Constraining CP violation in the Higgs–fermion interactions

Henning Bahl

THE UNIVERSITY OF
CHICAGO

Argonne HEP Theory Seminar, December 6th 2022

Talk based on

- **2007.08542, JHEP 11 (2020) 127**:

  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, and G. Weiglein.

- **2110.10177, JHEP 03 (2022) 017**:

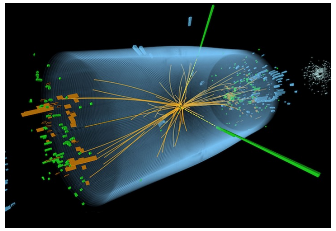
  Constraining CP-violation in the Higgs-top-quark interaction using machine-learning-based inference;
  in collaboration with S. Brass.

- **2202.11753, Eur.Phys.J.C 82 (2022) 7, 604**:

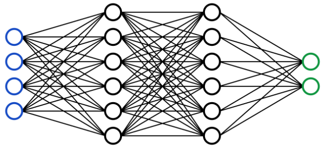
  Constraining the CP structure of Higgs-fermion couplings with a global LHC fit, the electron EDM and baryogenesis;
  in collaboration with E. Fuchs, S. Heinemeyer, J. Katzy, M. Menen, K. Peters, M. Saimpert, and G. Weiglein.

- **Work in preparation** in collaboration with E. Fuchs, and M. Menen

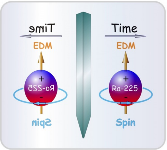
Outline of the talk

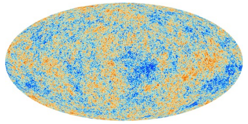


Global LHC fit



Constraining CP violation using machine learning



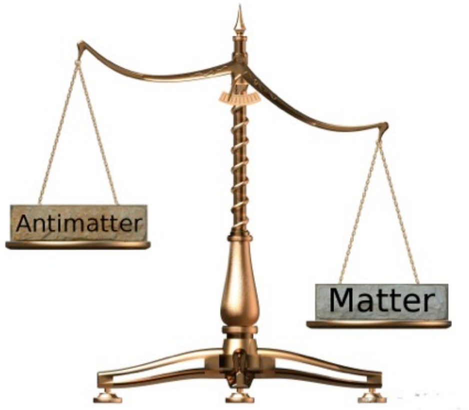


Complementarity with EDM and baryogenesis constraints

Introduction

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

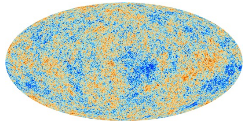
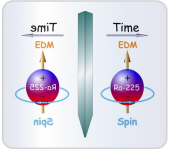
CP violation in the Higgs sector

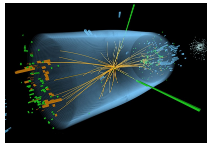


- New sources of CP violation are necessary to explain the baryon asymmetry of the Universe.
- One possibility: CP violation in the Higgs sector.

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.

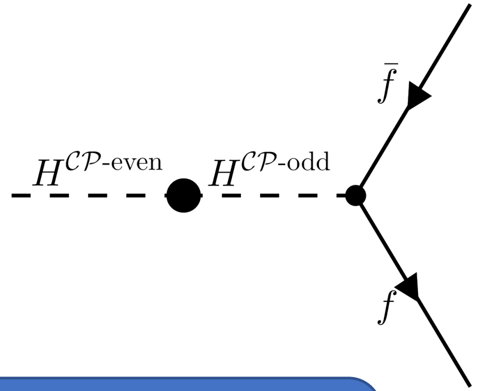


The CP nature of the Higgs boson

- CP violation in HVV couplings already tightly constrained via VBF and $pp \to VH$ production as well as $H \to 4l$ 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 → expected to be small in most BSM theories.

- CP violation in Higgs–fermion couplings can be induced at the tree level.

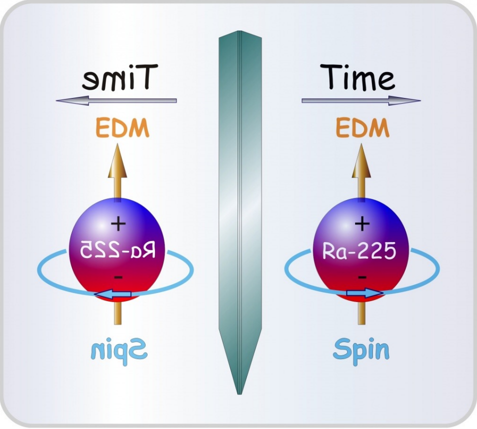


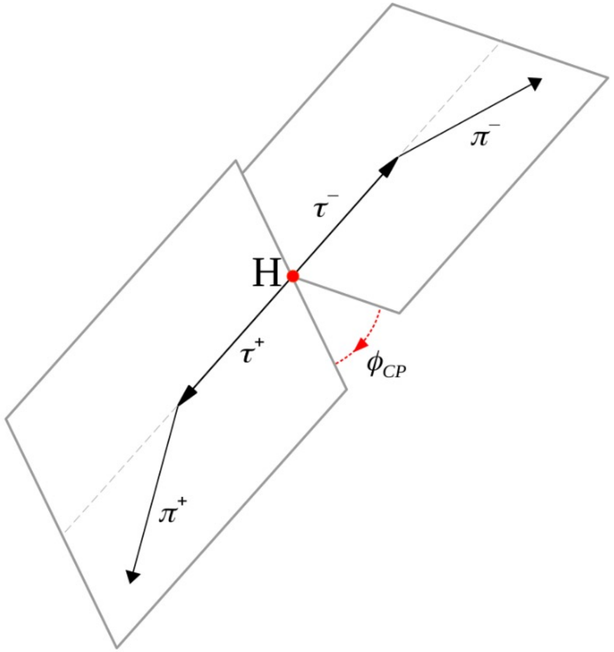
Focus of this talk: Constraining CP violation in the Higgs–fermion interactions.

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 $H \to \tau^+\tau^-$.
  - Experimentally difficult for some processes (i.e., top-associated Higgs production).

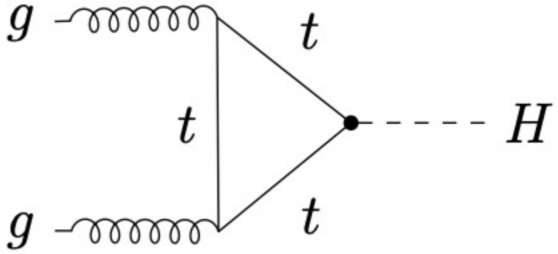


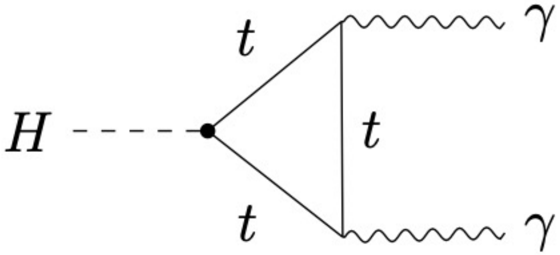


Constraining CP violation

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,
    - $H \to \gamma\gamma$.
  - Deviations from SM need not be due to CP violation.

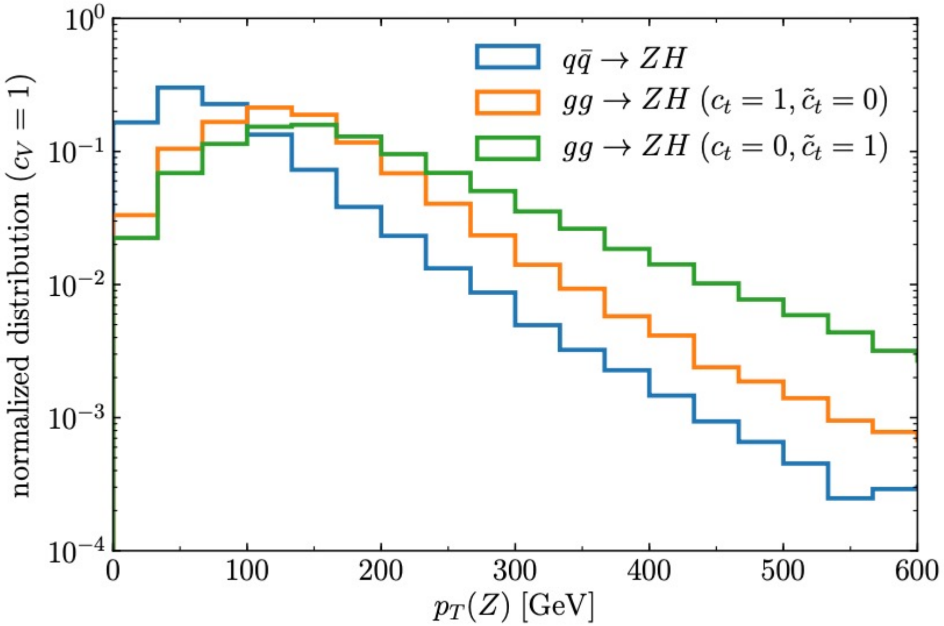




Constraining CP violation

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.

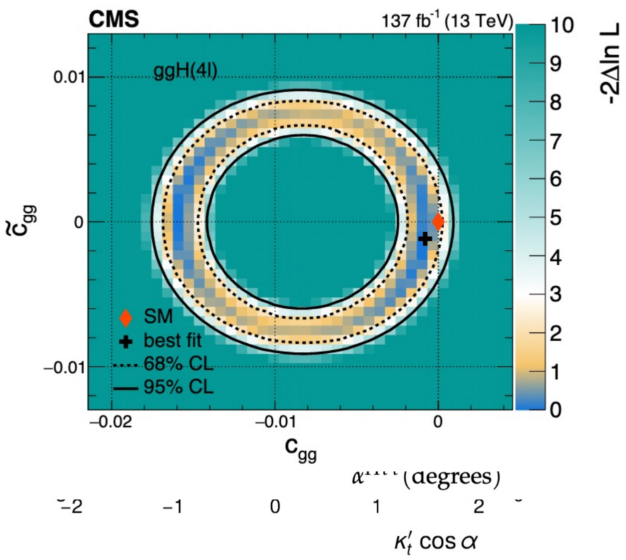


Exploit all three complementary approaches to learn as much as possible!

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

[ATLAS-CONF-2022-016]
[CMS 2110.04836]
[CMS, 2104.12152]



- 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

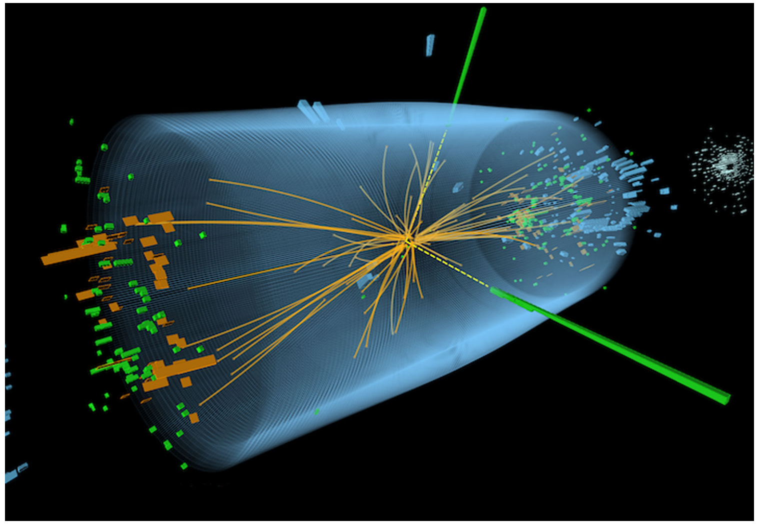
- Modify Yukawa interactions by (e.g. generated by dim-6 $(\phi^\dagger\phi)Q_L\tilde{\phi}t_R$ operator)

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

- Allow moreover for CP-conserving modification of HVV couplings

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

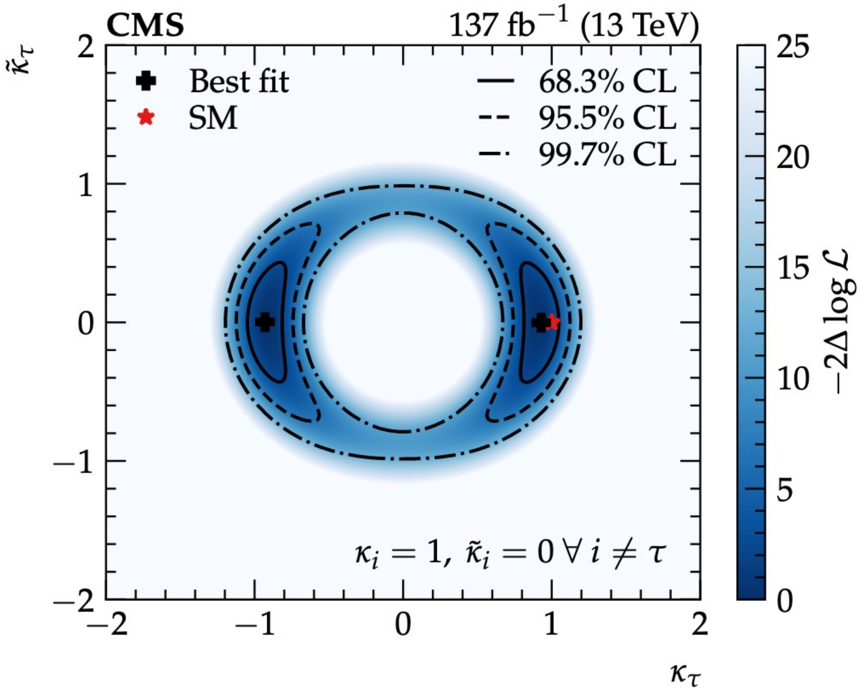
- SM: $c_f = 1$, $\tilde{c}_f = 0$, $c_V = 1$.
- Parametrize effect of undiscovered colored and neutral BSM particles via effective Higgs–gluon and Higgs–photon interactions.



Global LHC fit

What can we learn from current LHC data?

