrix},$$

Information about c_V
Information about c_t

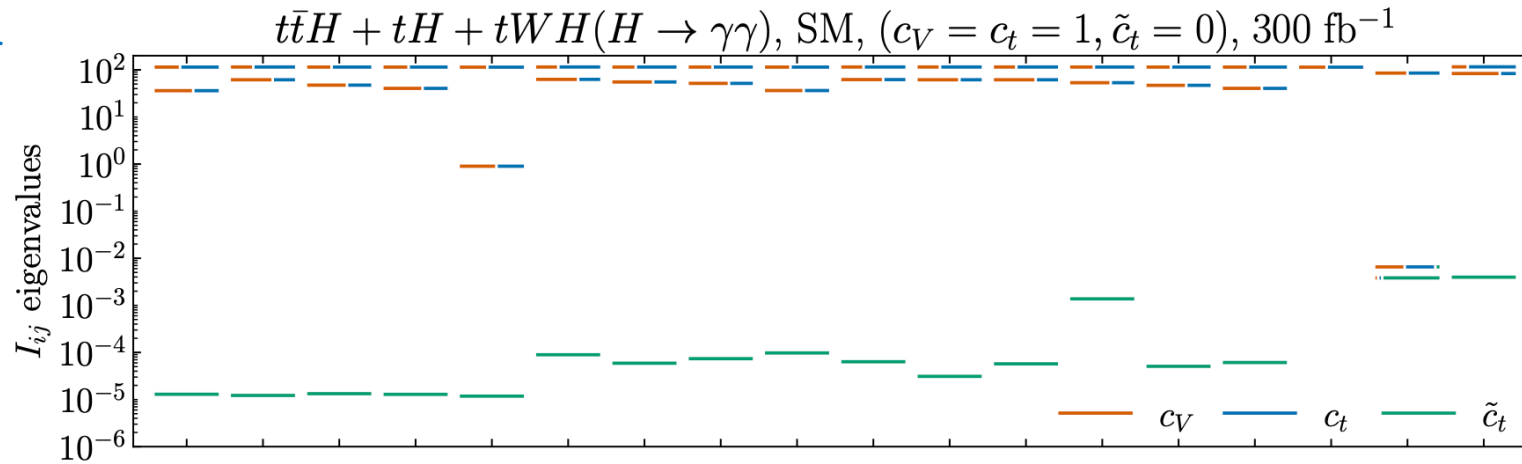
Correlation of c_t and c_V
Information about \tilde{c}_t

- Evaluate Fisher matrix for various 1D and 2D histograms, full likelihood, XS only, kinematics only.

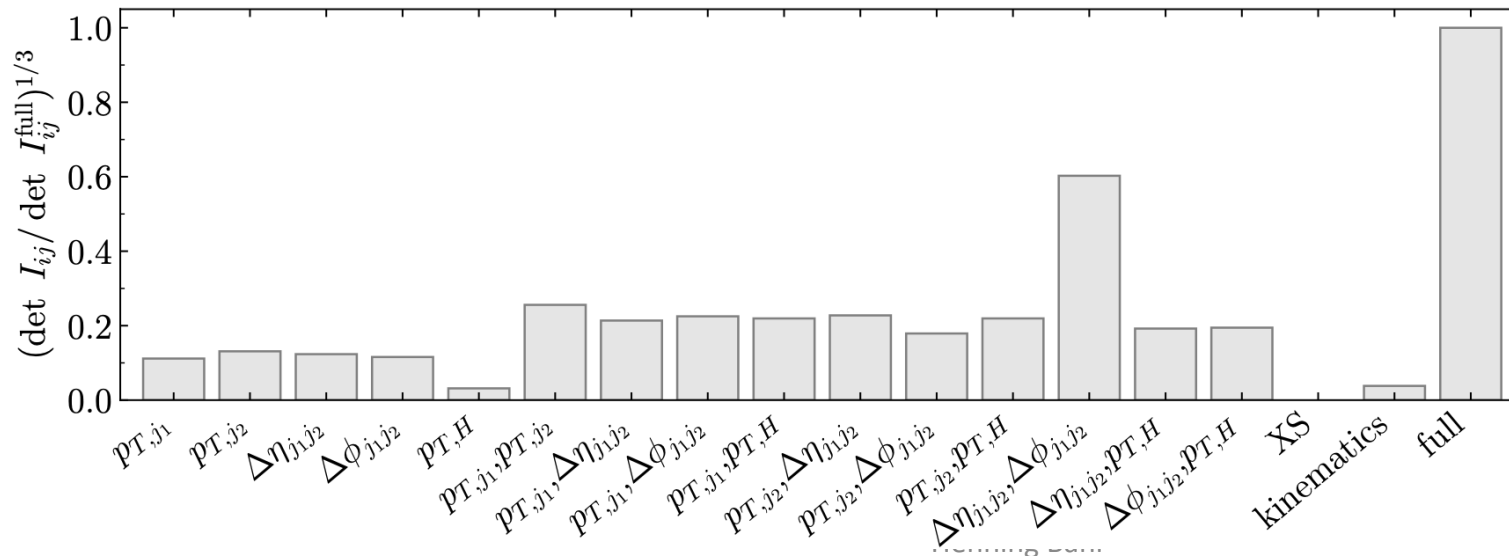
Fisher information for SM scenario

[HB&Brass,2110.10177]

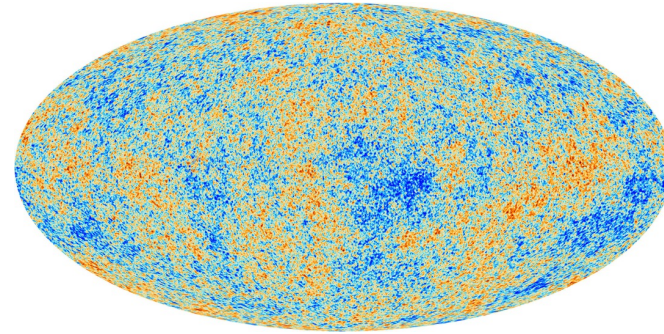
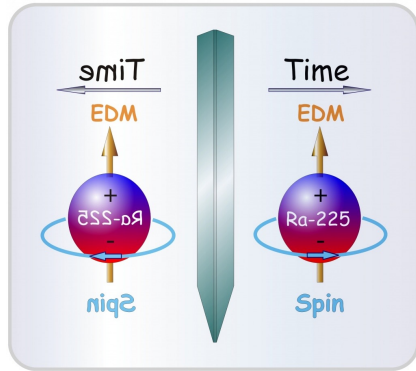
Which combinations of couplings
can we constrain how well?



