# Constraining the CP character of the Higgs–top-quark interaction

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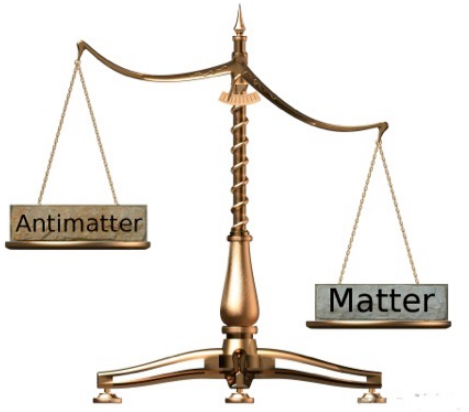
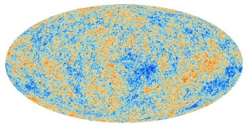
# CP violation in the Higgs sector

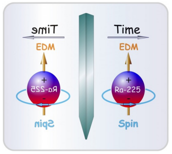


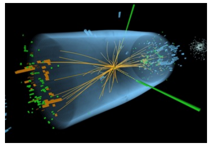

- New sources of CP violation are necessary to explain the baryon asymmetry of the Universe.
- One possibility: CP violation in the Higgs sector.

Focus of this talk: Constraining CP violation in the top-Yukawa interaction at the LHC.

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





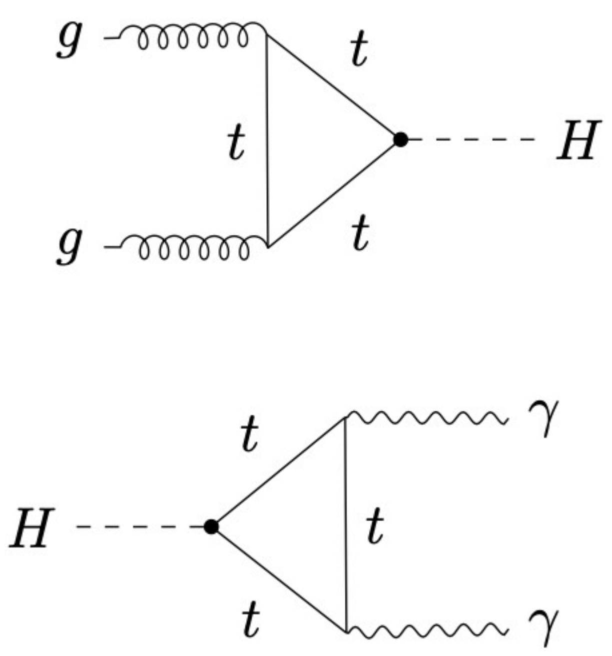



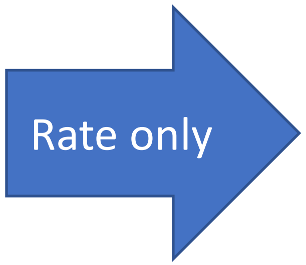
# Collider constraints @ loop level

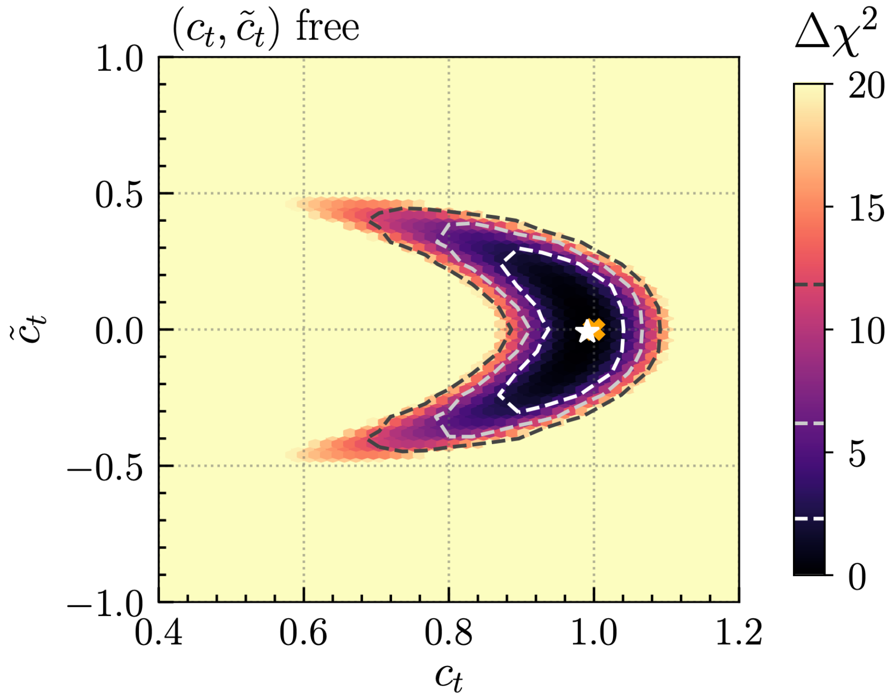
[HB et al., 2007.08542]

- Effective model: $$\mathcal{L}_{\text{top-yuk}} = -\frac{y_t^{\text{SM}}}{\sqrt{2}}\bar{t}\left(c_t + i\gamma_5\tilde{c}_t\right)tH.$$