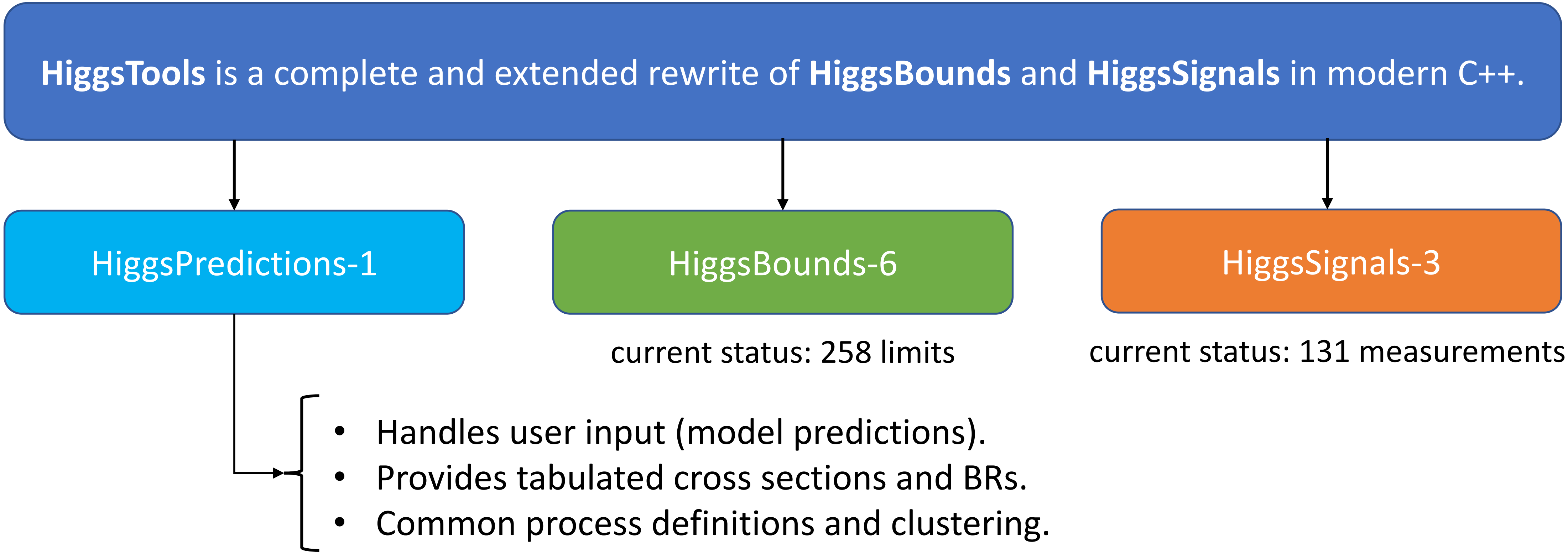
LHC constraints — setup



- Experimental input:
  - All relevant Higgs measurements:
    - Rate measurements (production + decay),
    - ZH STXS measurements (p_T shape),
    - CMS $H \to \tau\tau$ 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.

Interlude: HiggsTools

[HB et al., 2210.09332]



HiggsTools is a complete and extended rewrite of **HiggsBounds** and **HiggsSignals** in modern C++.

HiggsPredictions-1

HiggsBounds-6

current status: 258 limits

HiggsSignals-3

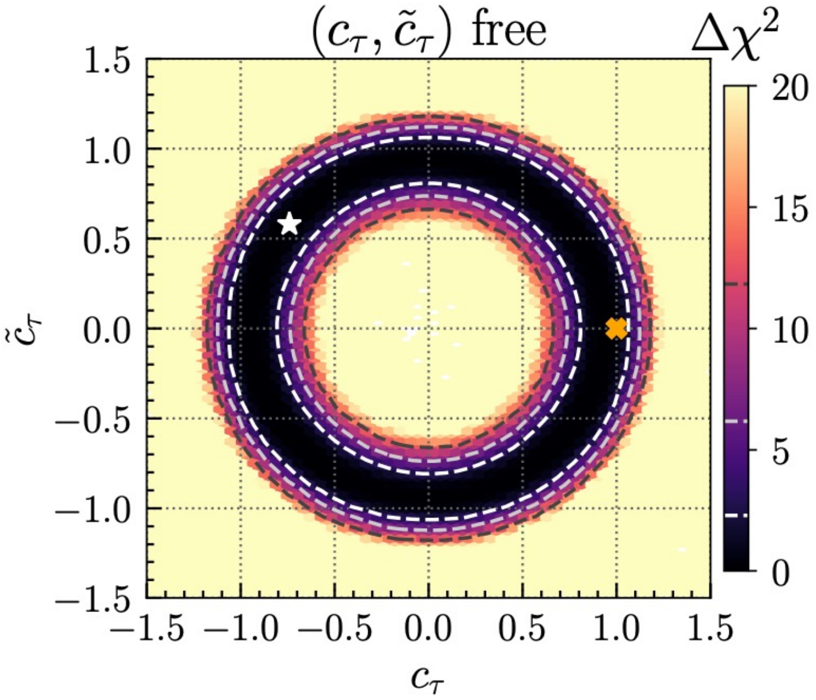
current status: 131 measurements

- Handles user input (model predictions).
- Provides tabulated cross sections and BRs.
- Common process definitions and clustering.

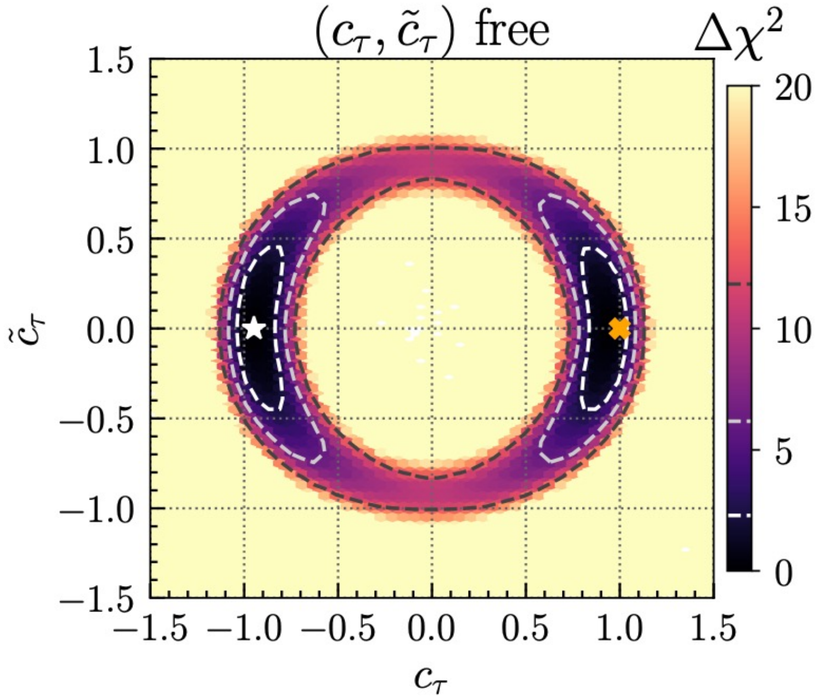
→ C++ interface for high performance; Python and Mathematica interfaces for ease of use.

Starting point — 1 flavor fits: τ

[HB et al.,2202.11753]



Without CMS $H \to \tau\tau$ CP analysis.

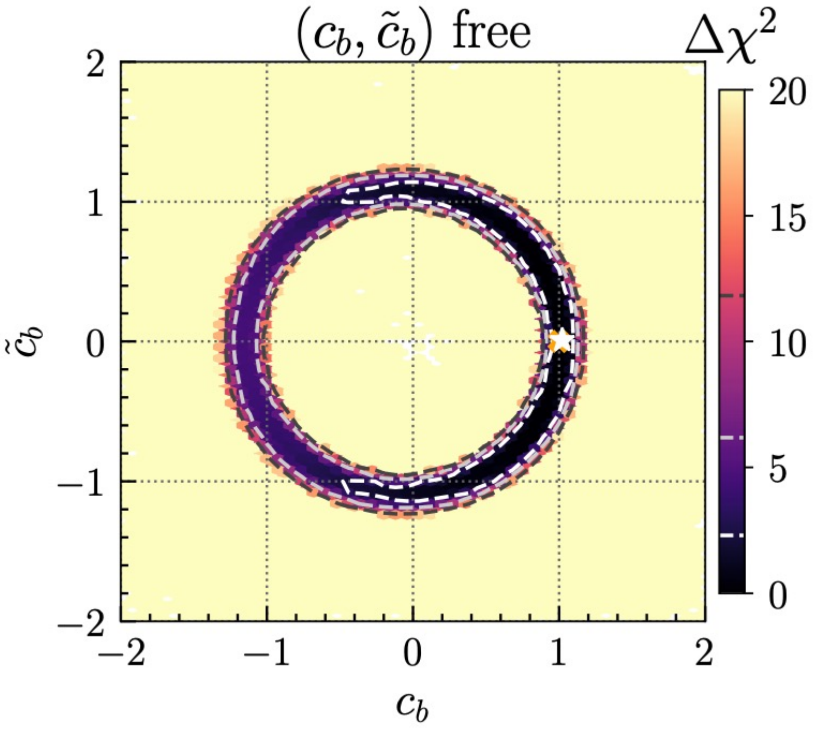


With CMS $H \to \tau\tau$ CP analysis.

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

1 flavor fits: b

[HB et al.,2202.11753]

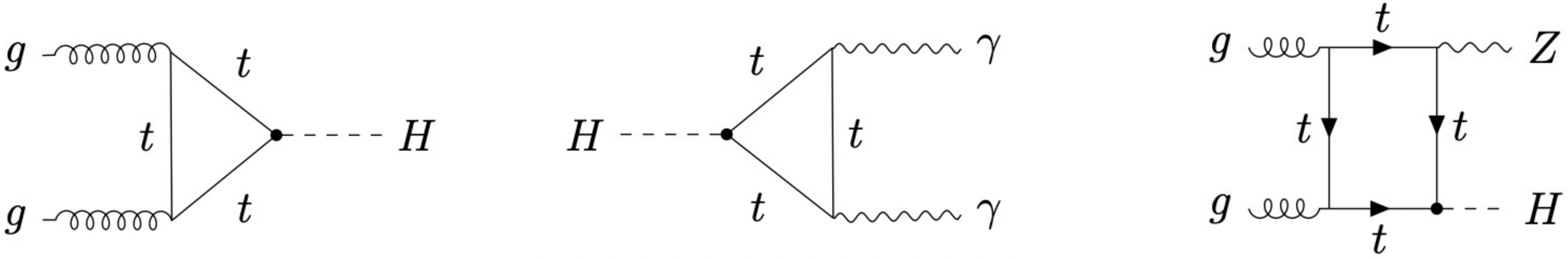


- Ring-like structure since $\Gamma_{H\to bb} \propto c_b^2 + \tilde{c}_b^2$.
- Bottom-Yukawa coupling, however, also affects ggH rate:
  - $\frac{\sigma_{gg\to H}}{\sigma_{gg\to H}^{\text{SM}}} \simeq 1.1c_t^2 + 2.6\tilde{c}_t^2 \boxed{-\,0.1c_tc_b} + \cdots.$
- Negative c_b values disfavored since 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

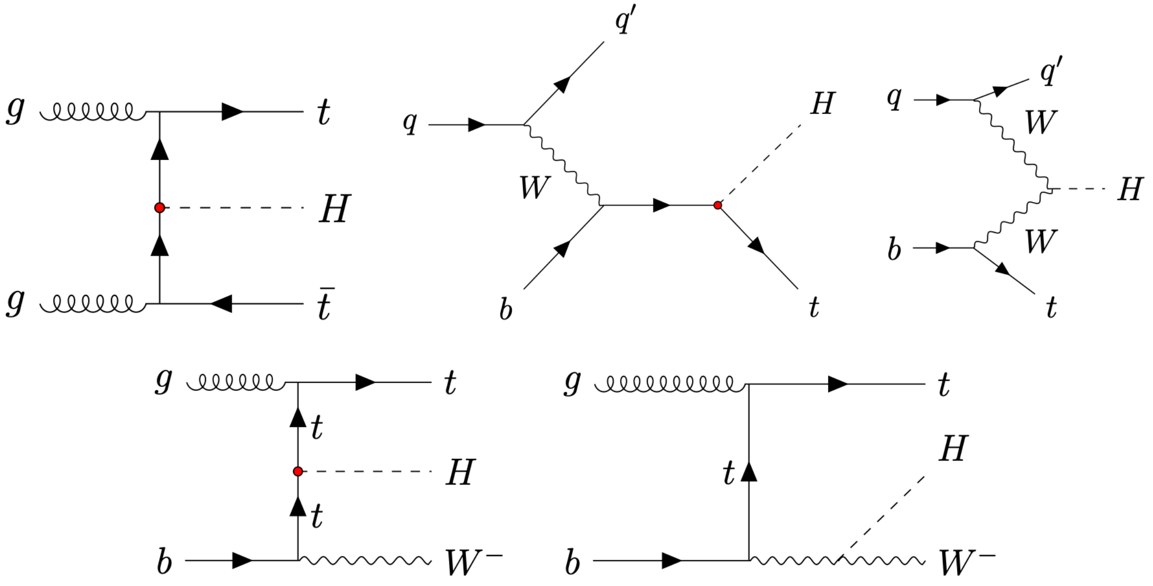
- Probe top-Yukawa coupling at the loop-level via $gg \to H, H \to \gamma\gamma$, gg $\to ZH$:

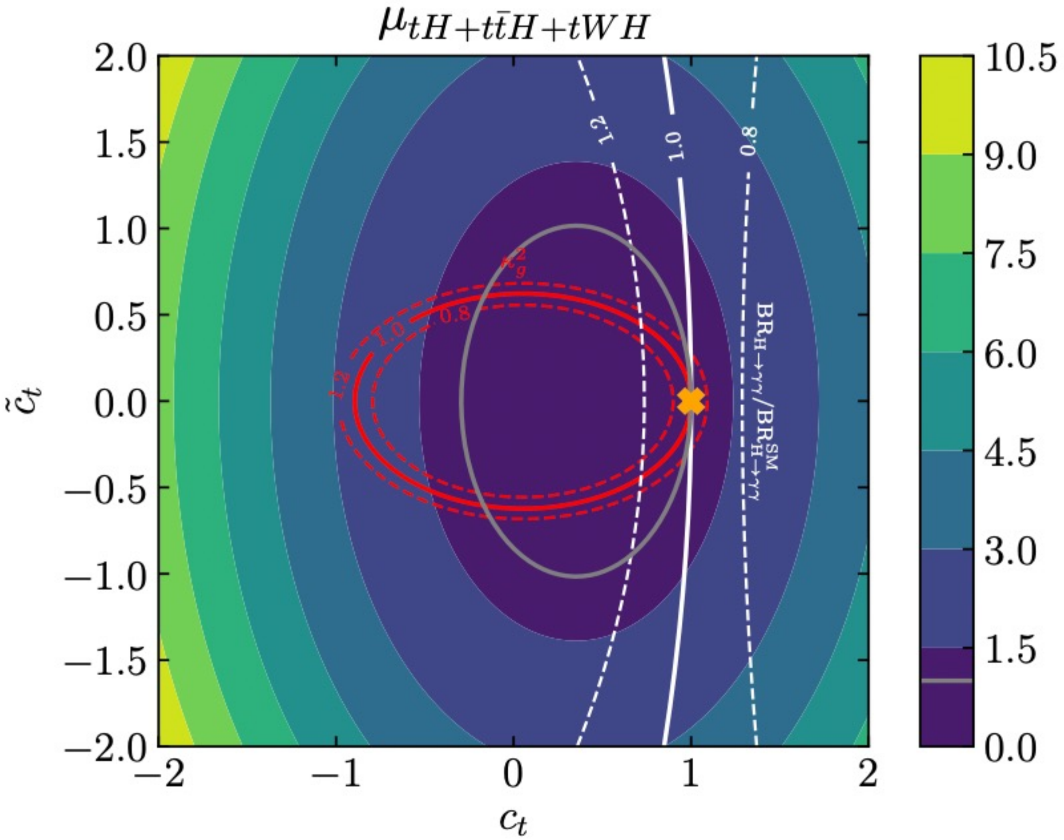


- $\kappa_g^2 \equiv \frac{\sigma_{gg\to H}}{\sigma_{gg\to H}^{\text{SM}}} \simeq \boxed{1.1c_t^2 + 2.6\tilde{c}_t^2} - 0.1c_t c_b - 0.2\tilde{c}_t\tilde{c}_b + \cdots$, disfavors large $\tilde{c}_t$.
- $\kappa_\gamma^2 \equiv \frac{\Gamma_{H\to\gamma\gamma}}{\Gamma_{H\to\gamma\gamma}^{\text{SM}}} \simeq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

Top-Yukawa coupling

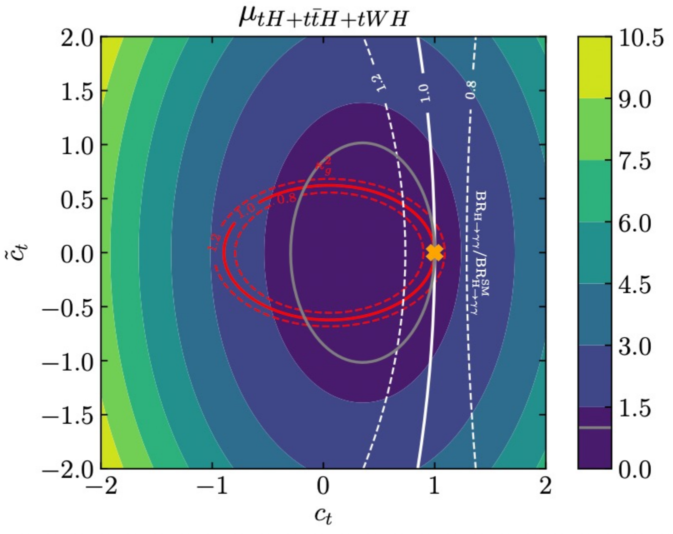
- Probe top-Yukawa coupling at the tree-level via top-associated Higgs production:
  - Three subchannels: $t\bar{t}H, tH, tWH$.
  - Difficult to disentangle experimentally.
  - Consider combined signal strength.