Total amount of
capture information



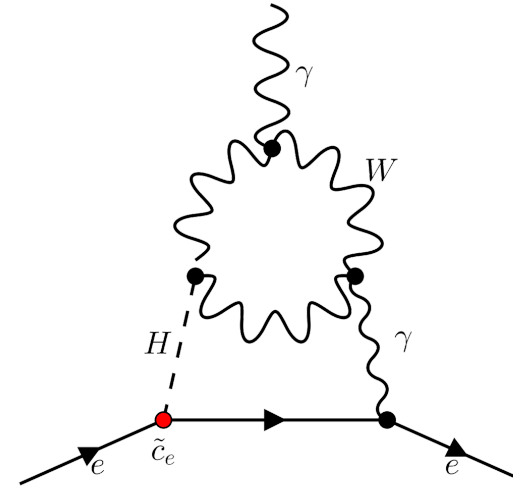
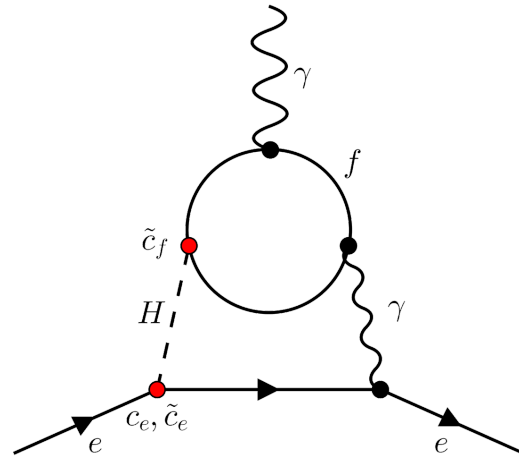
- \tilde{c}_t not constrained by rate.
- Use of kinematic information mandatory.
- No single observable able to capture information about \tilde{c}_t .



Complementarity with EDM and baryogenesis constraints

Can CP violation in the Higgs sector explain the BAU?

EDM constraints



- Several EDMs are sensitive to CP violation in the Higgs sector.
- We consider only constraints from theoretically cleanest EDM: the electron EDM.
[Brod et al.,1310.1385,1503.04830, 1810.12303, 2203.03736;Panico et al.,1810.09413;Altmannshofer et al.,2009.01258]
- Strongest limit by ACME collaboration: $d_e^{\text{ACME}} = 1.1 \cdot 10^{-29} e \text{ cm}$ at 90% CL. [ACME, *Nature* 562 (2018) 7727, 355-360]
- $\frac{d_e}{d_e^{\text{ACME}}} \simeq c_e (870.0 \tilde{c}_t + 3.9 \tilde{c}_b + 3.4 \tilde{c}_\tau + \dots) + \tilde{c}_e (610.1 c_t + 3.1 c_b + 2.8 c_\tau - 1082.6 c_V + \dots)$
- Bounds strongly depend on assumptions about electron-Yukawa coupling.

Baryon asymmetry of the Universe

- Different techniques used in the literature to calculate BAU Y_B :

- Vev-insertion approach (VIA),

[Huet&Nelson,9504427,9506477;Carena et al., 9603420;Riotto, 9712221;Lee et al.,0412354]

- WKB (or FH) approximation.

[Joey et al.,9410282;Kainulainen et al.,0105295, 0202177;Prokopec et al., 0312110, 0406140;Konstandin et al.,1302.6713, 1407.3132]

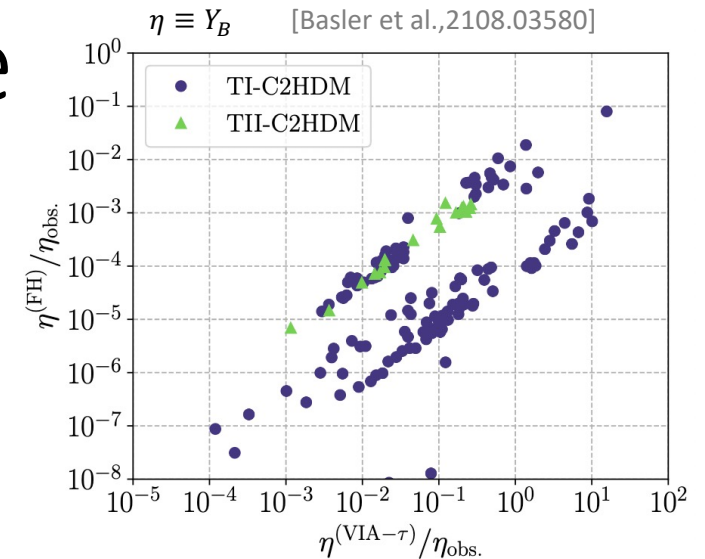
- VIA approach yields consistently higher results by orders of magnitude.
- We use VIA approach with bubble wall parameters close to optimal values for Y_B :

[de Vries,1811.11104;Fuchs et al.,2003.00099,2007.06940;Shapira,2106.05338]

$$\frac{Y_B}{Y_B^{\text{obs}}} \simeq 28\tilde{c}_t - 0.2\tilde{c}_b - 11\tilde{c}_\tau + \dots$$

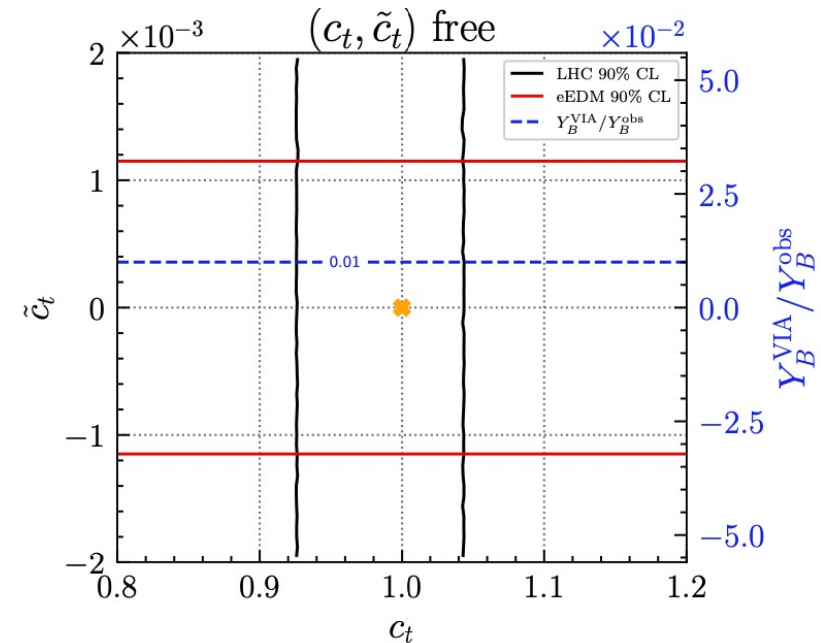
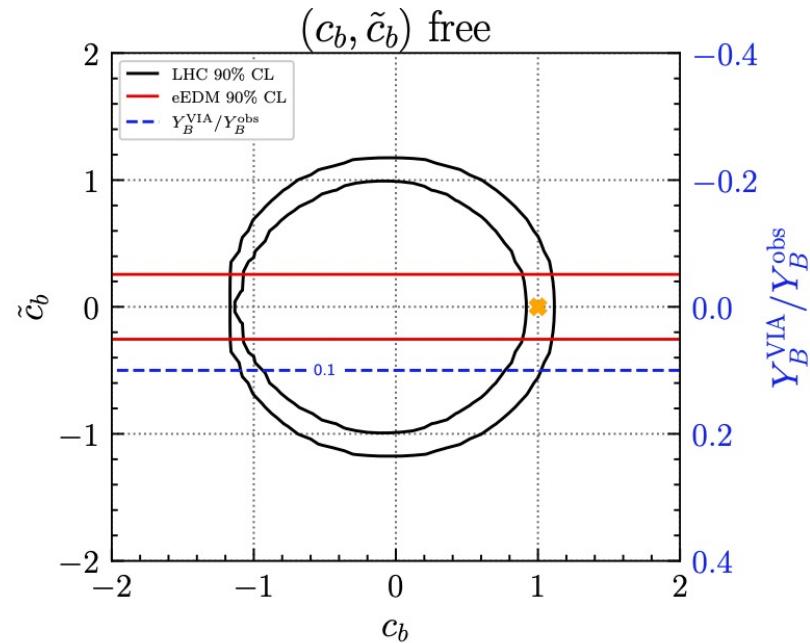


Y_B values should be regarded as **upper bound** on what is theoretically achievable.