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

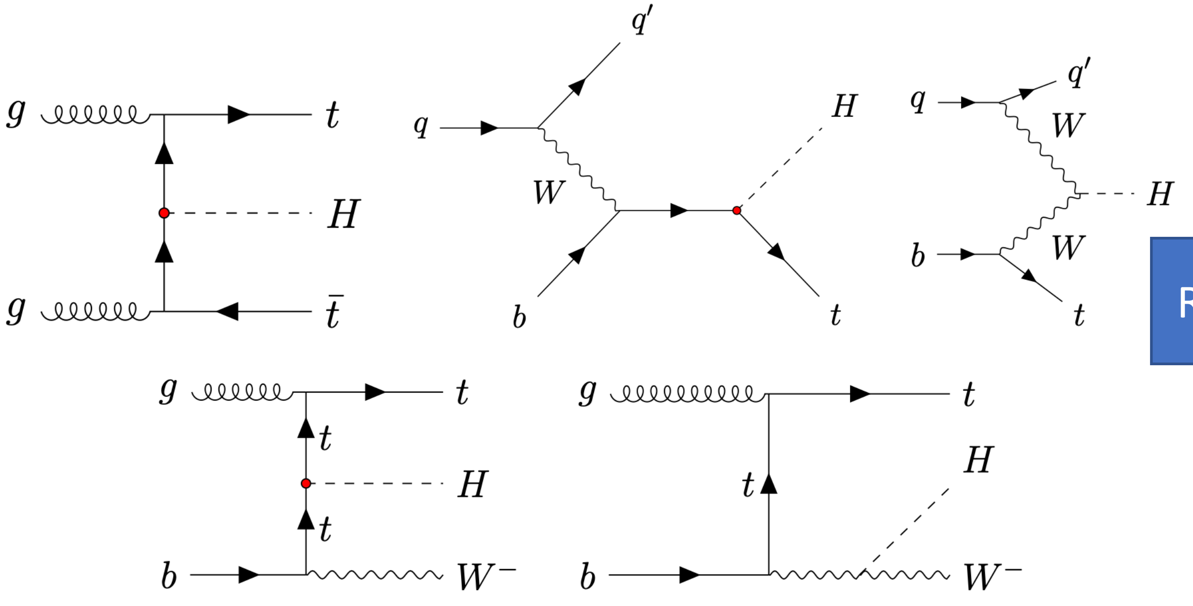


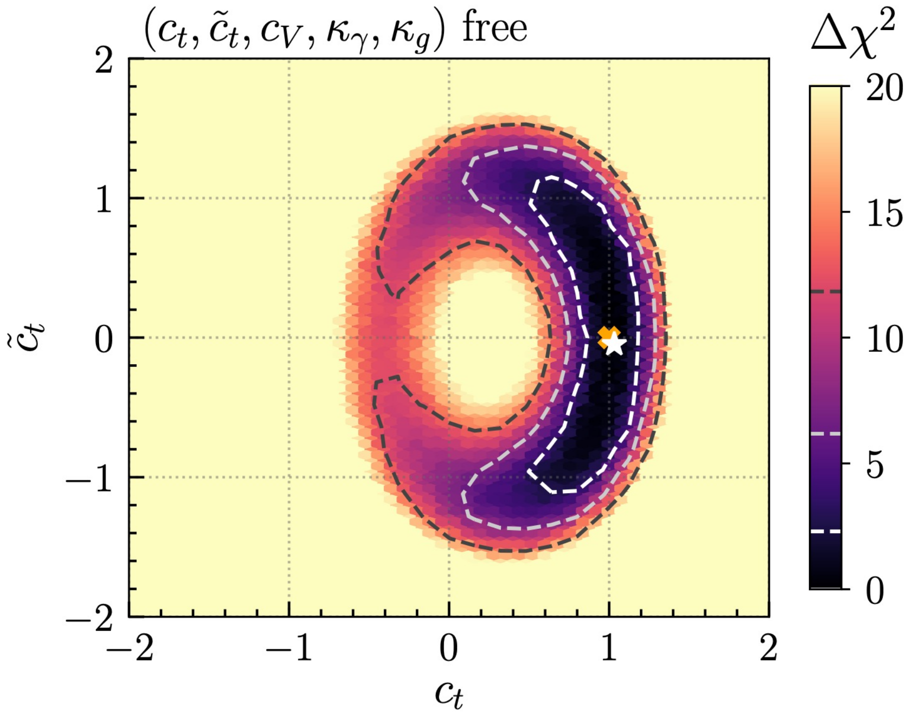



# Collider constraints @ tree level

- Tree-level constraints: **top associated Higgs production**
- Direct access to top-Yukawa interaction → less model dependence.
- Three sub channels contribute: $\bar{t}tH,\ tH$ (or $tHq$), $tWH$.