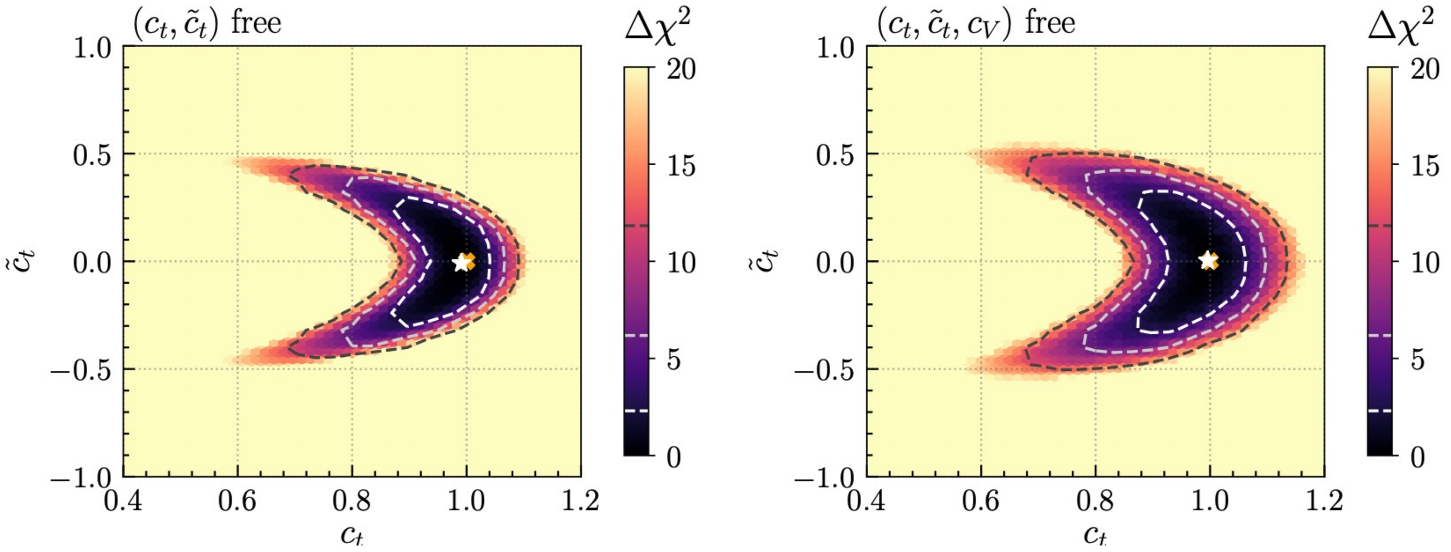




1 flavor fits: t

[HB et al.,2007.08542]

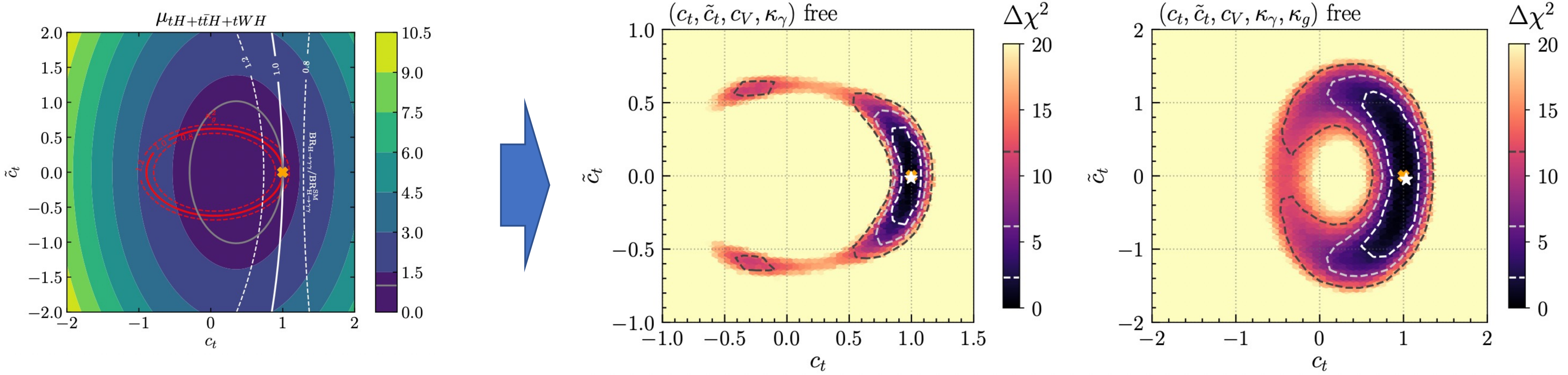




- ggH and $H \to \gamma\gamma$ total rates strongly constraint CP violation in top-Yukawa coupling.
- Relies on assumption that no other BSM physics affect ggH and $H \to \gamma\gamma$.
- What happens if we allow κ_γ and κ_g to float freely?

1 flavor fits: t — free κ_γ, κ_g

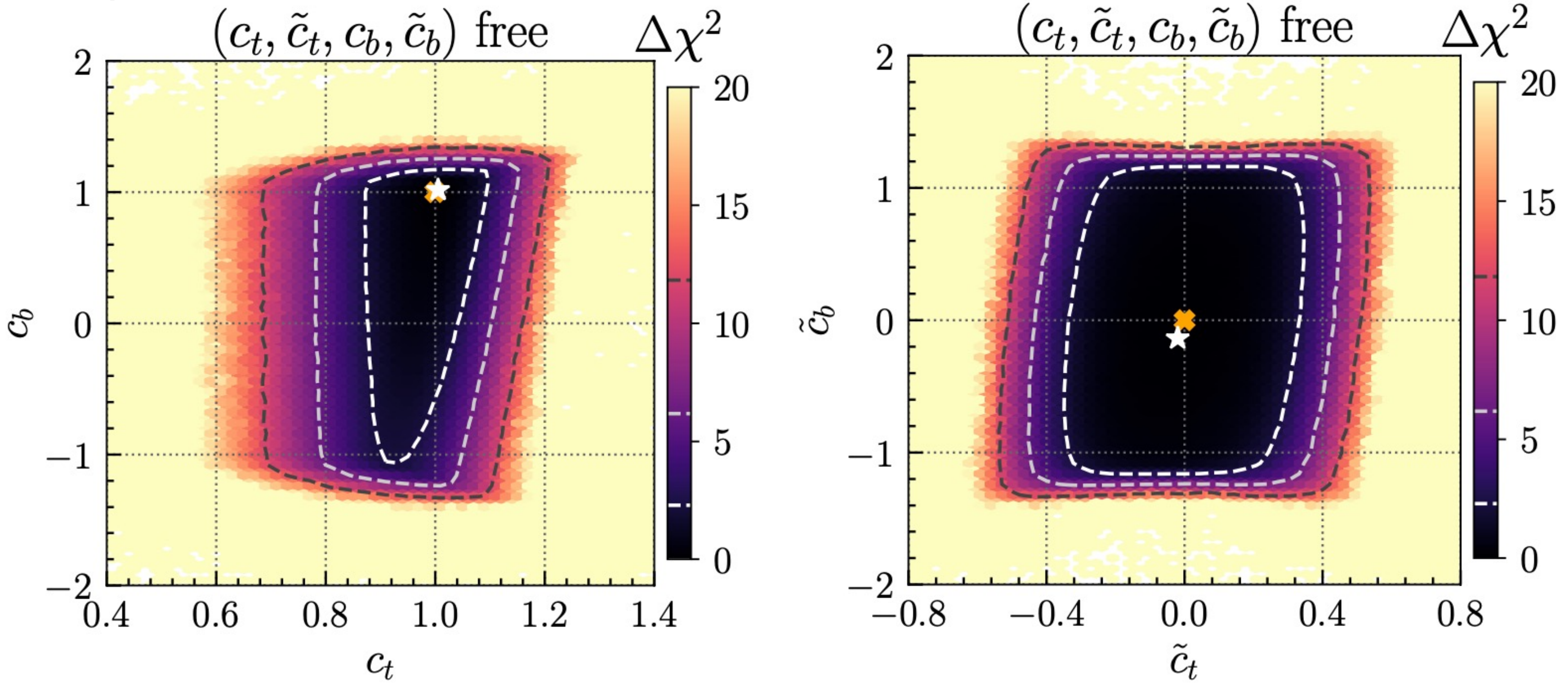
[HB et al.,2007.08542]



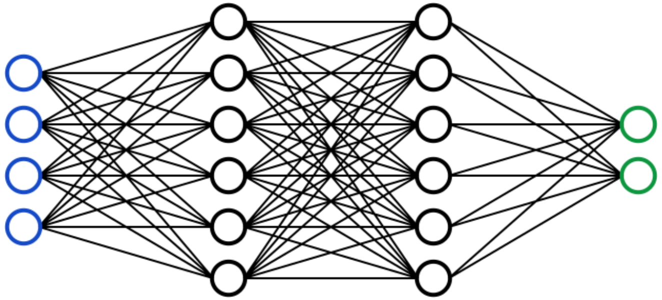
- Colored and charged BSM particles can cancel the effect of a modified top-Yukawa coupling.
- Top-associated Higgs production is a more model-independent but weaker probe.

2 flavor fits: t and b

[HB et al.,2202.11753]



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



Constraining CP-violation using machine learning

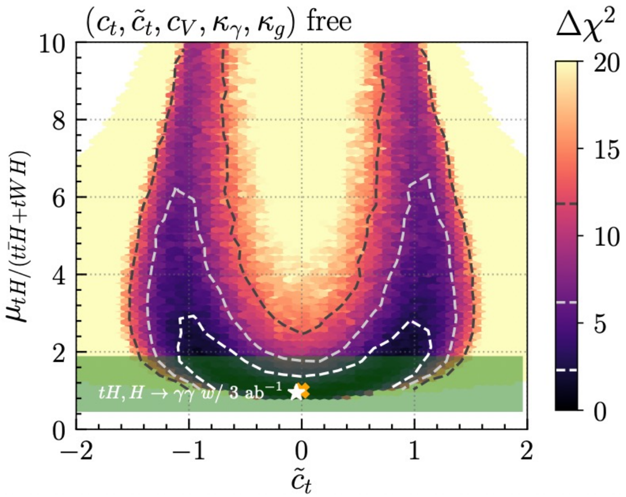
How can we improve the LHC bounds on the top-Yukawa coupling in the future?

Future probes of the top-Yukawa interaction

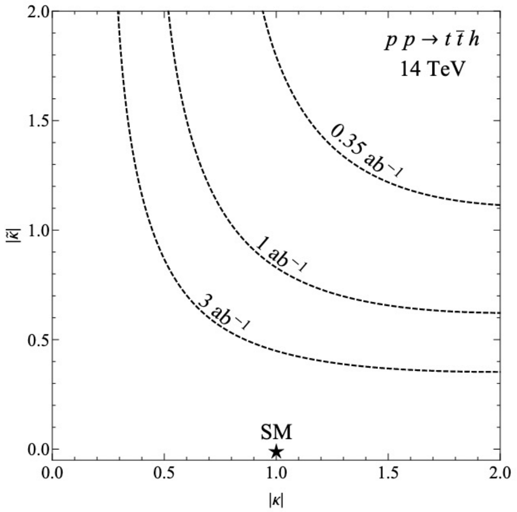
- Future rates measurements:
    - Need to disentangle $t\bar{t}H$ and tH to improve sensitivity on $\tilde{c}_t$. [HB et al., 2007.08542]
    - Possible alternative channels: $t\bar{t}$, $t\bar{t}t\bar{t}$. [Cao et al.,1901.04567;Martini et al.,2104.04277]
    - Even at HL-LHC comparably weak bounds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

- 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.

- 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.