1 flavor results: t and b

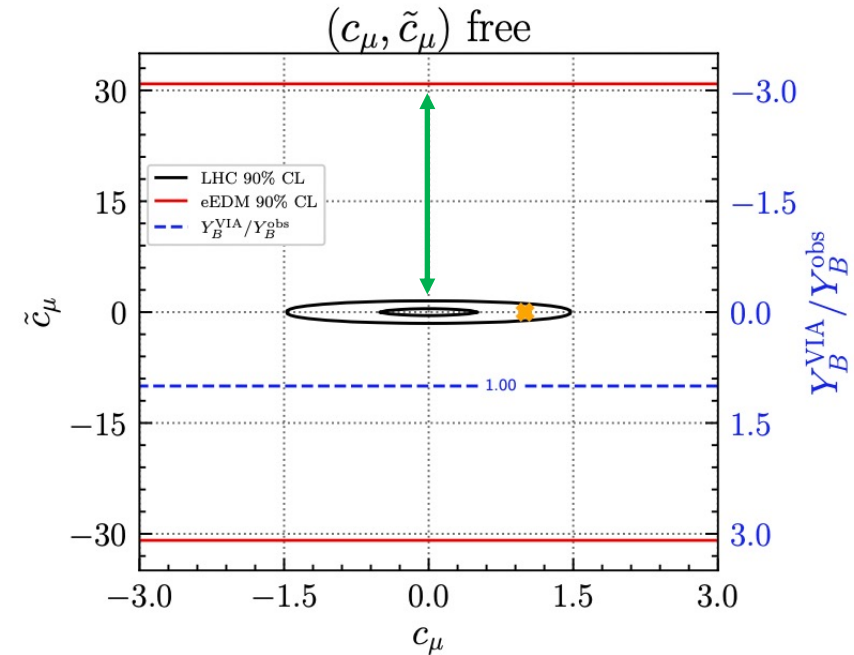
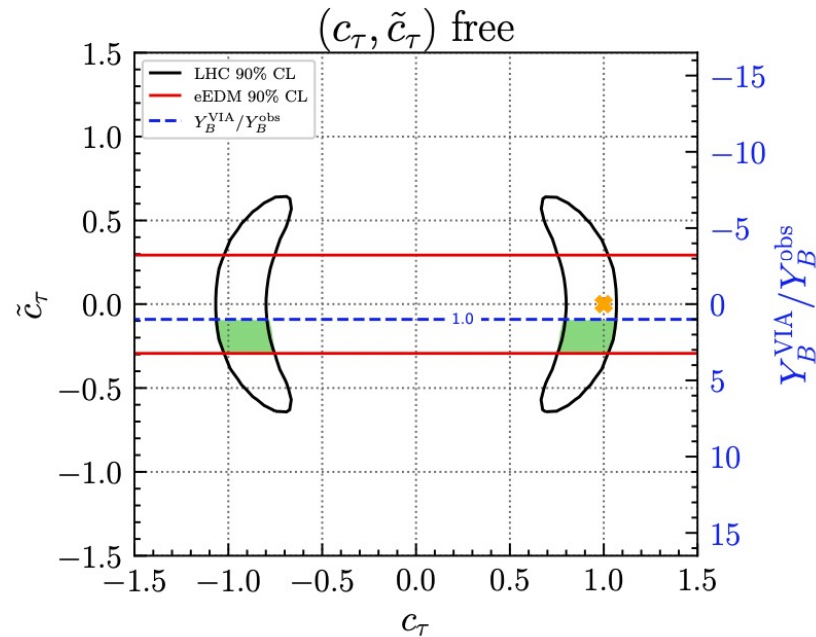
[HB et al.,2202.11753]



- CP-violating bottom-Yukawa coupling contributes too less to BAU.
- CP-violating top-Yukawa coupling strongly constrained by eEDM → not able produce sufficient BAU.

1 flavor results: τ and μ

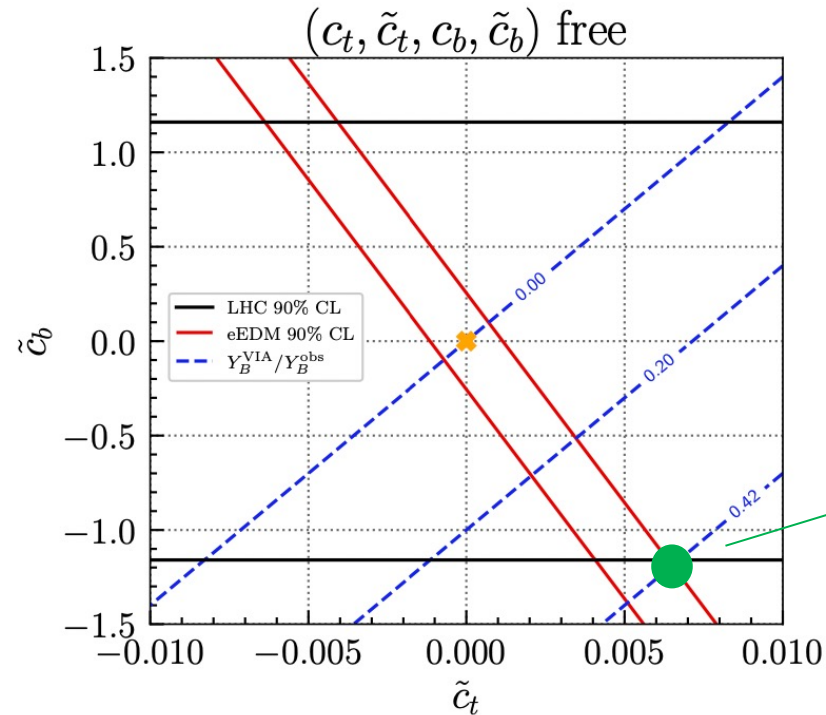
[HB et al.,2202.11753]



- CP-violating tau-Yukawa coupling can potentially explain BAU within LHC and eEDM constraints.
- LHC constraints on CP-violating muon-Yukawa coupling are **stronger** than eEDM bounds.