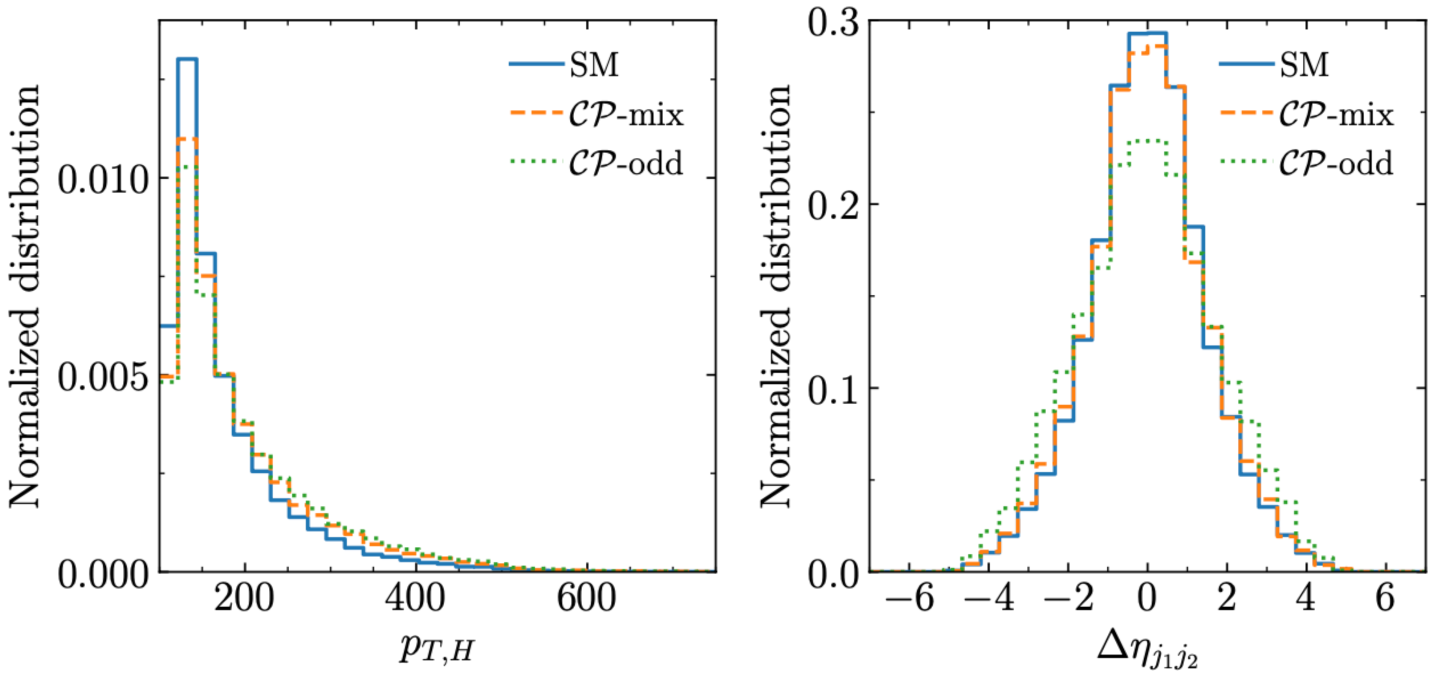



Rate only



# Exploiting the kinematic information [HB & Brass, 2110.10177]

Exemplary kinematic distributions for top-associated Higgs production

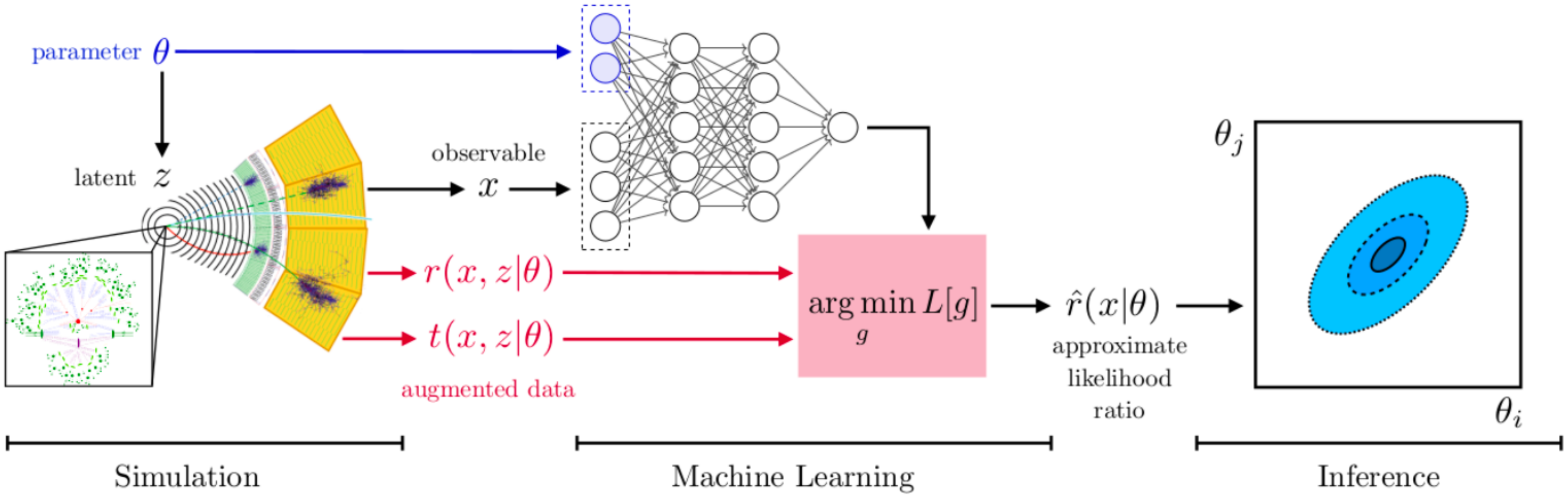



How to best exploit the full available information to constraint top-Yukawa interaction?