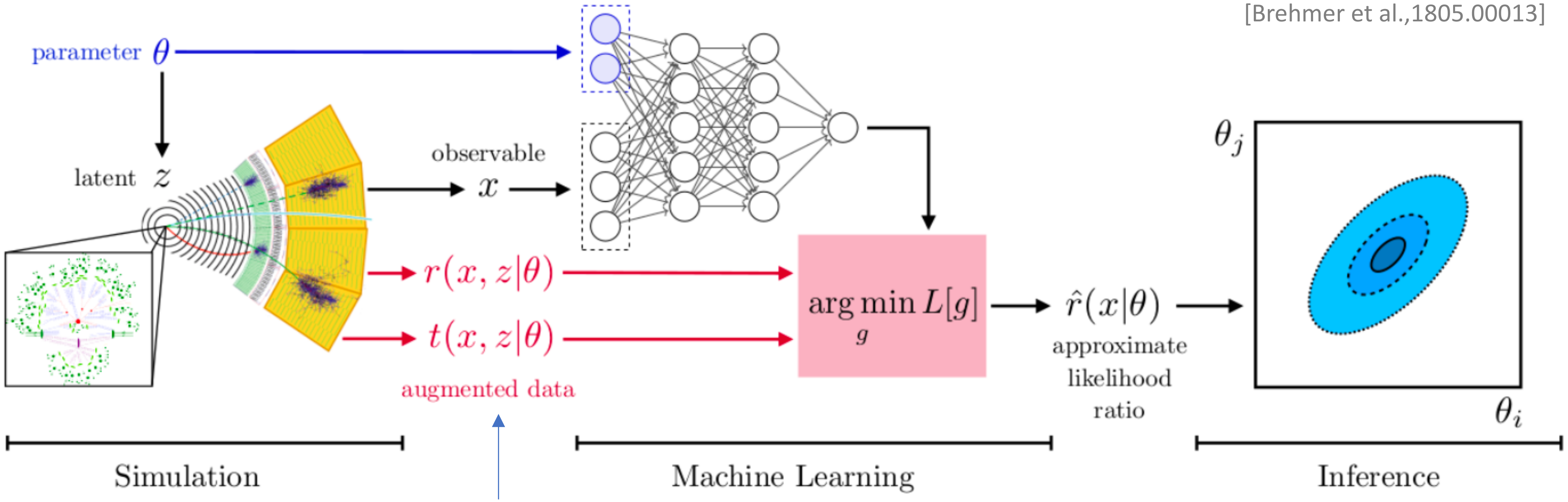
[HB et al., 2007.08542]



[Faroughy et al.,1909.00007]

Kinematic analysis using ML-based inference I

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



[Brehmer et al.,1805.00013]

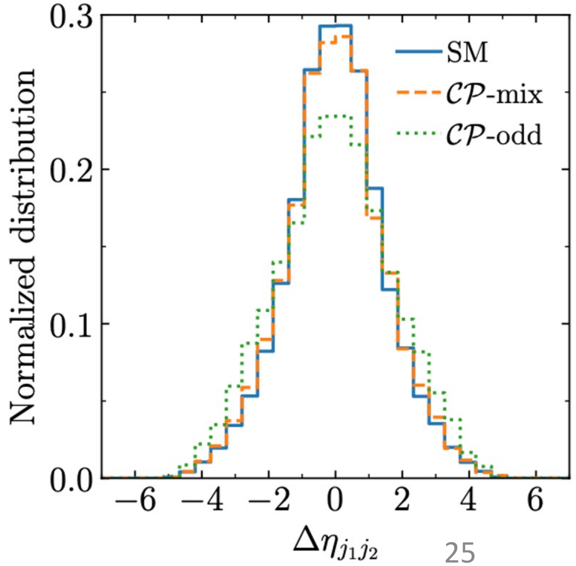
Matrix element information

- 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]

Kinematic analysis using ML-based inference II

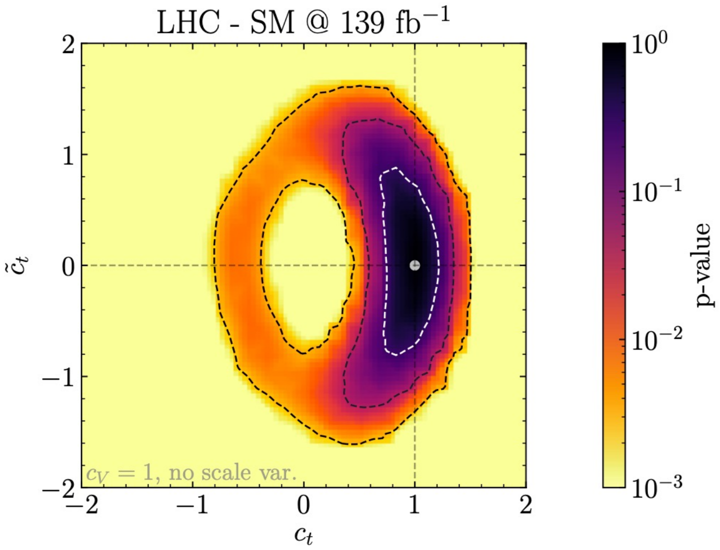
- Focus on top-associated Higgs production ($t\bar{t}H$,tH,tWH) with $H \to \gamma\gamma$.
- We require at least one lepton → consider ZH, WH as backgrounds.
- Non-Higgs backgrounds are assumed to be subtracted by fit to smoothly falling $m_{\gamma\gamma}$ distribution.
- Free parameters: c_t, $\tilde{c}_t$, 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.

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

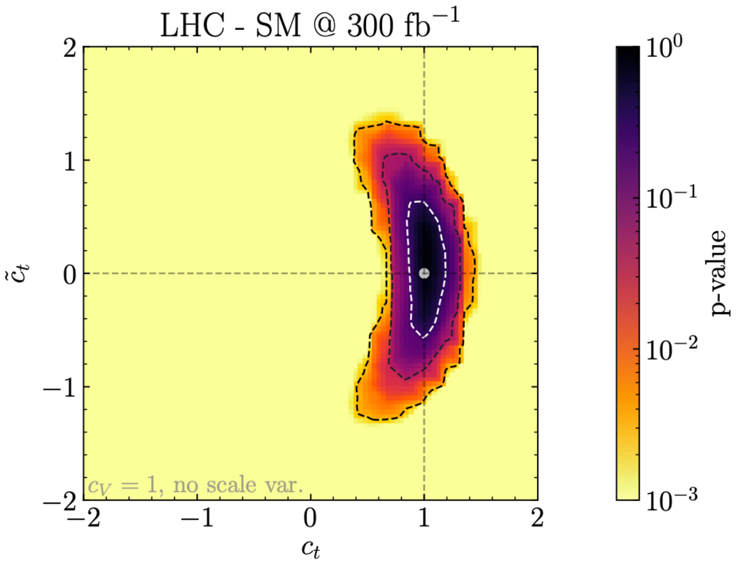


Expected limits at the (HL-)LHC

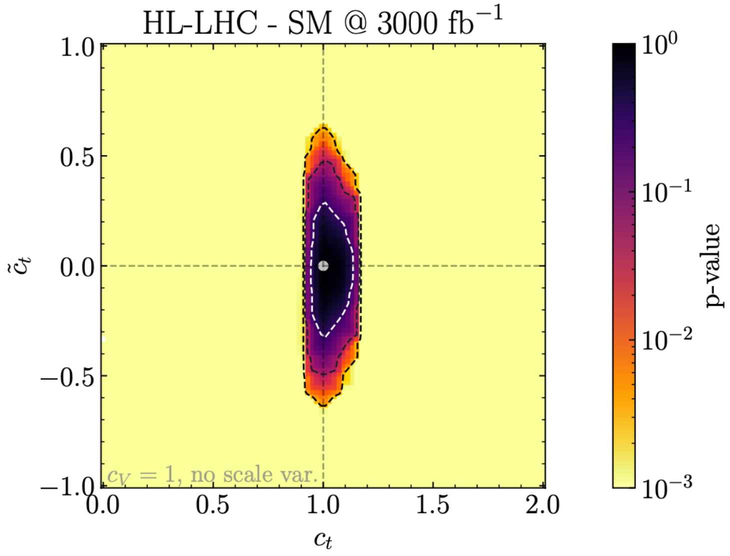
[HB&Brass,2110.10177]



$\alpha \leq 60°$ at 95% CL



$\alpha \leq 40°$ at 95% CL



$\alpha \leq 22°$ at 95% CL

- 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 ($\sim 5°$ for $300\ \text{fb}^{-1}$).

Using ML to construct CP-odd observables I

[HB, Fuchs, Menen, in preparation, results preliminary]

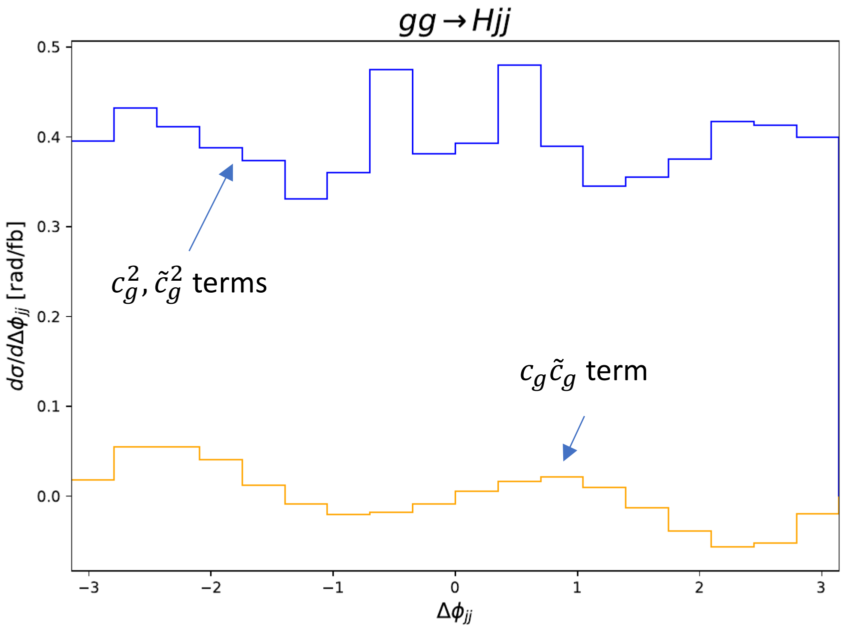
- **Goal**: probe CP-violating Higgs–gluon interaction via $H + 2j$ production.

$$\mathcal{L}_{Hgg} = -\frac{1}{4v} H \left(-\frac{\alpha_s}{3\pi} c_g G^a_{\mu\nu} G^{a,\mu\nu} + \frac{\alpha_s}{2\pi} \tilde{c}_g G^a_{\mu\nu} G^{a,\mu\nu} \right) \qquad \text{(heavy top limit: } c_g = c_t, \tilde{c}_g = \tilde{c}_t\text{)}$$

- The squared amplitude is then decomposed as:

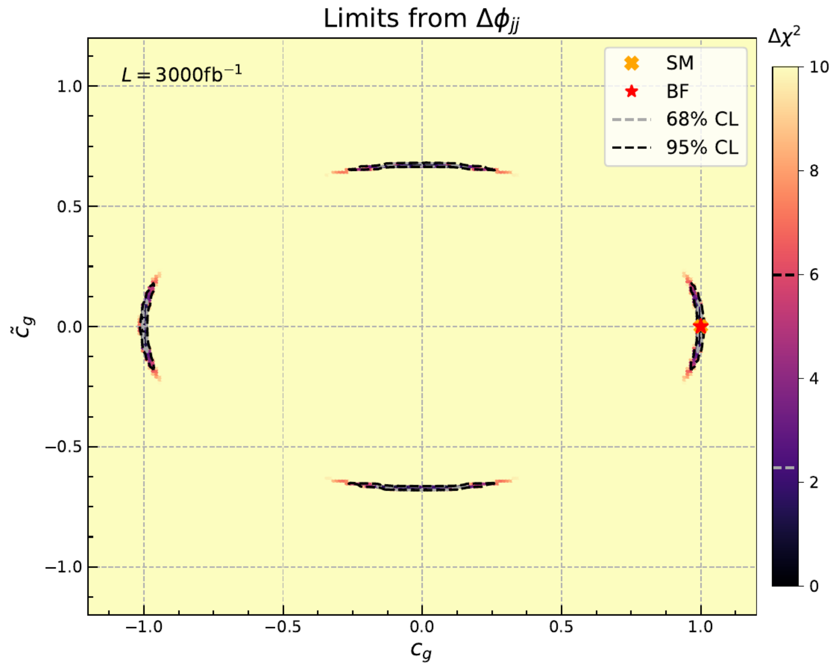
$$|\mathcal{M}_{Hjj}|^2 = c_g^2 |\mathcal{M}_{Hjj}^{\text{CP-even}}|^2 + 2 c_g \tilde{c}_g Re[\mathcal{M}_{Hjj}^{\text{CP-even}} \mathcal{M}_{Hjj}^{\text{CP-odd}^*}] + \tilde{c}_g^2 |\mathcal{M}_{Hjj}^{\text{CP-odd}}|^2$$

- Construct CP-odd observables via $\Delta\Phi_{jj}$:


$c_g^2, \tilde{c}_g^2$ terms

$c_g \tilde{c}_g$ term

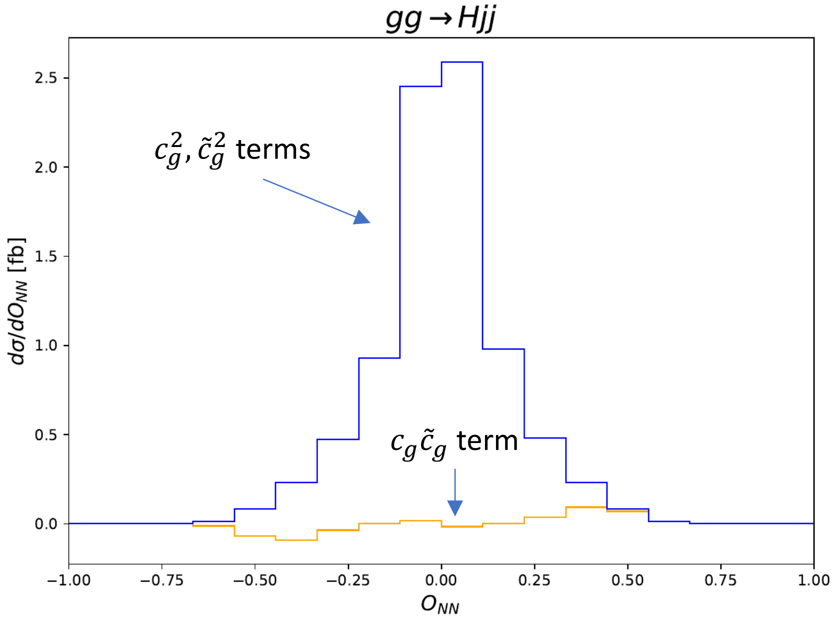
projected limit



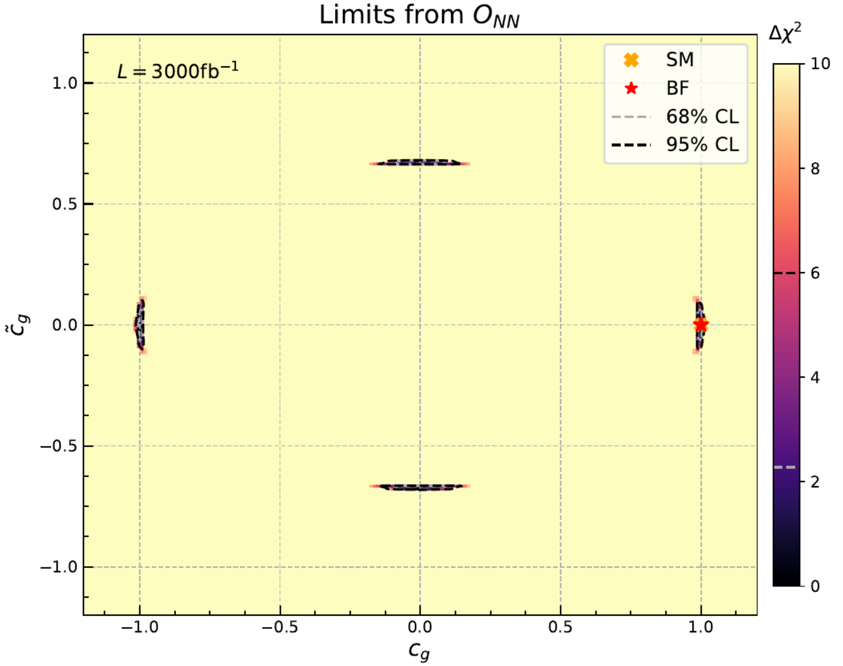
Using ML to construct CP-odd observables II

[HB, Fuchs, Menen, in preparation , results preliminary]

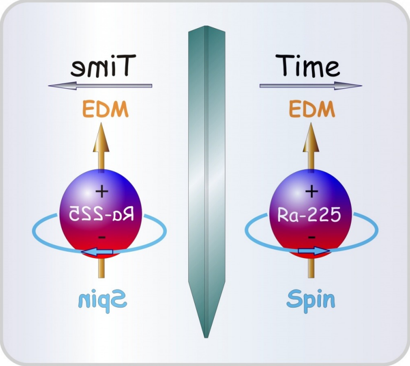
- ML approach: train two neural networks
  1. signal–background separation,
  2. interference term ($c_g\tilde{c}_g$) vs. squared terms ($c_g^2, \tilde{c}_g^2$).
- Define CP-odd observables: $\boldsymbol{O_{NN} = P_+ - P_-}$. ($P_{+/-}$: probability for pos./neg. interference event)
  [Bhardway et al., 2112.05052]

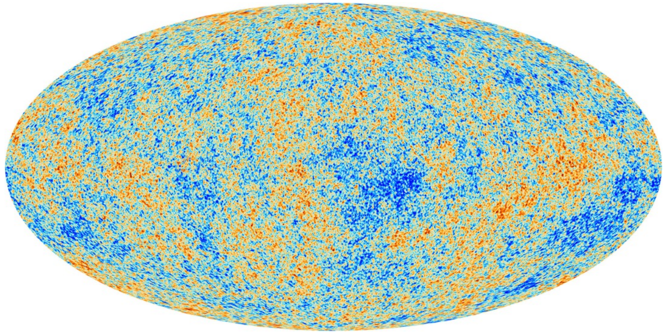


projected limit



→ Significant improvement in sensitivity when using O_{NN} instead of $\Delta\Phi_{jj}$.