2 flavor results: t and b

[HB et al., 2202.11753]



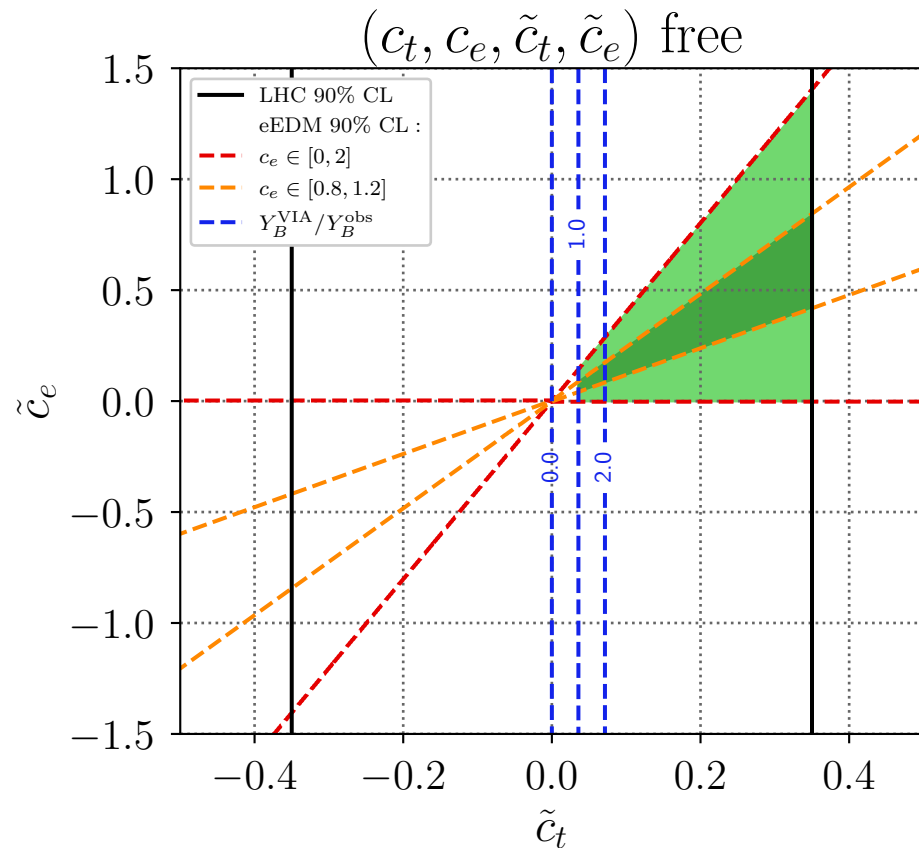
Maximal Y_B/Y_B^{obs} within LHC and eEDM constraints:

	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

- Presence of more than one CP-violating coupling allows for cancellation in eEDM.
 → Larger values for Y_B/Y_B^{obs} can be reached.

Dependence on electron-Yukawa coupling

[HB et al., 2202.11753]

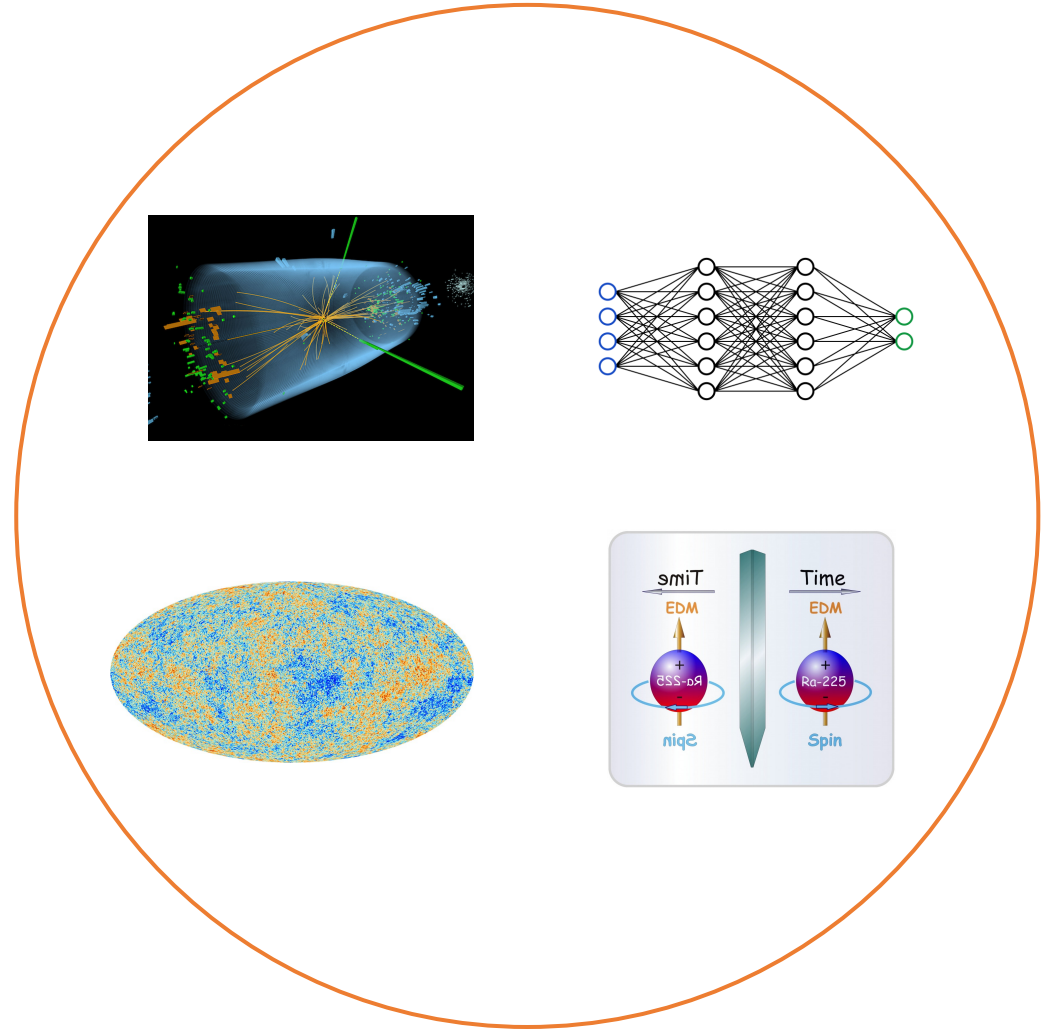


- Electron Yukawa-coupling only very weakly constrained ($g_e \leq 268$ at 95% CL).
- If c_e smaller, eEDM significantly weakened.
- Moreover, we can fine-tune CP-odd electron-Yukawa coupling such that $d_e < d_e^{\text{ACME}}$.
- Neutron EDM has similar dependence on first-generation quark-Yukawa couplings.



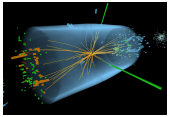
LHC bounds important since they do not depend on 1st gen. Yukawa couplings.

Conclusions

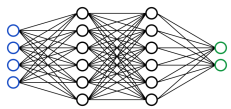


Conclusions

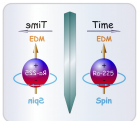
Initial question: how well can we constrain **CP violation in the Higgs–fermion interactions** and what are the implications for the BAU?



LHC already tightly constrains CP violation in the **top- and tau-Yukawa couplings**.

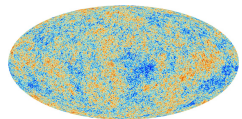


To improve bounds in the **future**, we need to exploit all available information using e.g. **machine-learning based inference**.



Complementarity of LHC, EDM, and baryogenesis constraints:

- CP violation in tau-Yukawa coupling remains viable source for electroweak baryogenesis.
- LHC allows to distinguish between CP violation in various Yukawa couplings (beginning to probe 2nd generation).
- EDM interpretation strongly depends on first generation Yukawa couplings.