→ Focused on top-associated Higgs production with $H \to \gamma\gamma$ (demanding at least one lepton).

# Machine-learning based inference

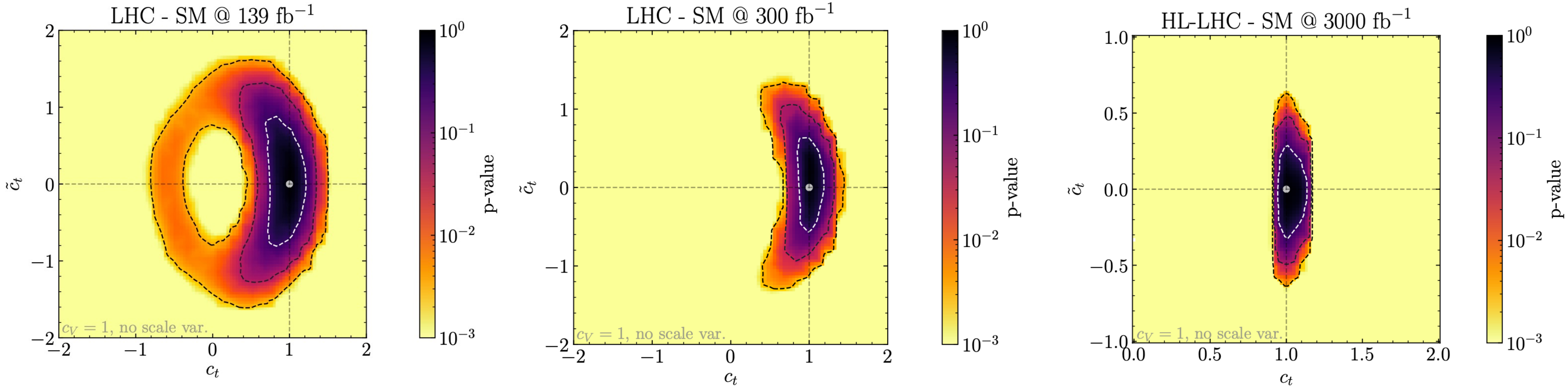
[Brehmer et al.,1906.01578,1805.12244,1805.00013,1805.00020,1808.00973]




- Allows to extract the full available information (maximal sensitivity).
- Use implementation in public code MadMiner [Brehmer,Kling,Espejo,Cranmer,1907.10621] designed to work with MadGraph + Pythia + Delphes.
- Defined 47 observables as input for neural network.

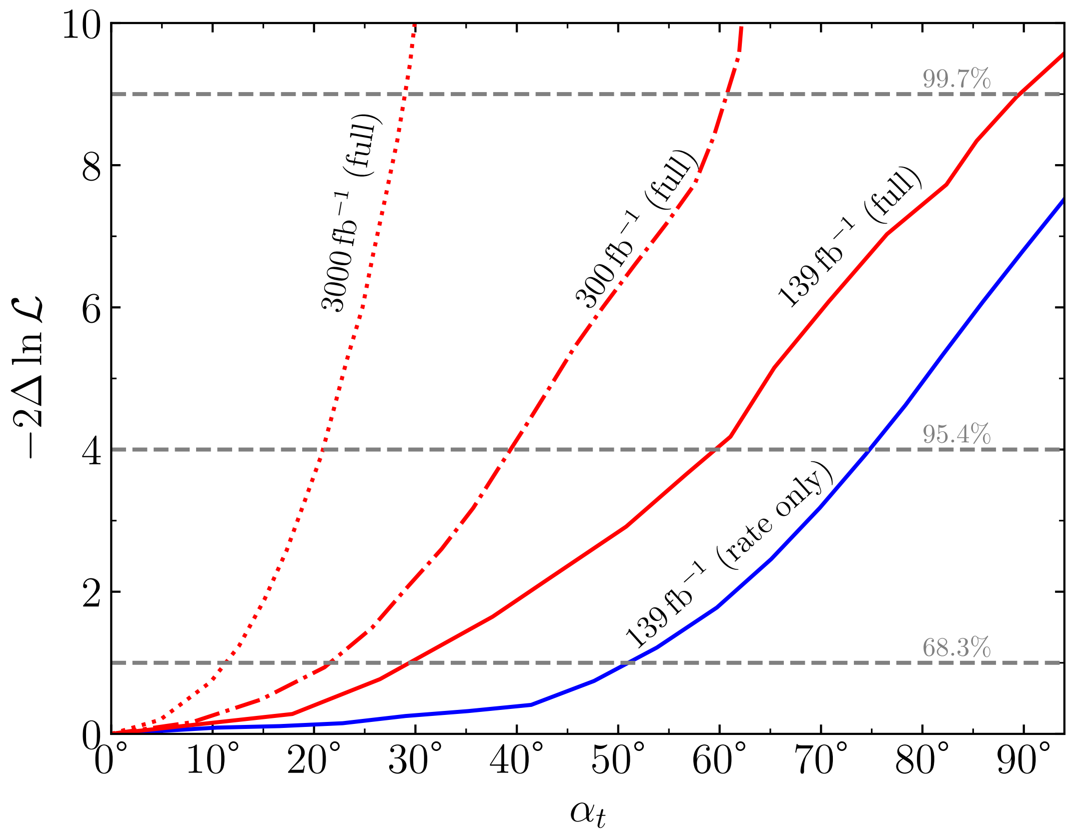
Averaged over ensemble of six neural networks to minimize ML uncertainty.