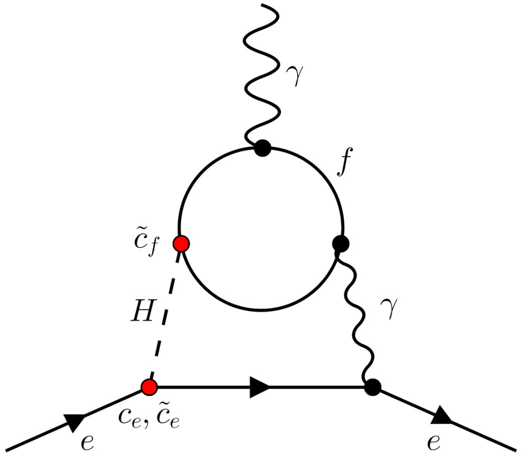


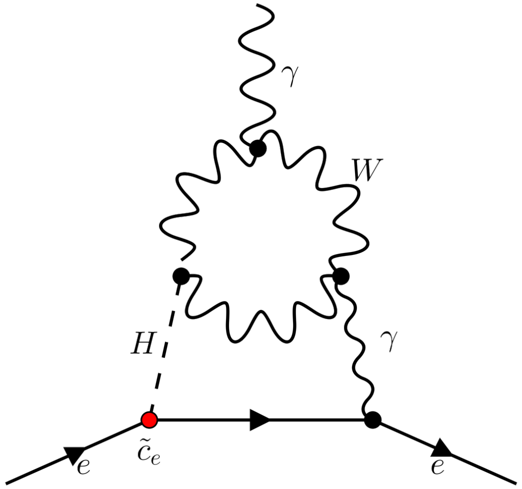


Complementarity with EDM and baryogenesis constraints

Can CP violation in the Higgs sector explain the BAU?

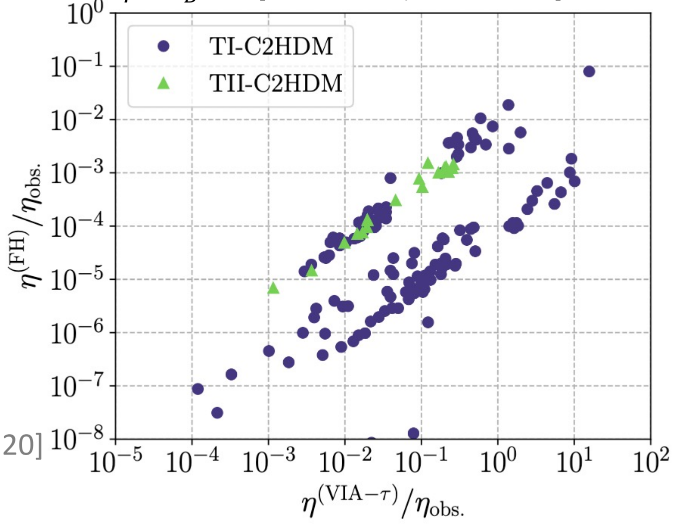
EDM constraints





- 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: $d_e^{\text{ACME}} = 1.1 \cdot 10^{-29} e$ cm at 90% CL. [ACME, *Nature* 562 (2018) 7727, 355-360]
- $\frac{d_e}{d_e^{\text{ACME}}} \simeq c_e(870.0\tilde{c}_t + 3.9\tilde{c}_b + 3.4\tilde{c}_\tau + \cdots) + \tilde{c}_e(610.1c_t + 3.1c_b + 2.8c_\tau - 1082.6c_V + \cdots)$
- Bounds strongly depend on assumptions about electron-Yukawa coupling.

Baryon asymmetry of the Universe



$\eta \equiv Y_B$ [Basler et al.,2108.03580]

- 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;Postma et al.,2206.01120]
  - WKB (or FH) approximation.

    [Joecy 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:

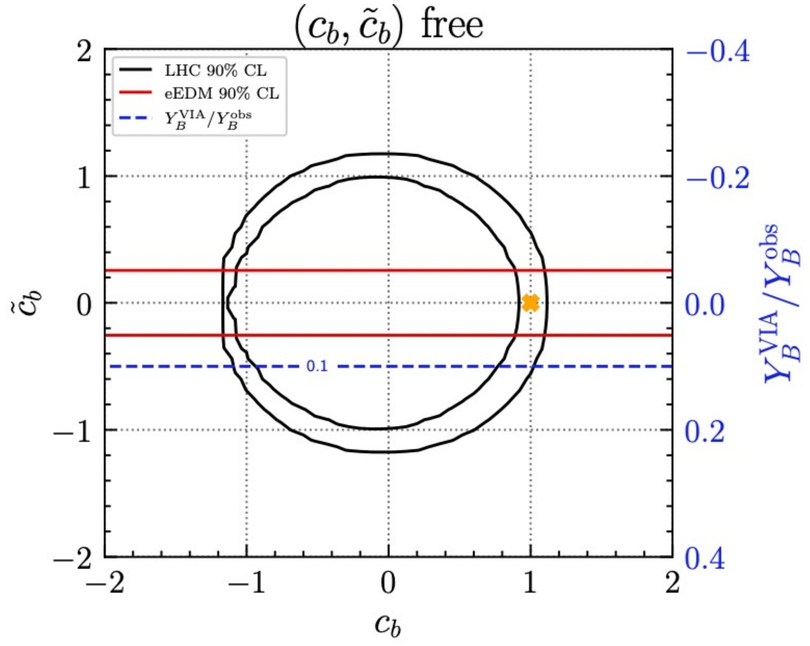
  [de Vries,1811.11104;Fuchs et al.,2003.00099,2007.06940;Shapira,2106.05338]

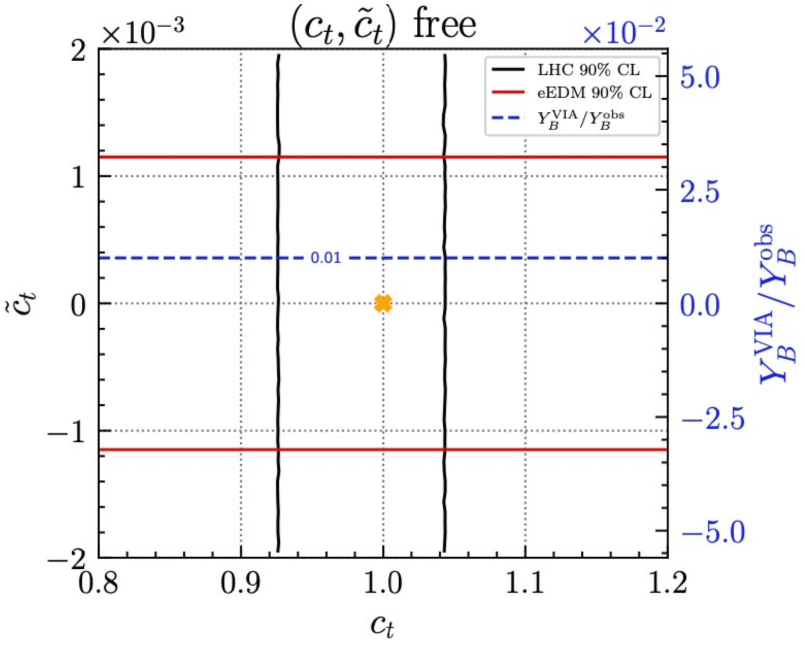
$$\frac{Y_B}{Y_B^{\mathrm{obs}}} \simeq 28\tilde{c}_t - 0.2\tilde{c}_b - 11\tilde{c}_\tau + \cdots$$

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]

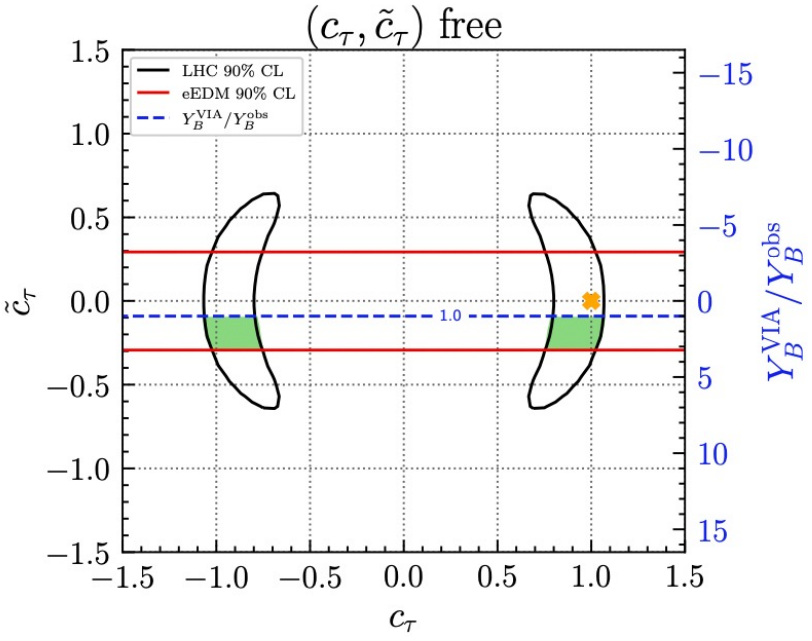


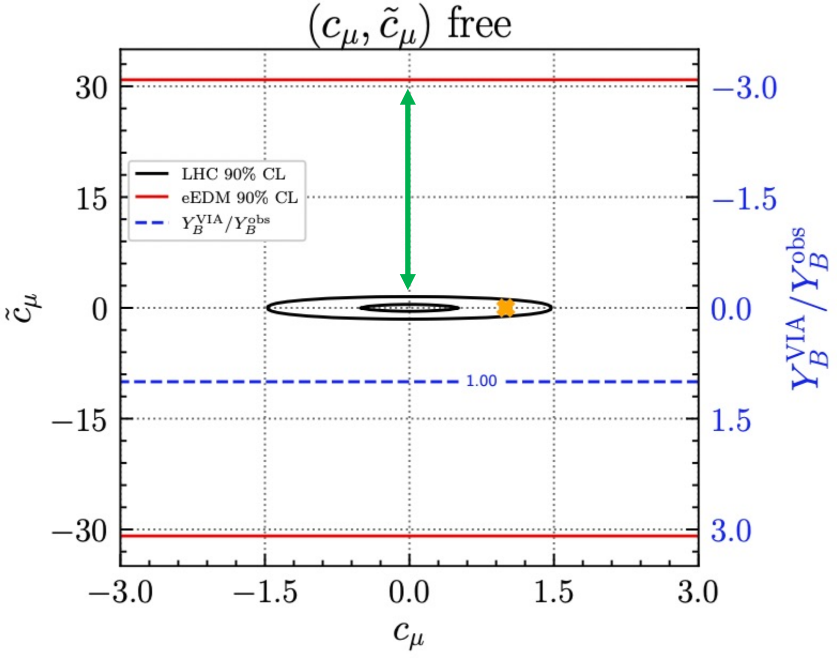


- CP-violating bottom-Yukawa coupling contributes too less to BAU.
- CP-violating top-Yukawa coupling strongly constrained by eEDM → not able produce sufficient BAU.

1 flavor results: τ and μ

[HB et al.,2202.11753]

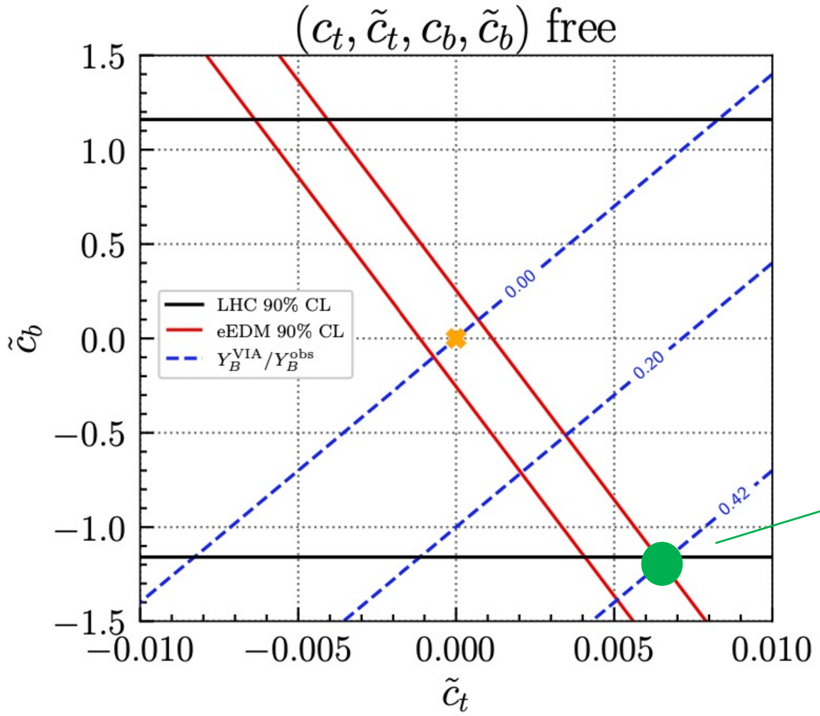




- CP-violating tau-Yukawa coupling can potentially explain BAU within LHC and eEDM constraints.
- LHC constraints on CP-violating muon-Yukawa coupling are stronger than eEDM bounds.