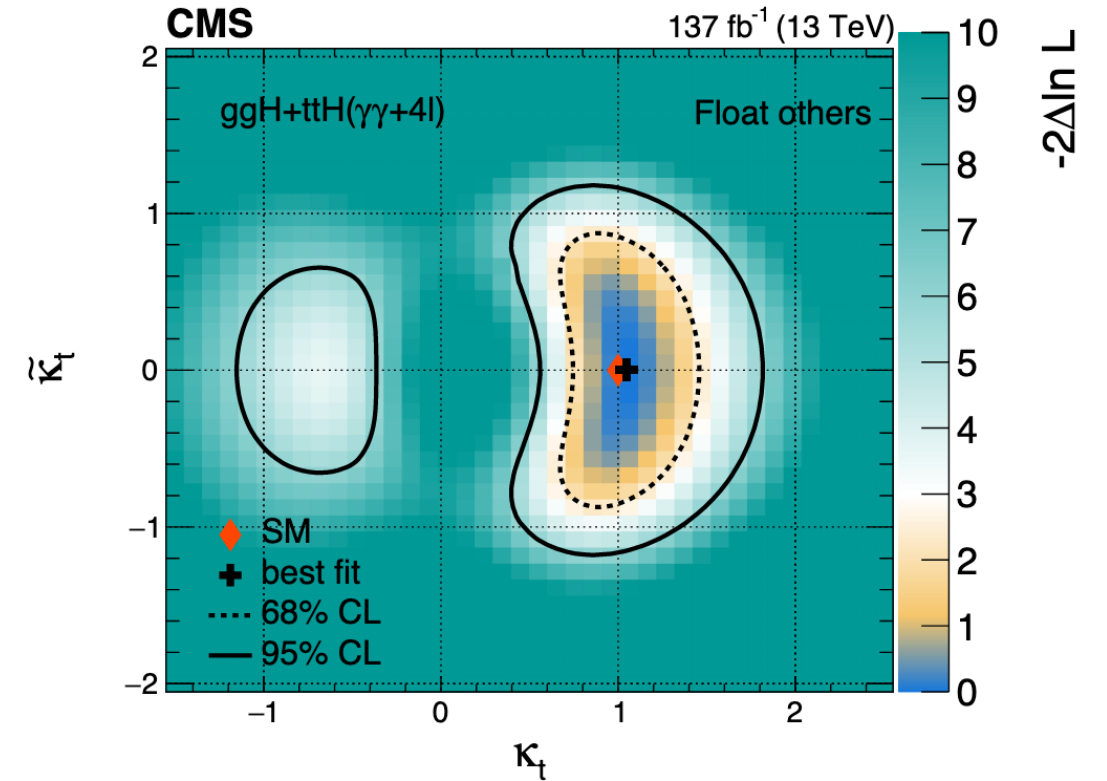
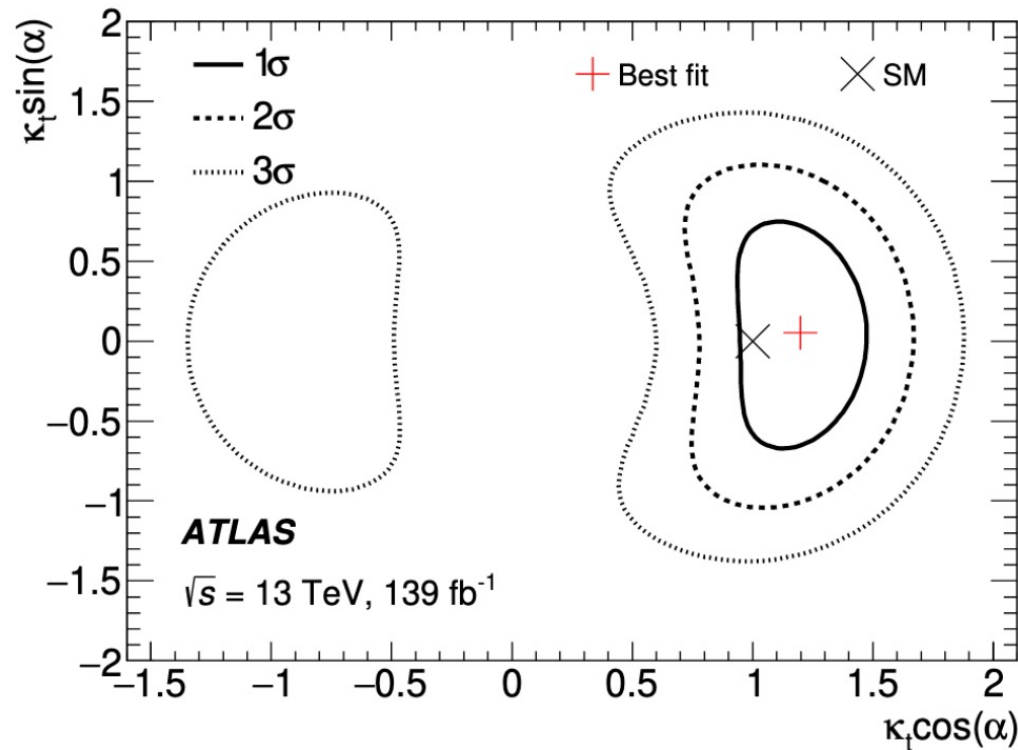
Thanks for your attention!

Appendix

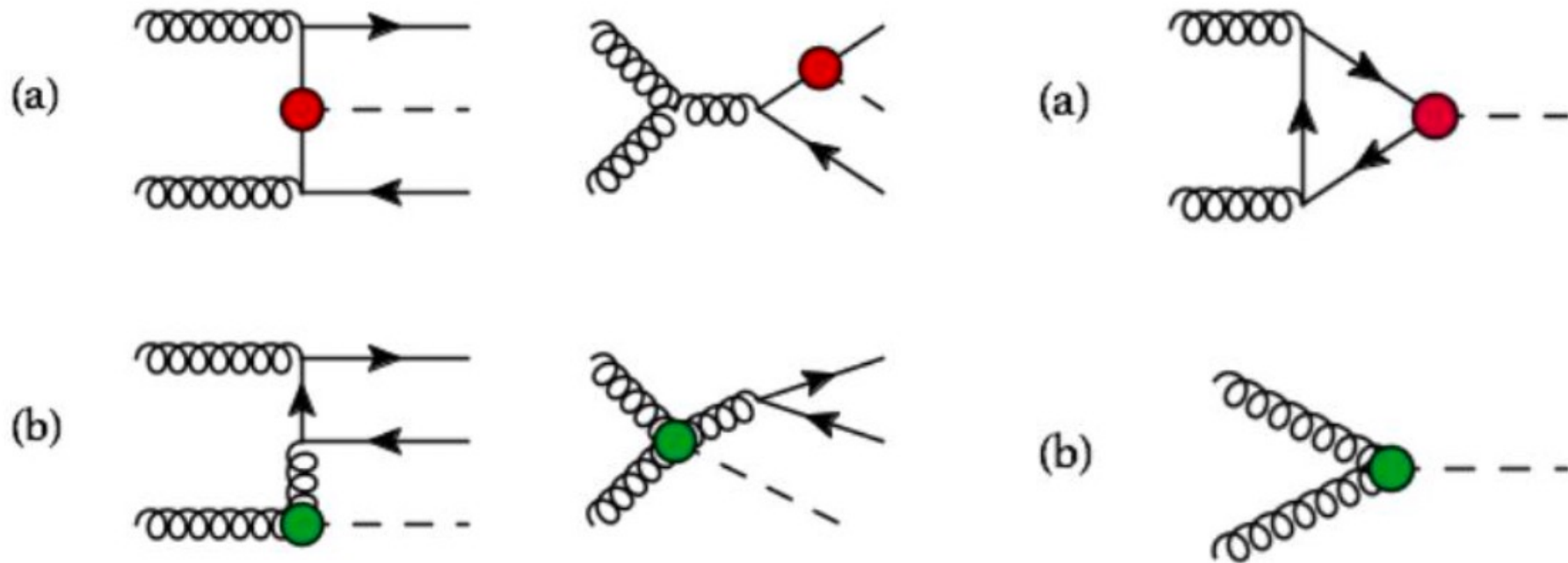
Reasons for not including ATLAS and CMS top CP studies