# Expected limits at the (HL-)LHC




- Assumed here that Higgs–vector-boson coupling is SM-like ($c_V = 1$).
- Additional variation of $c_V$ (and of the renormalization scale) only slightly weakens bounds.

# Comparison of constraints on CP-violating phase




- CP-violating phase $\alpha_t$:

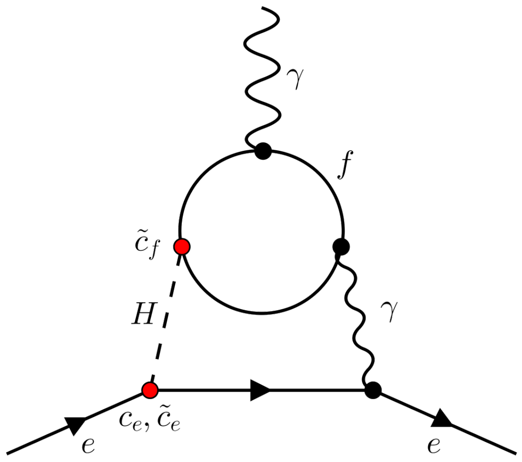
$$\tan\alpha = \tilde{c}_t / c_t$$

- Exploiting full kinematic information significantly strengthen limits.
- Including full-hadronic channel and other Higgs decay channels will allow to further improve sensitivity.

# Complementarity with eEDM and BAU [HB et al.,2202.11753]

**Electron EDM**

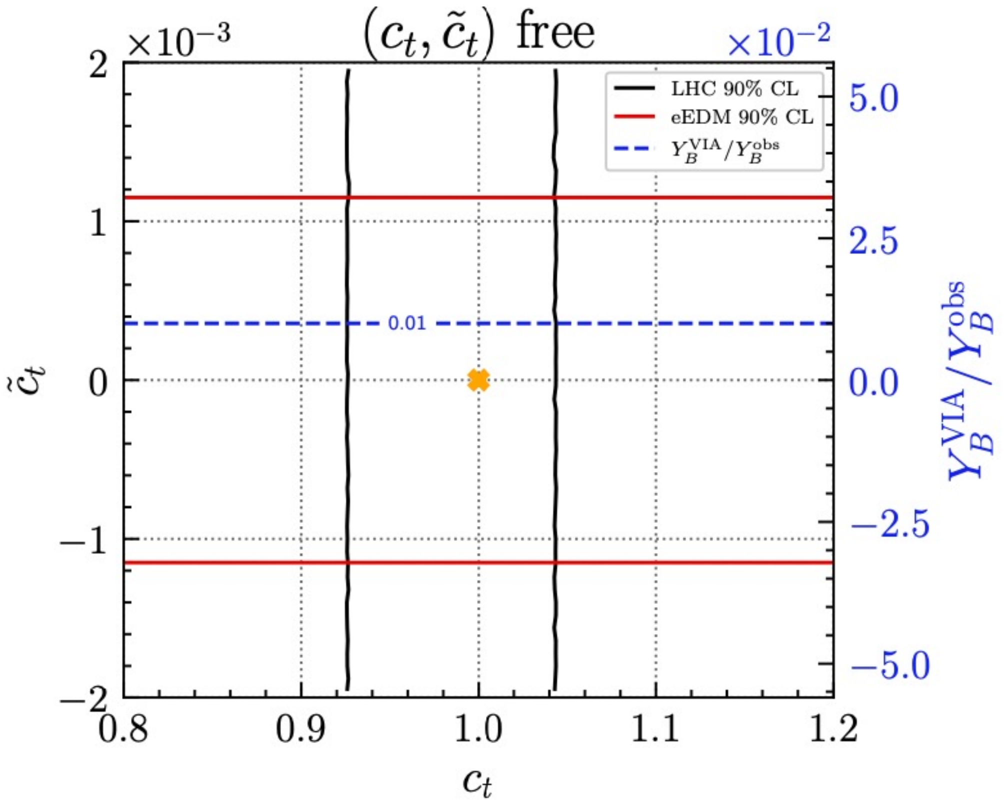
- Several EDMs are sensitive to CP violation in the Higgs sector.
- We consider only the electron EDM.
  [Brod et al.,`13,`15, `18,`22;Panico et al.,`18;Altmannshofer et al.,`20]
- $\frac{d_e}{d_e^{\text{ACME}}} \simeq 870 c_e \tilde{c}_t + \tilde{c}_e(610 c_t - 1082.6 c_V) + \cdots$
- Bounds strongly depend on assumptions about electron-Yukawa coupling.