2 flavor results: t and b

[HB et al.,2202.11753]



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

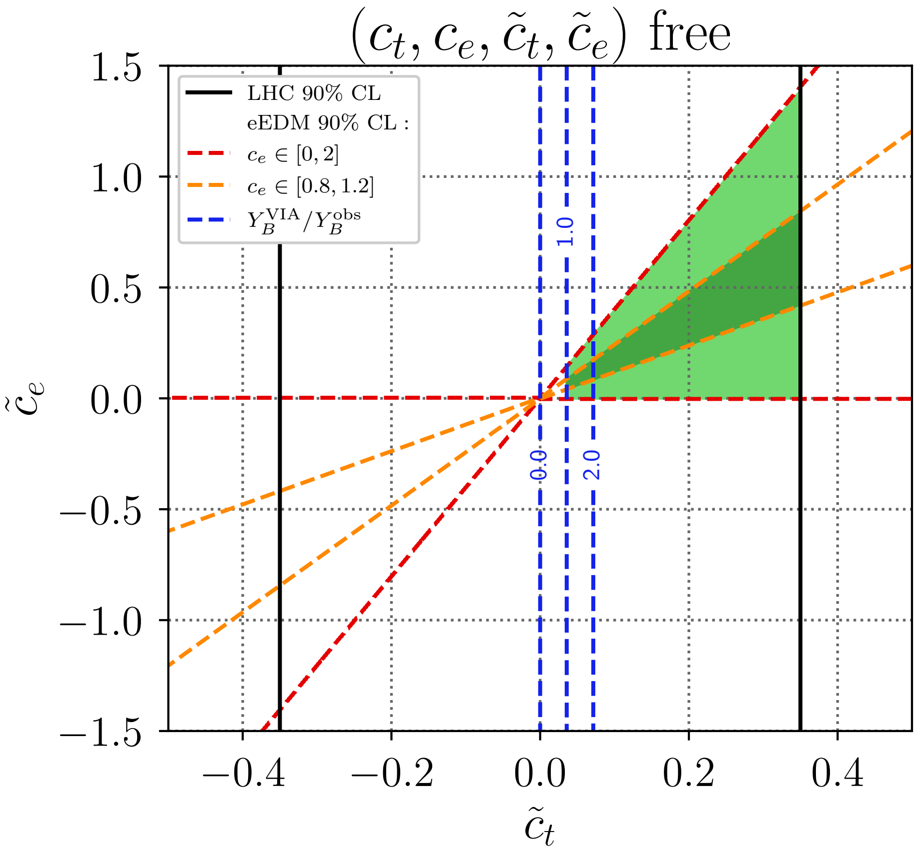
	t	b	c	τ	μ
t	0.03				
b	0.42	0.05			
c	0.37	0.19	0.01		
τ	6.9	6.9	6.9	3.2	
μ	0.18	0.19	0.16	3.2	0.16

- Presence of more than one CP-violating coupling allows for cancellation in eEDM.

  → Larger values for $Y_B/Y_B^{\rm obs}$ can be reached.

Dependence on electron-Yukawa coupling

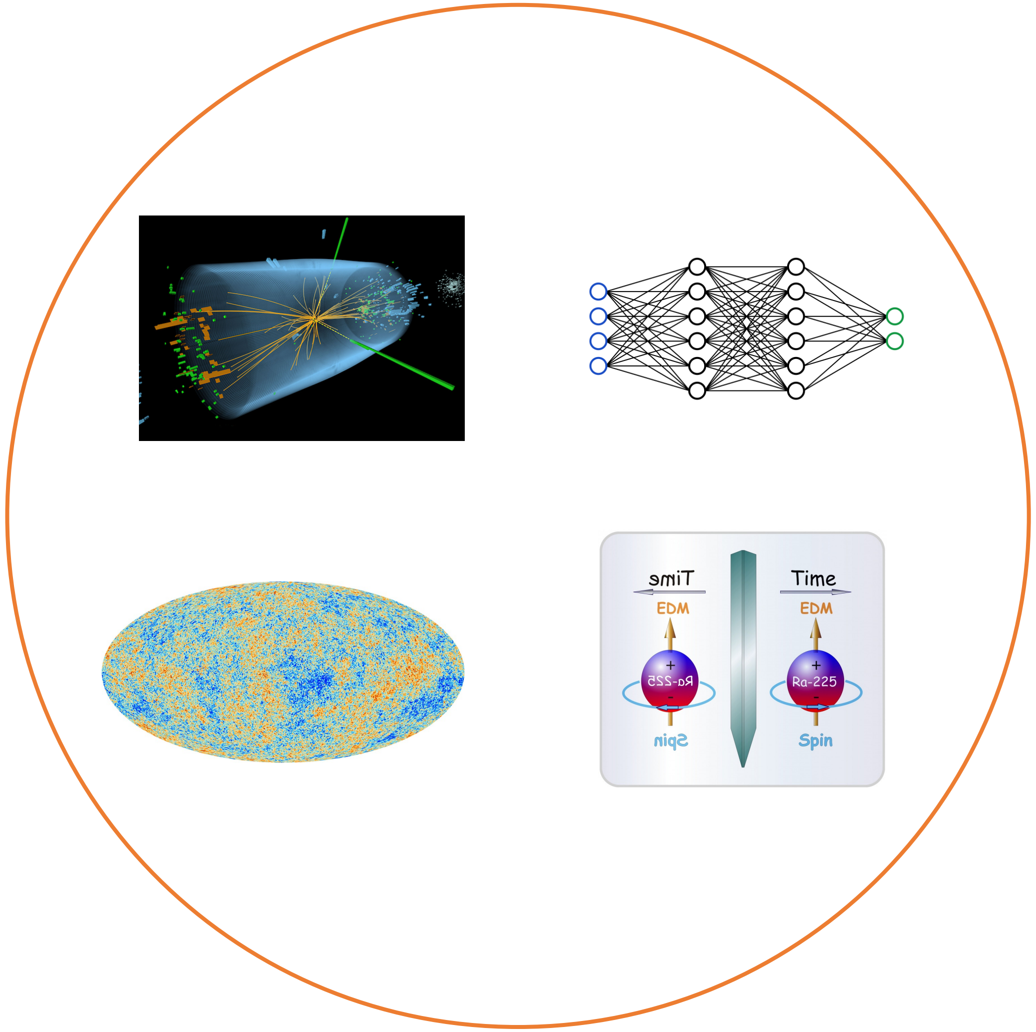
[HB et al.,2202.11753]



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

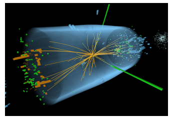
LHC bounds important since they do not depend on 1st gen. Yukawa couplings.

Conclusions

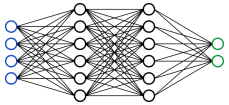


Conclusions

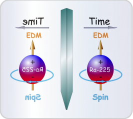
Initial question: how well can we constrain **CP violation in the Higgs–fermion interactions** and what are the implications for the BAU?

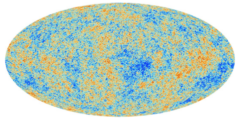


LHC already tightly constrains CP violation in the **top- and tau-Yukawa couplings**.



To improve bounds in the **future**, we need to exploit all available information using e.g. **machine-learning** to construct likelihood or CP-odd observables.





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.

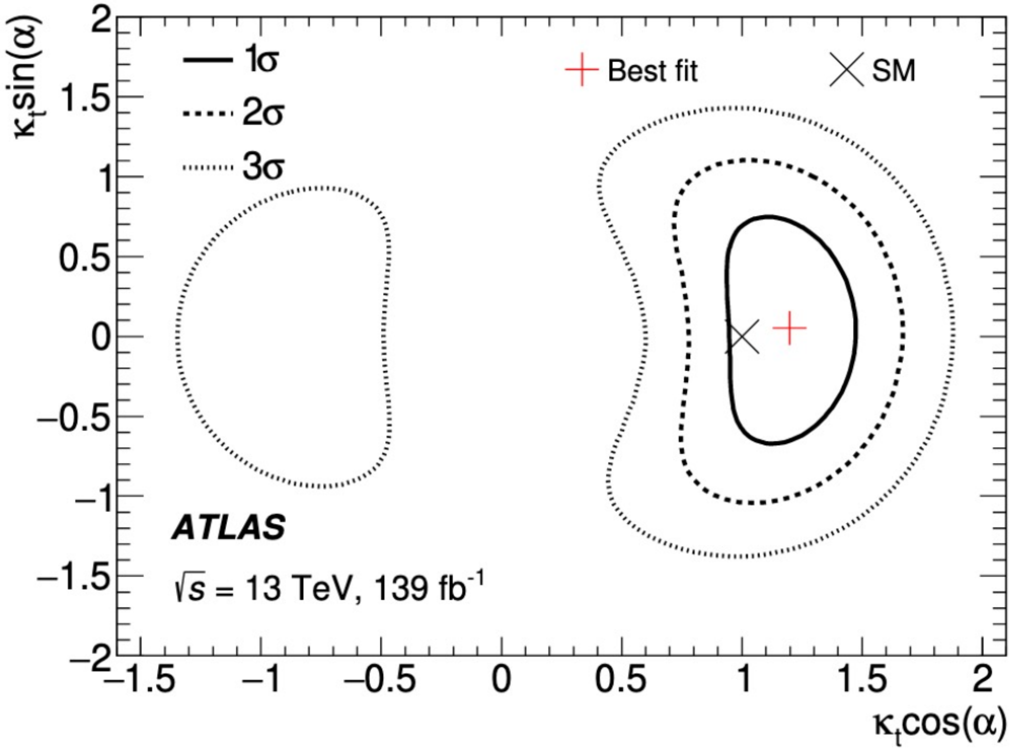
Thanks for your attention!

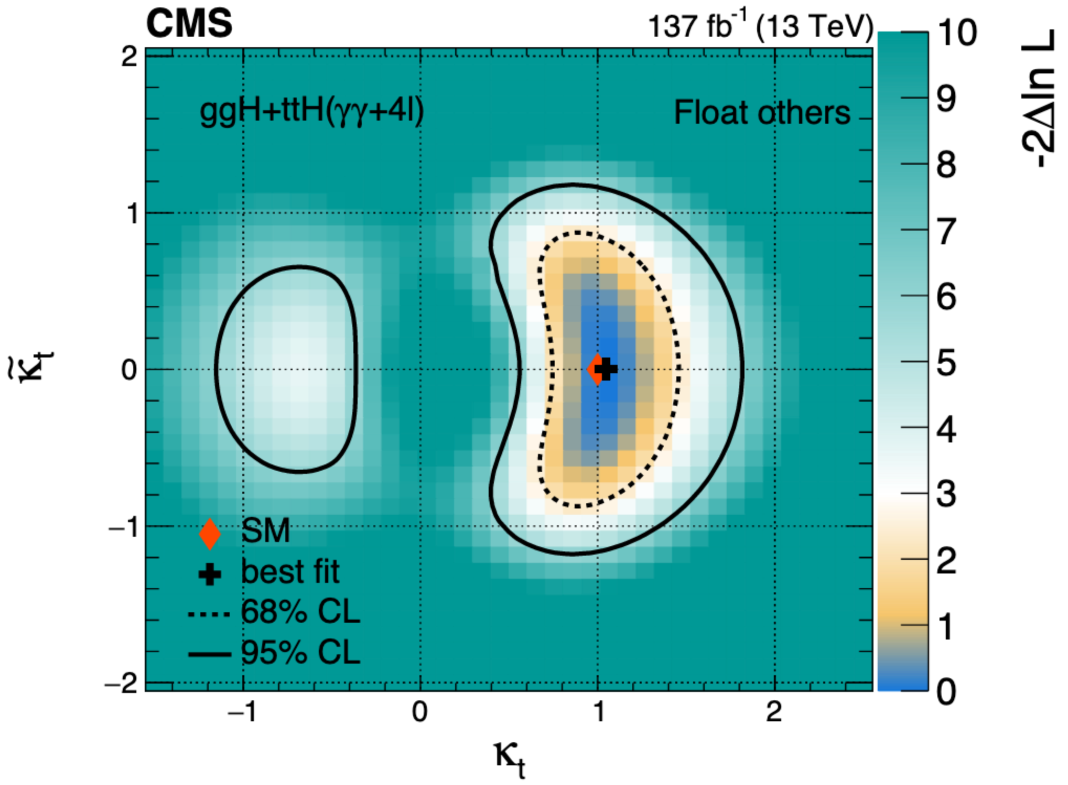
Appendix

Reasons for not including ATLAS and CMS top CP studies

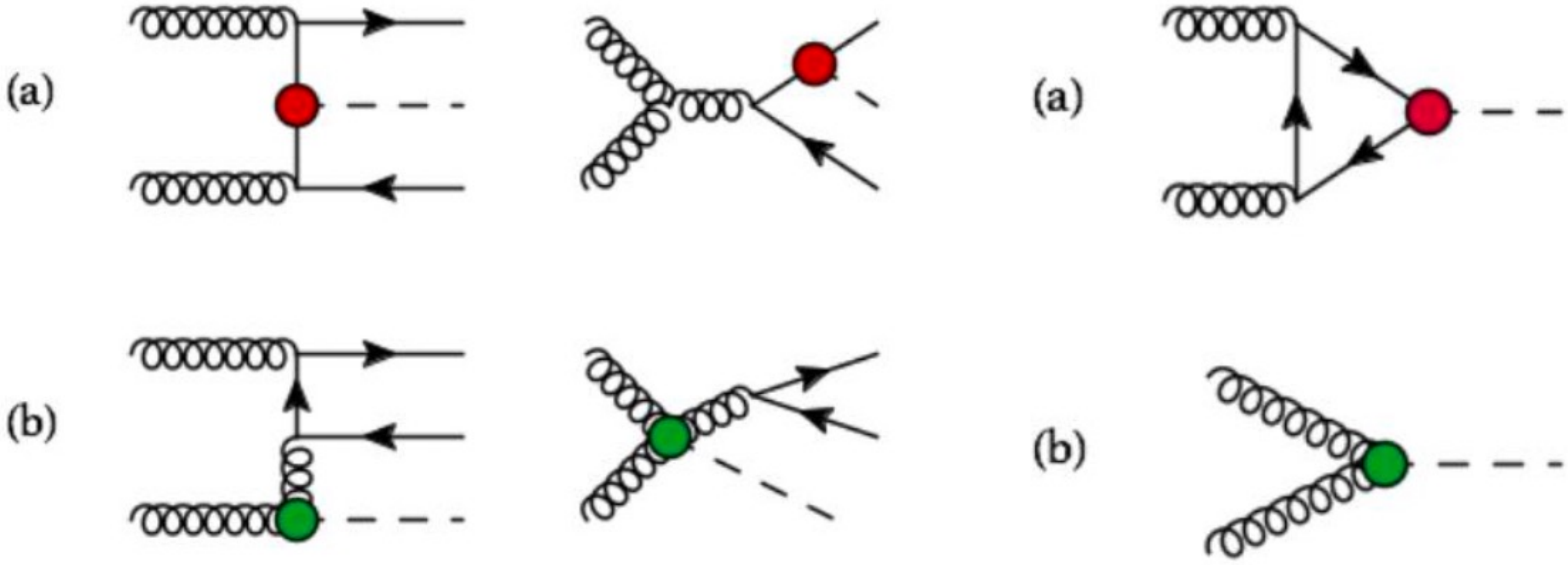
- CMS study: [2003.10866]
  - All Higgs production modes (apart form top-associated Higgs production) are constrained to their SM predictions.
  - No two-dimensional likelihood given when our study was published (now available in [CMS-PAS-HIG-19-009])
- ATLAS study: [2004.04545]
  - Two setups:
    1. κ_g (and κ_γ) constrained by other measurements (ggH) excluding $t\bar{t}H$ and tH but events generated at NLO → 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]