- CMS study: [2003.10866]
 - All Higgs production modes (apart from top-associated Higgs production) are constrained to their SM predictions.
 - No two-dimensional likelihood given when our study was published (now available in [CMS-PAS-HIG-19-009])
- ATLAS study: [2004.04545]
 - Two setups:
 1. κ_g (and κ_γ) constrained by other measurements (ggH) excluding $t\bar{t}H$ and tH but events generated at NLO \rightarrow top-associated Higgs production and gluon fusion cannot be regarded as independent.
 2. κ_g and κ_γ calculated as function of c_t and \tilde{c}_t .
 - Assumed HVV couplings equal to SM value.

Experimental top CP studies [ATLAS,2004.04545;CMS,2104.12152]

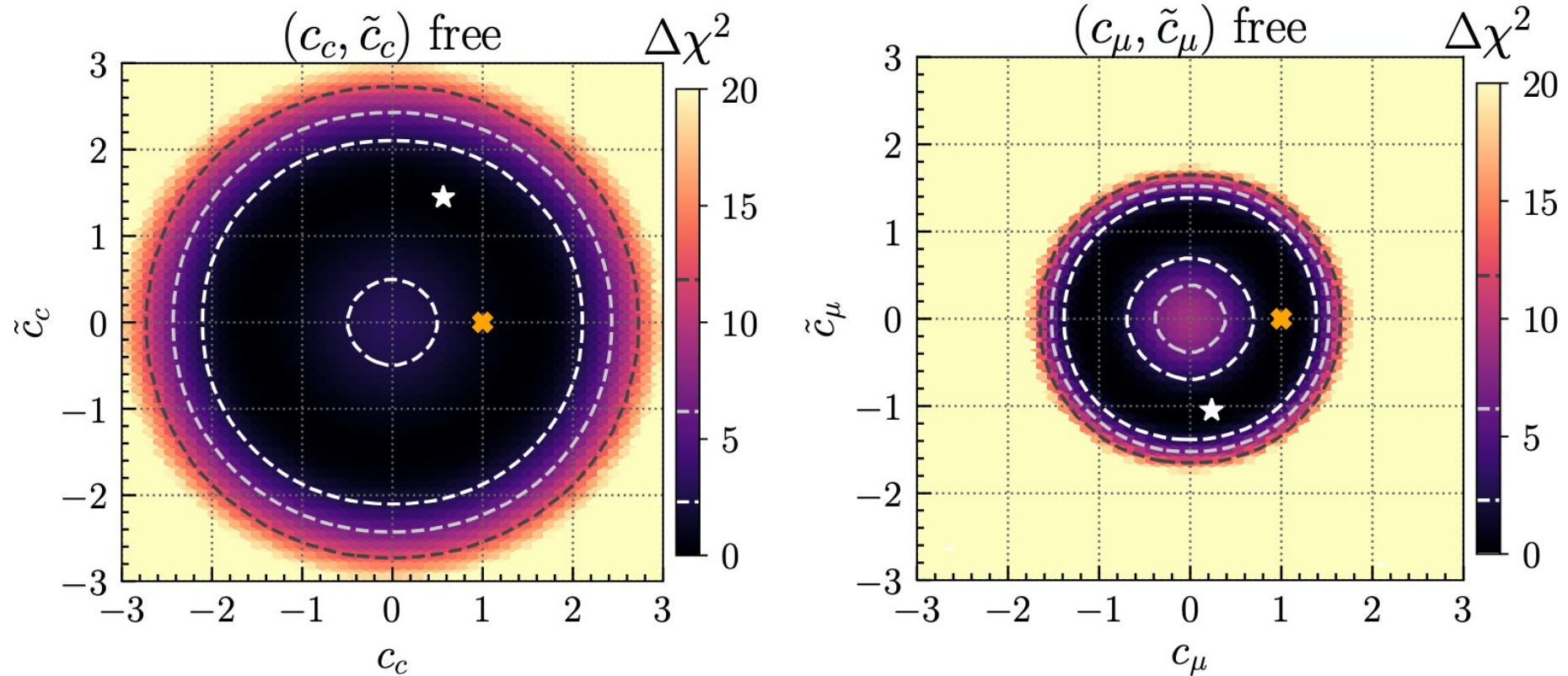


Correlation between ggH and $t\bar{t}H$ at NLO

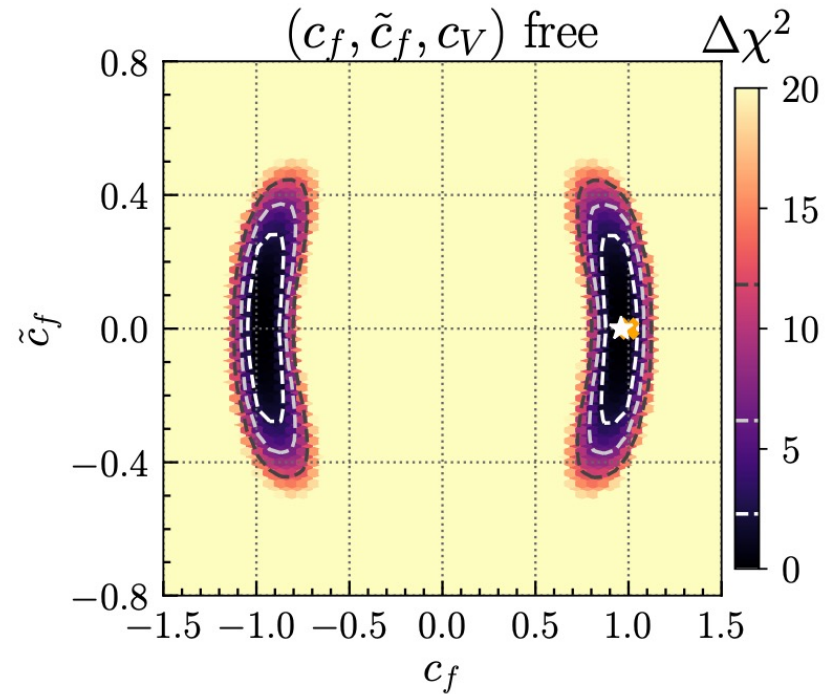
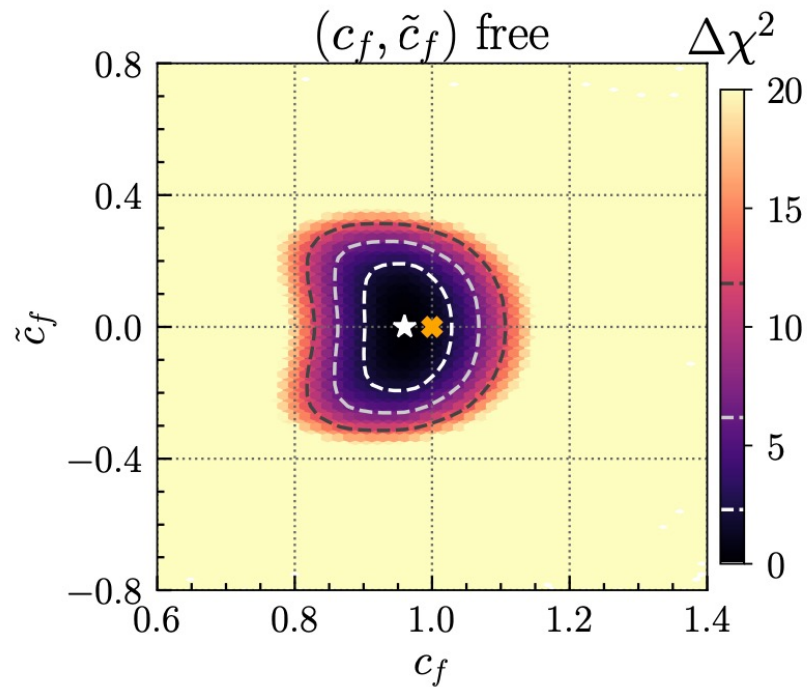