**BAU**

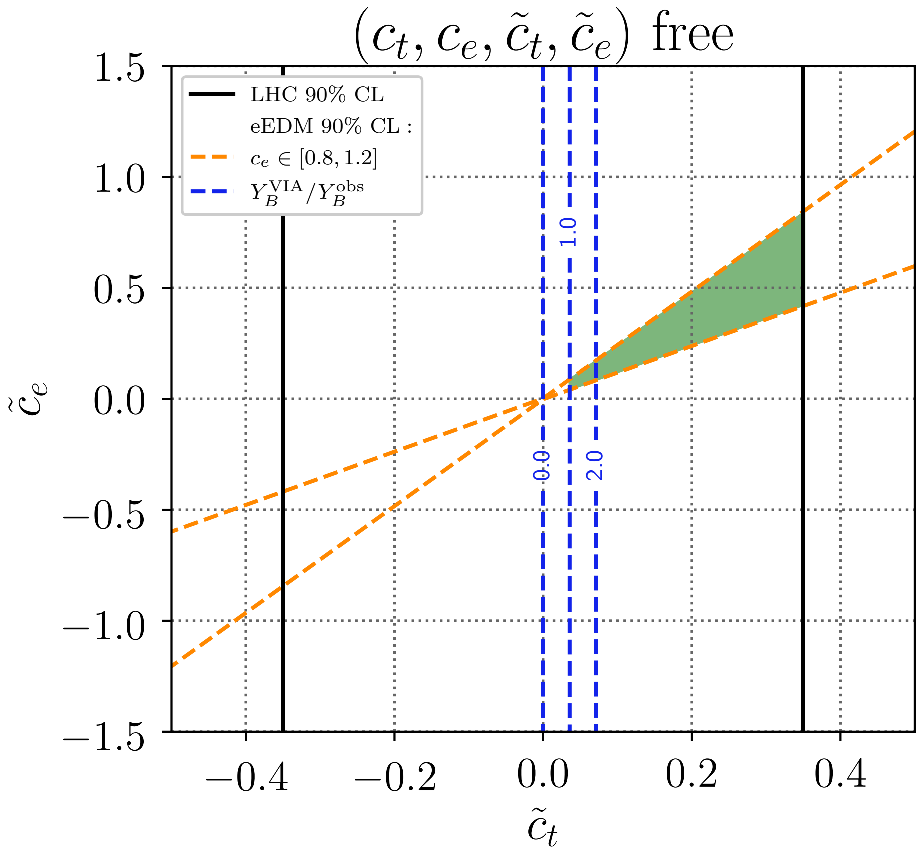
- Different techniques used in the literature to calculate BAU $Y_B$: vev-insertion approach (VIA) and WKB approximation.
  [Huet&Nelson,`95; Carena et al.,`96;Riotto,`97; Lee et al.,`04; Joecy et al.,`94; Kainulainen et al.,`01,`02; Prokopec et al.,`03,`04;Konstandin et al.,`13,`14; Basler,`21]
- VIA approach yields consistently higher results by orders of magnitude.
- We use VIA approach with bubble wall parameters close to optimal values for $Y_B \rightarrow$ $Y_B$ values should be regarded as **upper bound** on what is theoretically achievable. [de Vries et al.,`18; Fuchs et al.,`20; Shapira,`21]

# Constraints on top-Yukawa coupling




- EDM constraint strongly limits size of $\tilde{c}_t$
- Only tiny amount of BAU can be generated via CP-violating top-Yukawa coupling.
- However, strong dependence on electron-Yukawa coupling

# Dependence on electron-Yukawa coupling




- 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 $d_e < d_e^{\mathrm{ACME}}$.
- Neutron EDM has similar dependence on first-generation quark-Yukawa couplings.