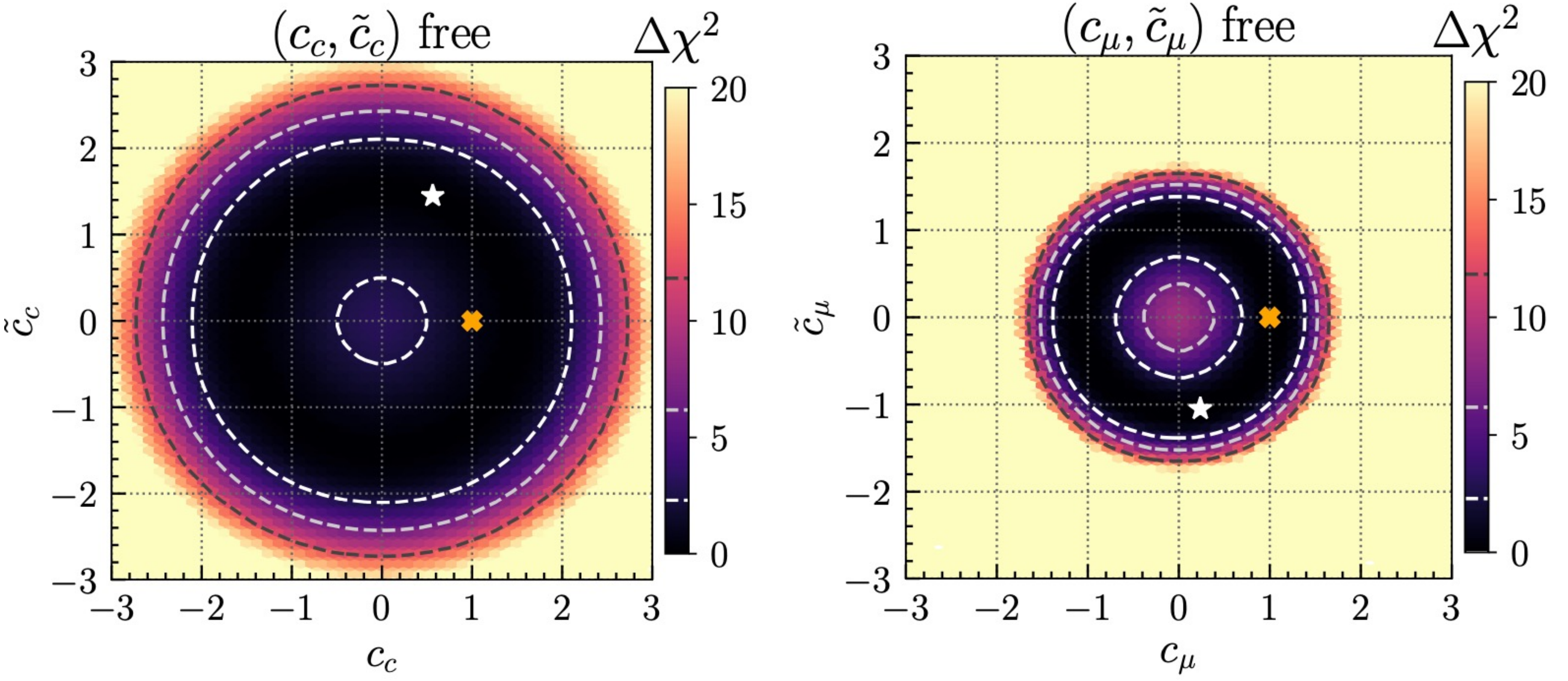


Correlation between ggH and $t\bar{t}H$ at NLO

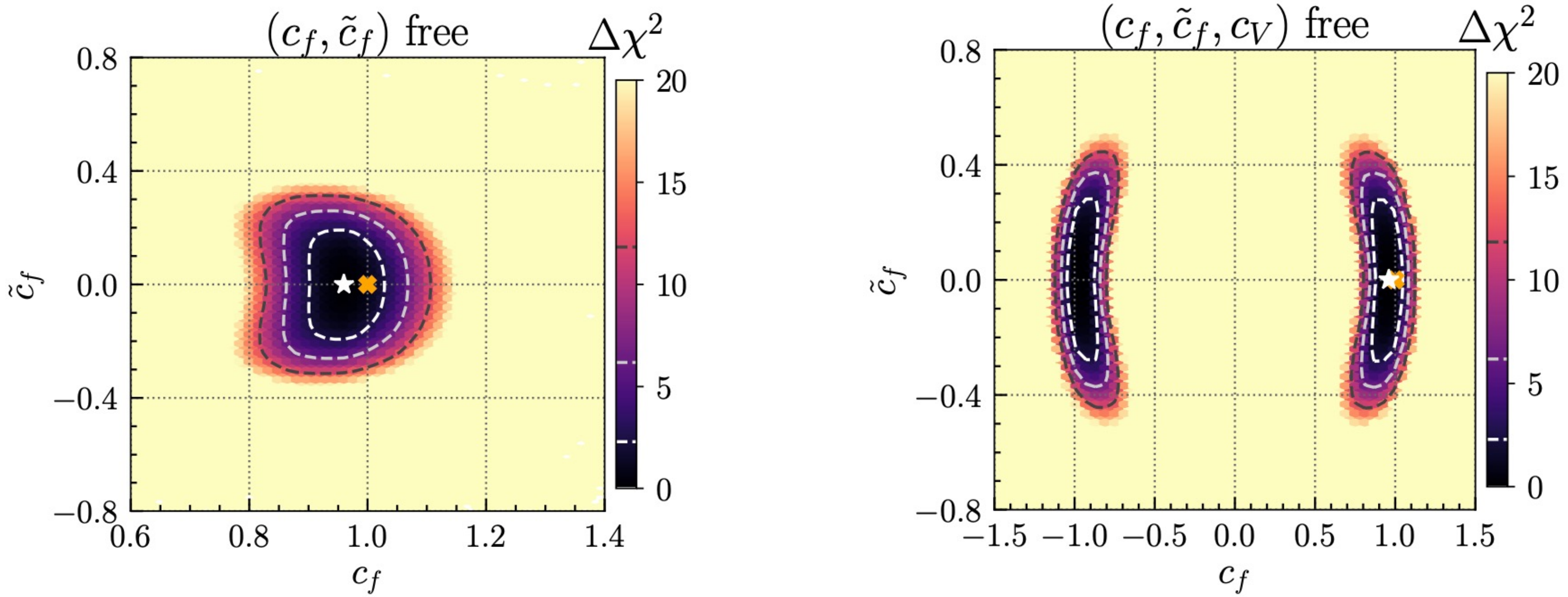


[Maltoni,Vryonidou,Zhang,1607.05330]

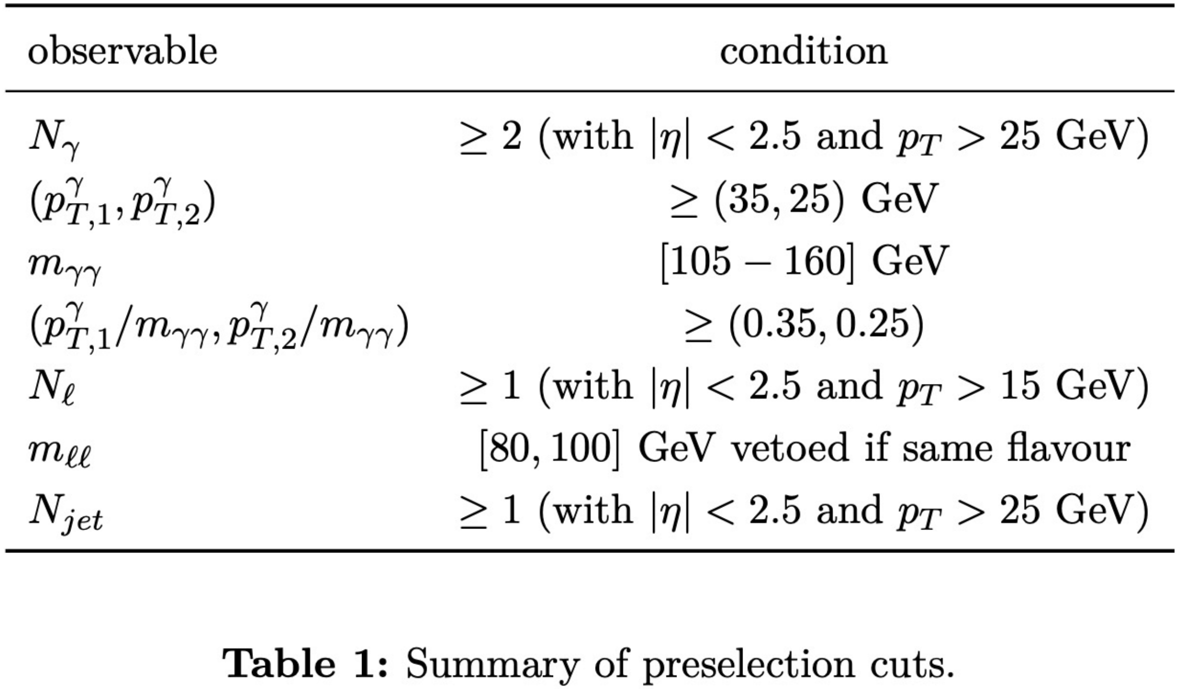
Charm- and muon-Yukawa couplings



Global modification fits



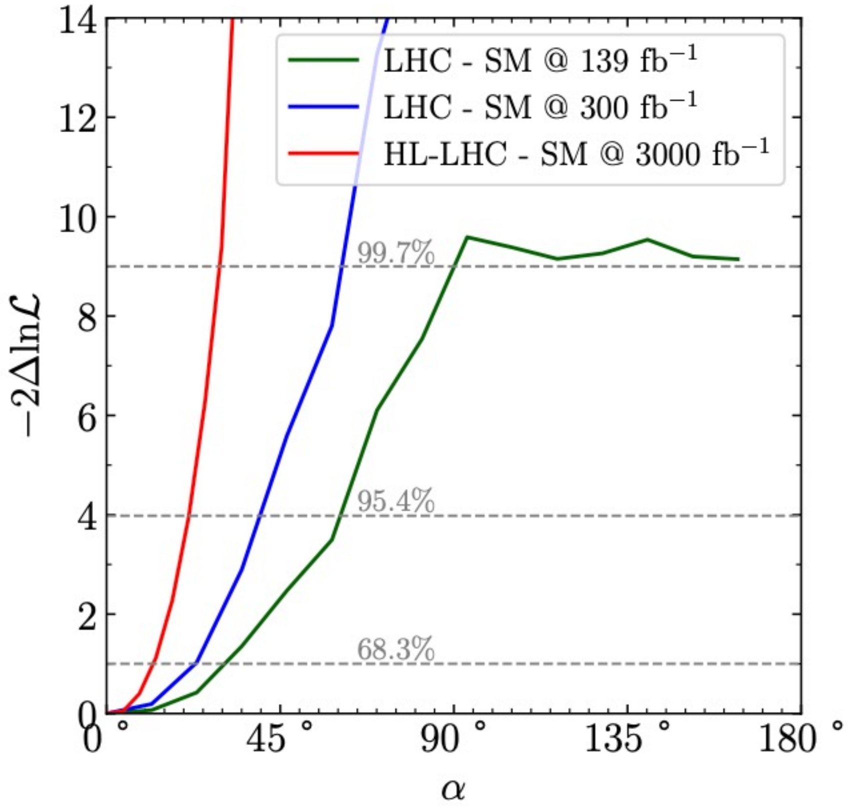
- Universal fermion coupling modifiers: $c_f = c_t = c_b = \cdots = c_\tau$, $\tilde{c}_f = \tilde{c}_t = \tilde{c}_b = \cdots = \tilde{c}_\tau$.
- Dominated by constraints on top-Yukawa coupling.
- Additional varying c_V reopens negative c_f range.



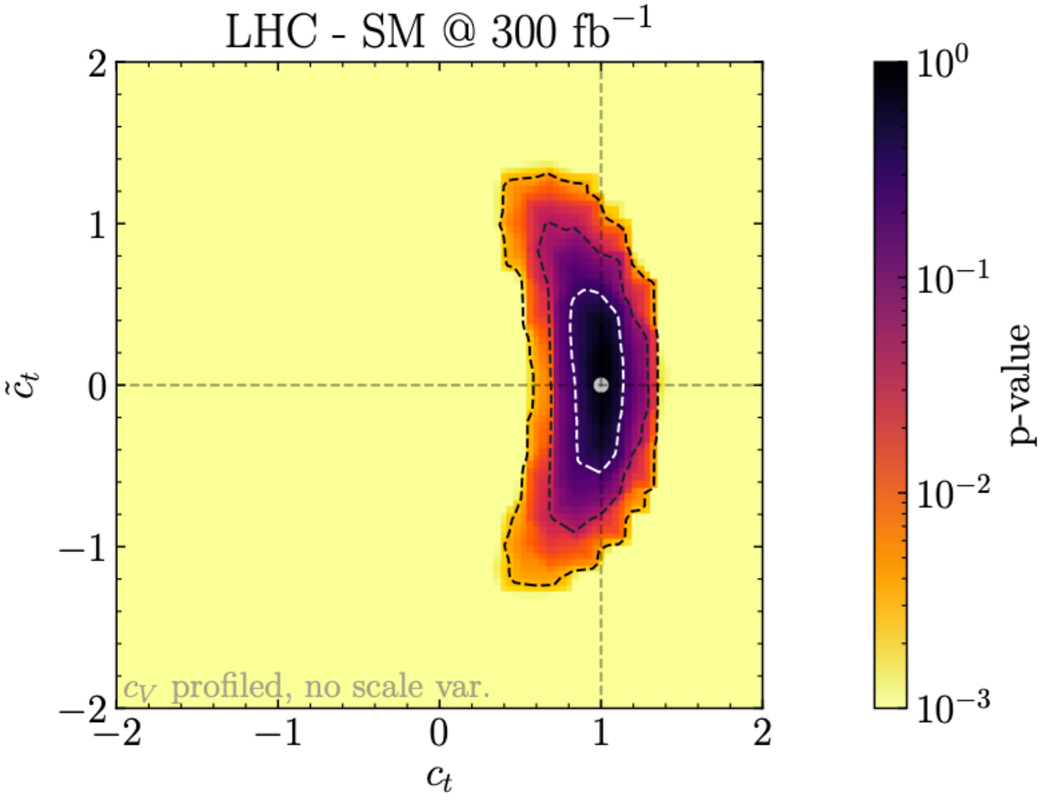
observable	condition
N_γ	≥ 2 (with $\lvert\eta\rvert < 2.5$ and $p_T > 25$ GeV)
$(p_{T,1}^\gamma, p_{T,2}^\gamma)$	$\geq (35, 25)$ GeV
$m_{\gamma\gamma}$	$[105 - 160]$ GeV
$(p_{T,1}^\gamma/m_{\gamma\gamma}, p_{T,2}^\gamma/m_{\gamma\gamma})$	$\geq (0.35, 0.25)$
N_ℓ	≥ 1 (with $\lvert\eta\rvert < 2.5$ and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

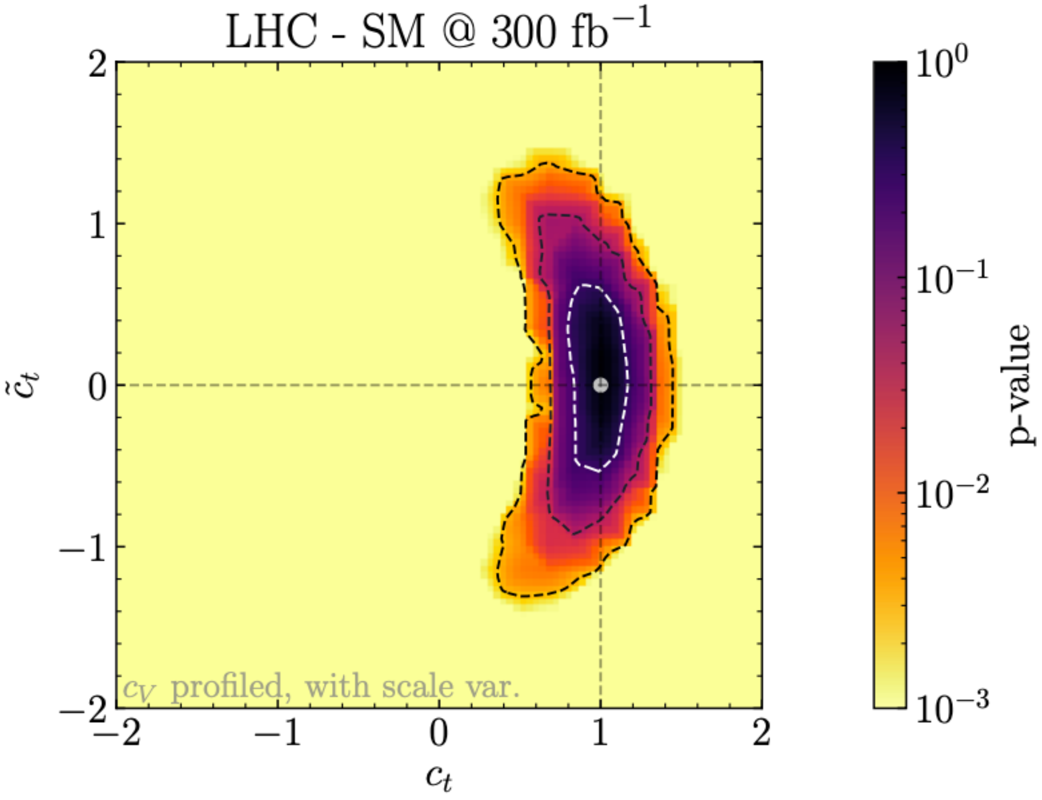
Table 1: Summary of preselection cuts.