[Maltoni,Vryonidou,Zhang,1607.05330]

Charm- and muon-Yukawa couplings



Global modification fits

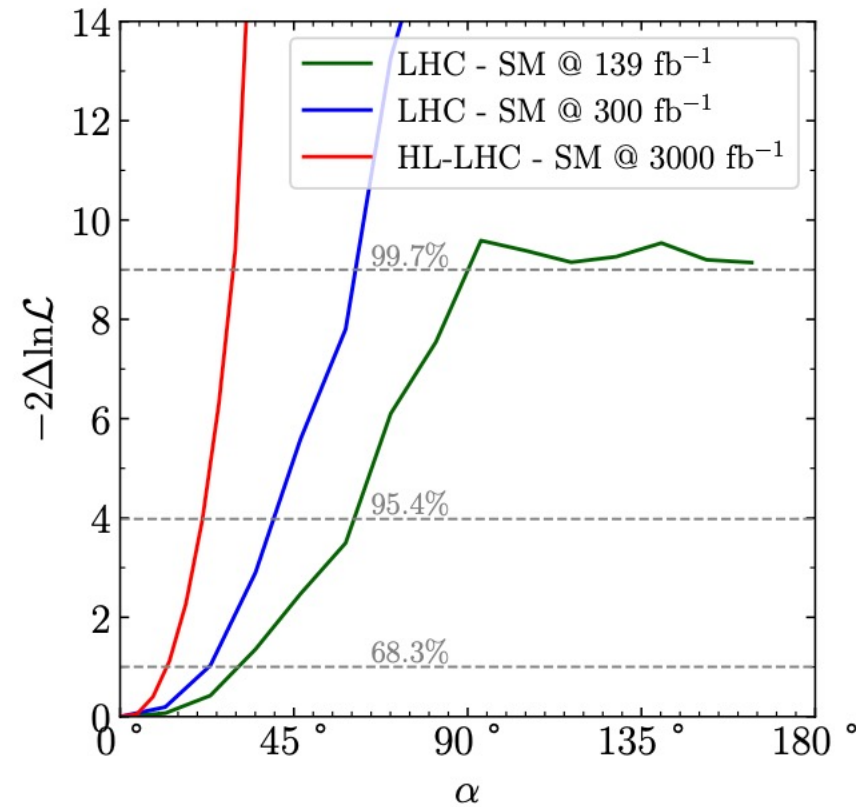


- Universal fermion coupling modifiers: $c_f = c_t = c_b = \dots = c_\tau$, $\tilde{c}_f = \tilde{c}_t = \tilde{c}_b = \dots = \tilde{c}_\tau$.
- Dominated by constraints on top-Yukawa coupling.
- Additional varying c_V reopens negative c_f range.

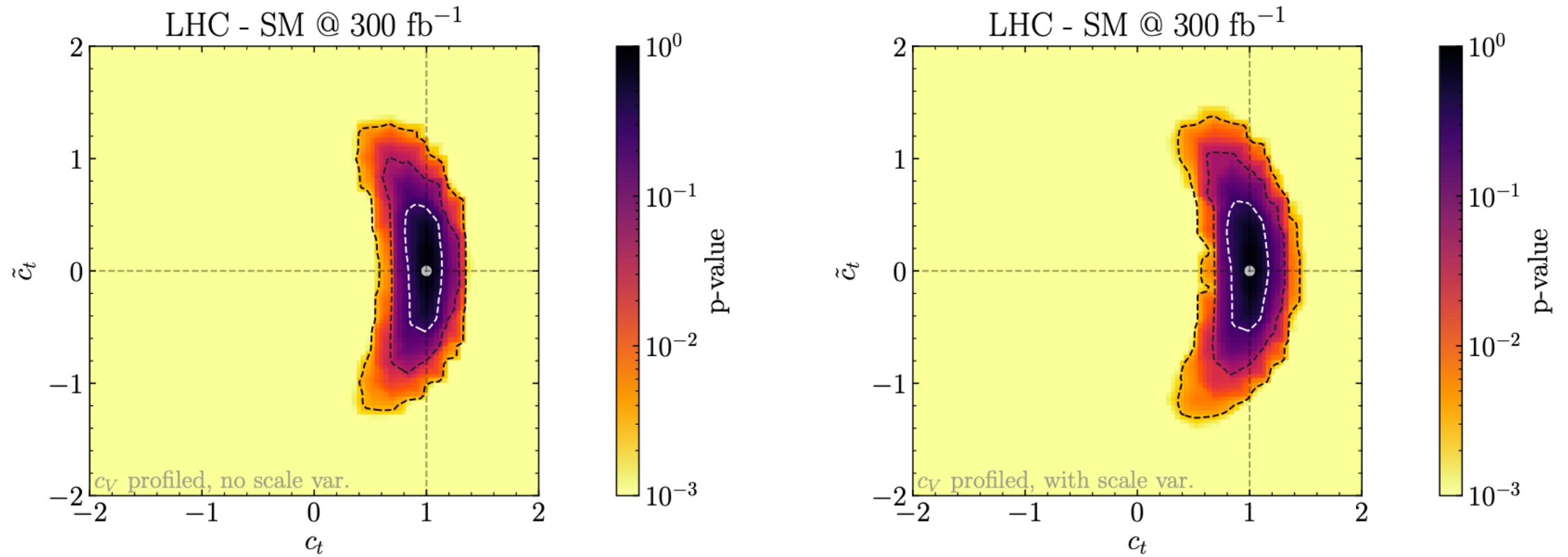
observable	condition
N_γ	≥ 2 (with $ \eta < 2.5$ and $p_T > 25$ GeV)
$(p_{T,1}^\gamma, p_{T,2}^\gamma)$	$\geq (35, 25)$ GeV
$m_{\gamma\gamma}$	$[105 - 160]$ GeV
$(p_{T,1}^\gamma/m_{\gamma\gamma}, p_{T,2}^\gamma/m_{\gamma\gamma})$	$\geq (0.35, 0.25)$
N_ℓ	≥ 1 (with $ \eta < 2.5$ and $p_T > 15$ GeV)
$m_{\ell\ell}$	$[80, 100]$ GeV vetoed if same flavour
N_{jet}	≥ 1 (with $ \eta < 2.5$ and $p_T > 25$ GeV)

Table 1: Summary of preselection cuts.