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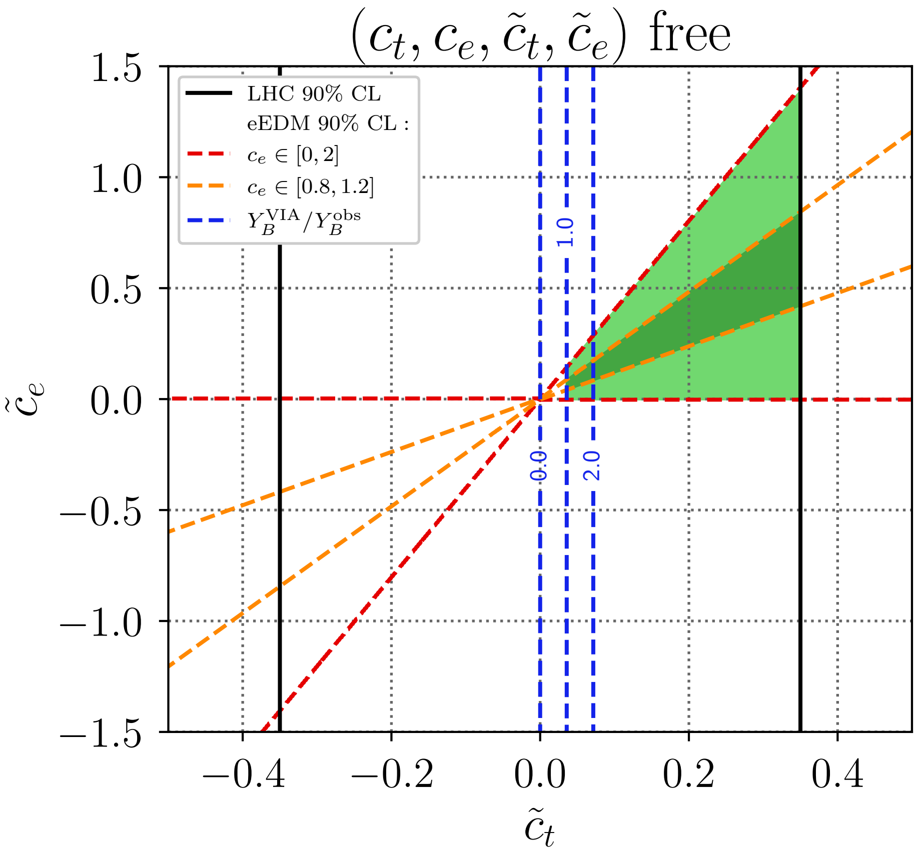


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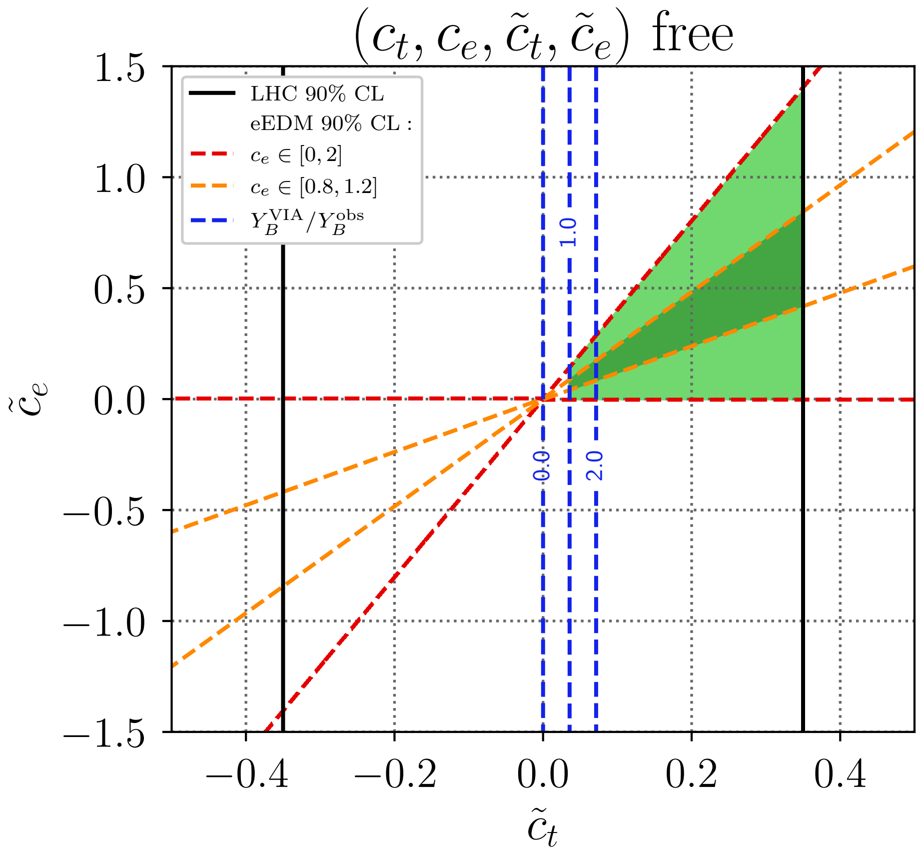


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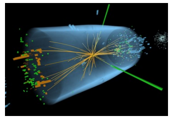
→ LHC bounds important since they do not depend on 1st gen. Yukawa couplings.

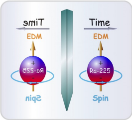
# Conclusions

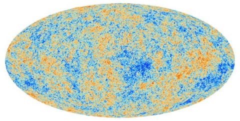
*Initial question*: how well can we constrain
**CP violation in the Higgs–top-quark interaction**?



**LHC** constraints:

- $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$ tightly constrain CP violation in the **top-Yukawa couplings** indirectly.
- Top-associated Higgs production is prime candidate to reduce model dependence.
- Strong constraints from top-associated Higgs production can be expected if full kinematic information is exploited.



**EDM and baryogenesis** constraints:

- EDM bounds put very strong bounds on a CP-violating top-Yukawa interaction.
- Only very small contribution to BAU realizable
- EDM interpretation, however, strongly depends on first generation Yukawa couplings.