Interpretation in terms of CP-violating angle

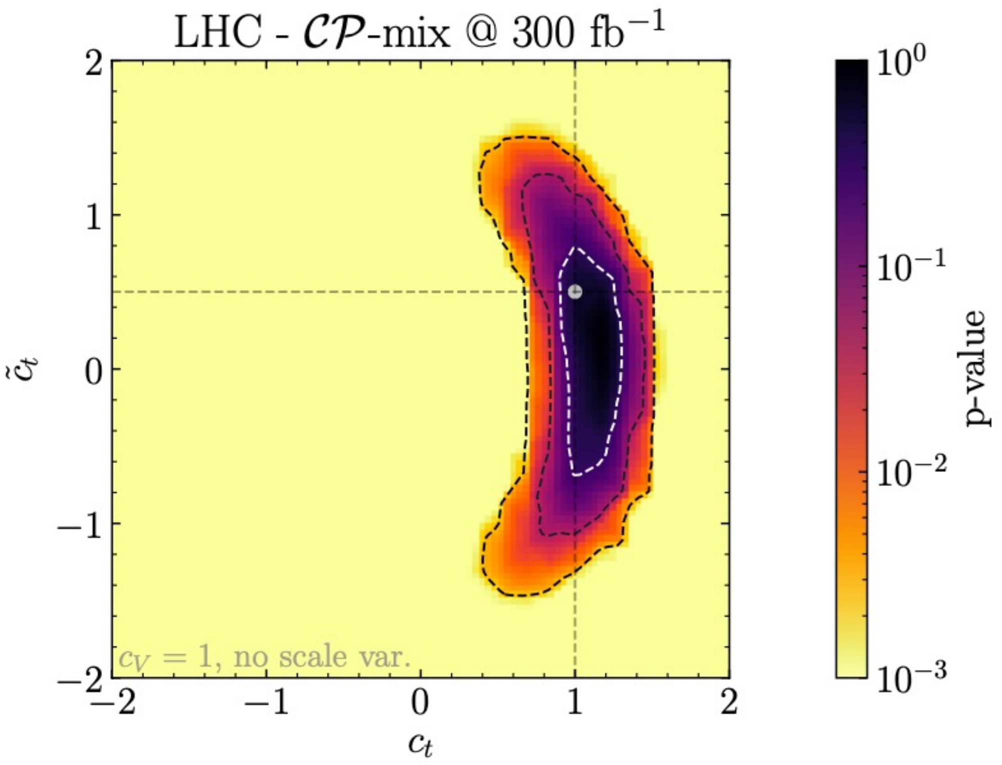


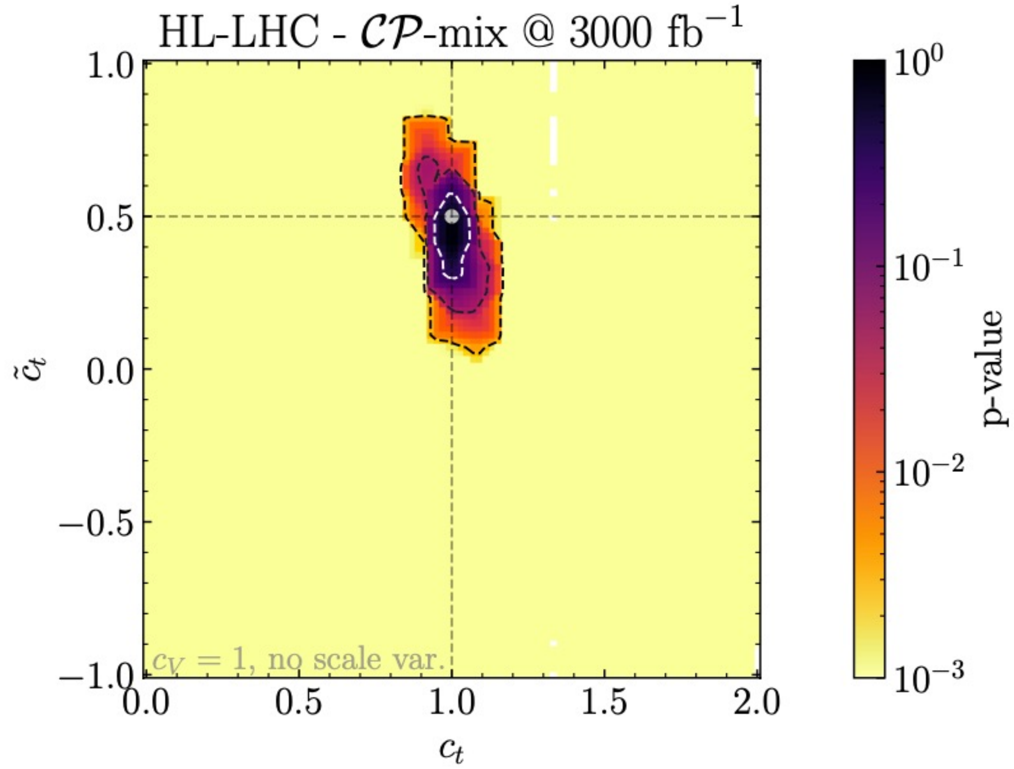
Variation of c_V and renormalization scale





Limits in case of deviation from SM





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

Which observables drive these constraints?

- Use Fisher matrix to evaluate information for different observables

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

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

- E.g., for SM point we have

Information about c_V

Information about c_t

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

Correlation of c_t and c_V

Information about $\tilde{c}_t$

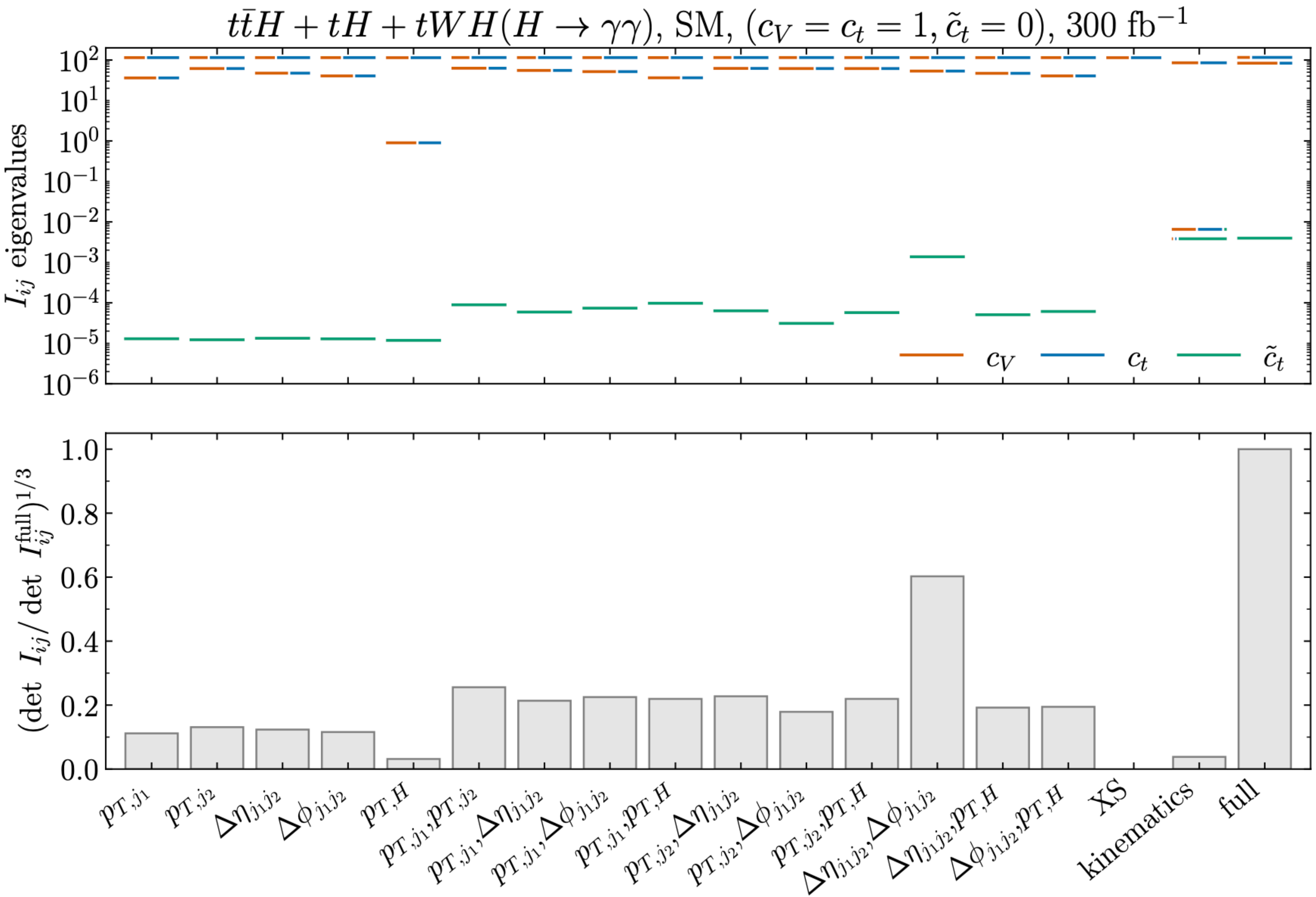
- Evaluate Fisher matrix for various 1D and 2D histograms, full likelihood, XS only, kinematics only.

Fisher information for SM scenario

[HB&Brass,2110.10177]

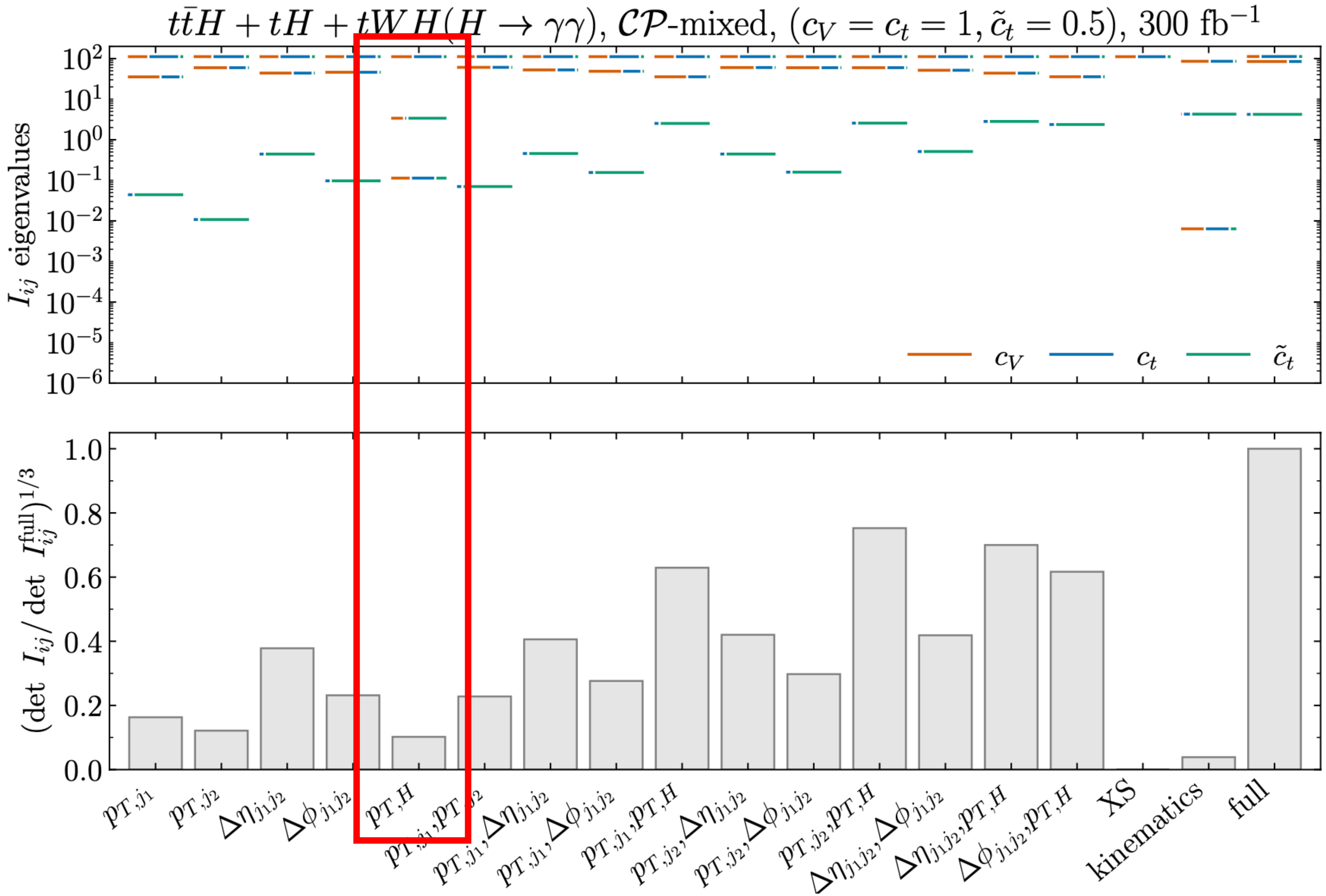
Which combinations of couplings can we constraint how well?

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 $\tilde{c}_t$.

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.