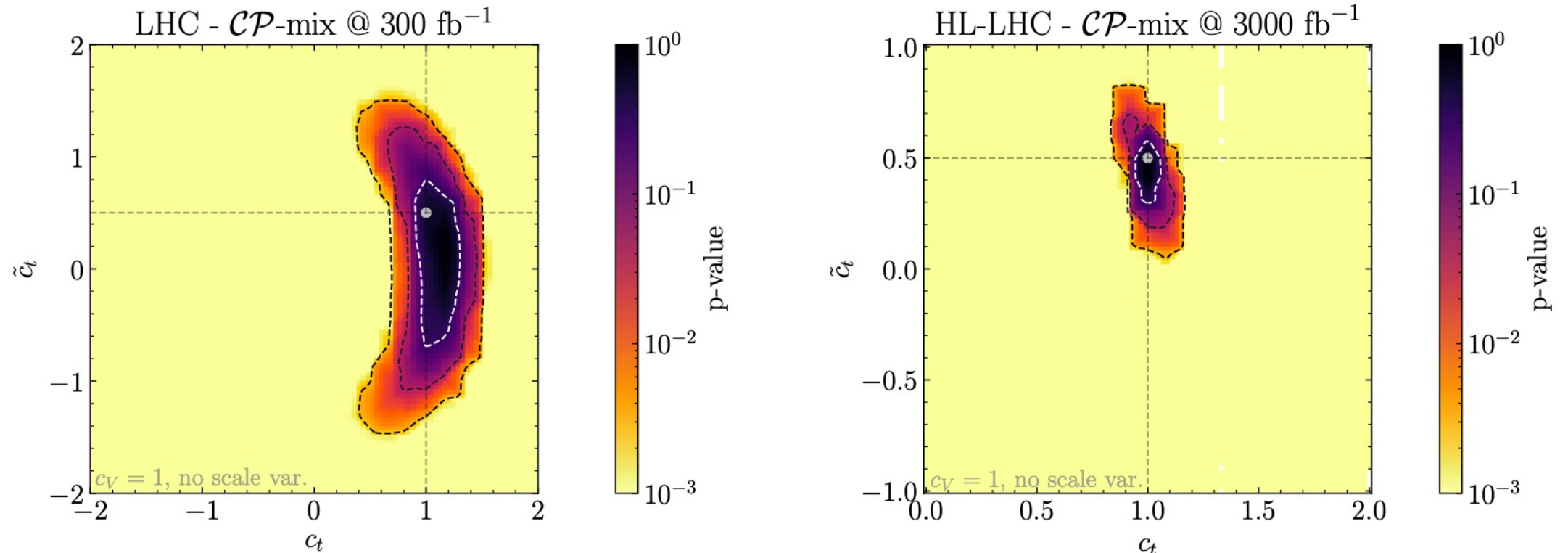
Interpretation in terms of CP-violating angle



Variation of c_V and renormalization scale

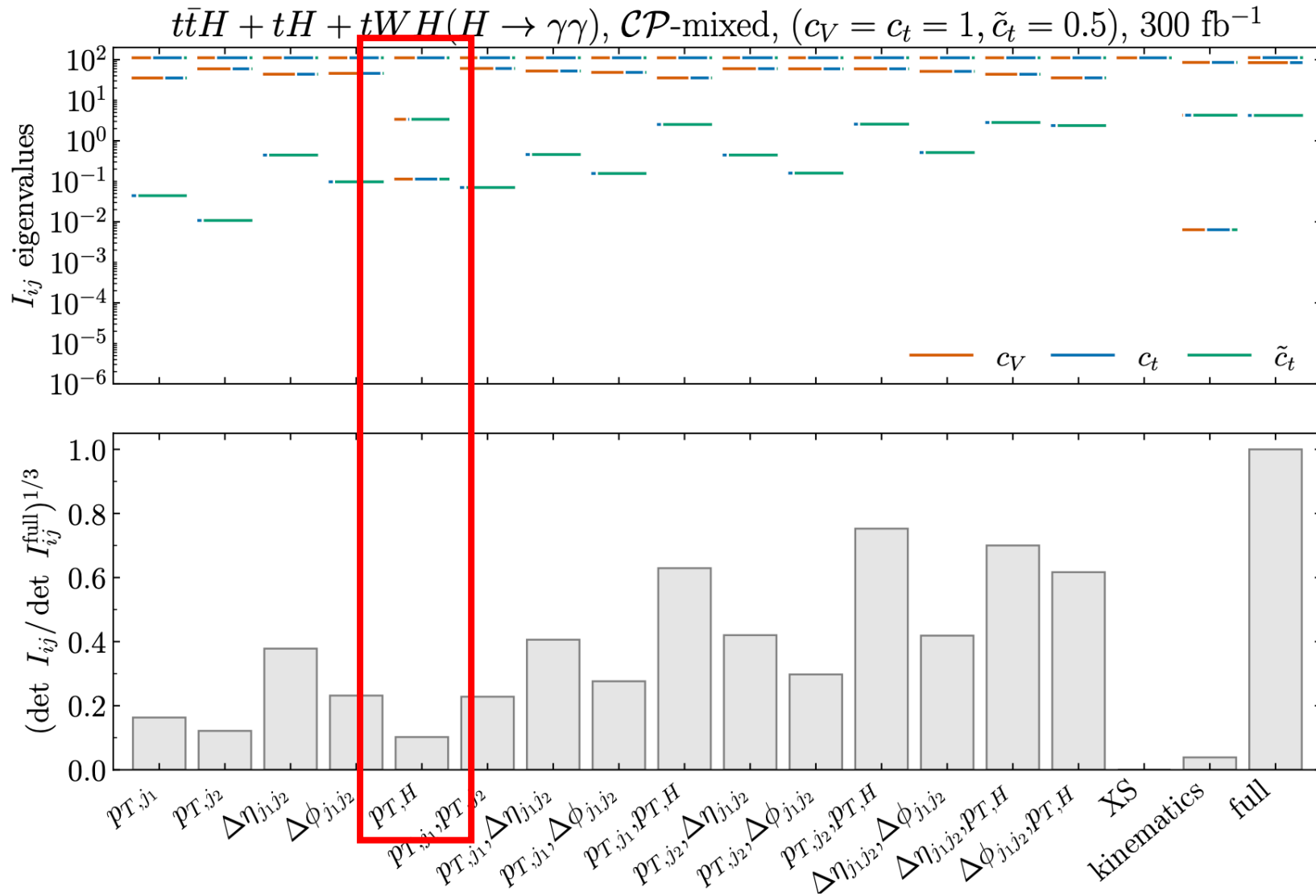


Limits in case of deviation from SM



- CP-mix: $c_t = 1, c_{\tilde{t}} = 0.5, c_V = 1.$

Fisher information for CP-mixed scenario



- For CP-mixed scenario, Higgs p_T captures sizeable amount of information on $c_{\tilde{t}}$.



- p_T binned STXS measurements useful to constrain CP violation in the top-Yukawa coupling.