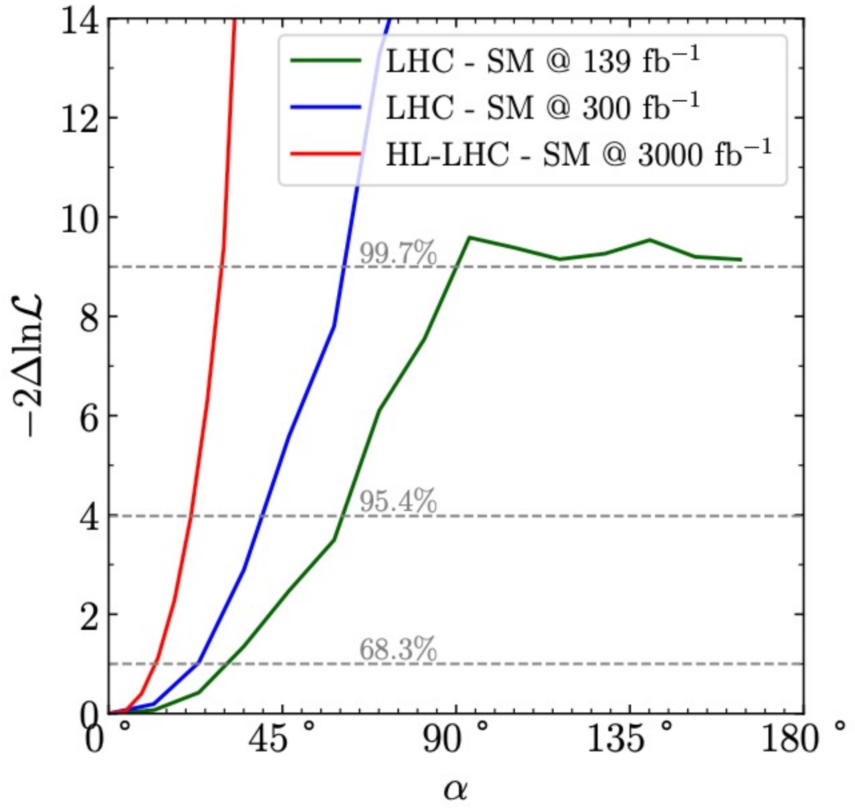
**Thanks for your attention!**

# Appendix

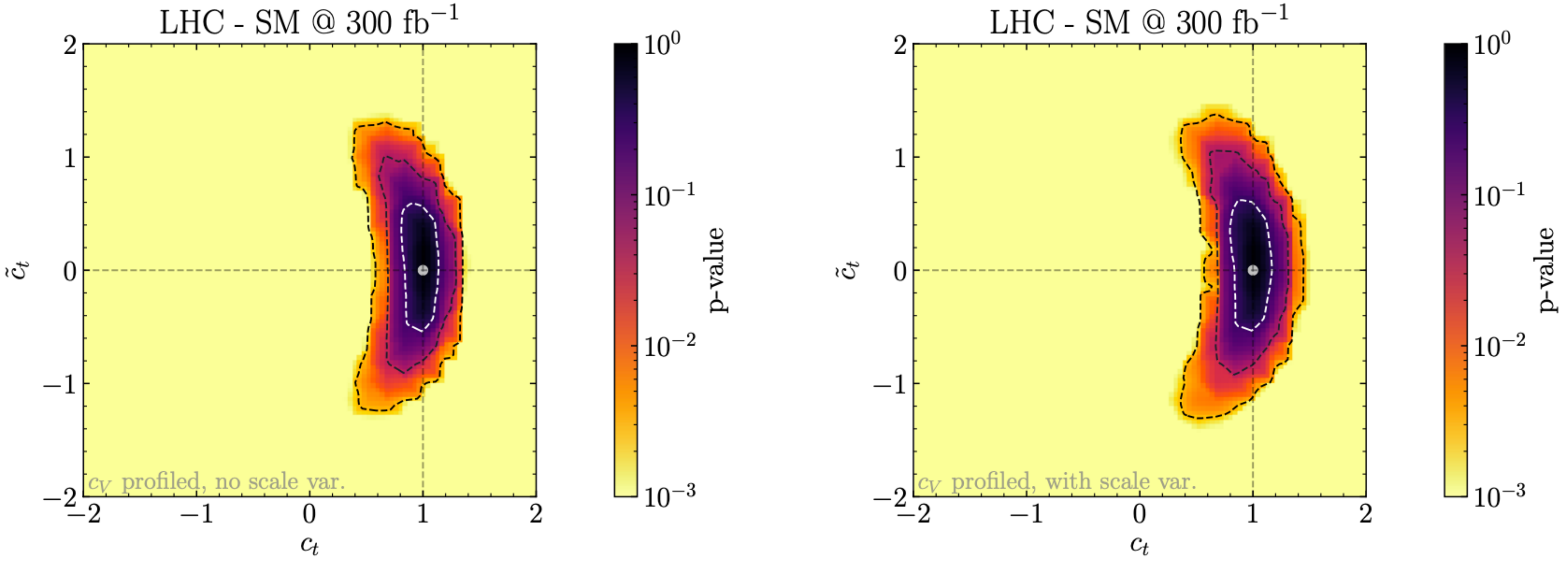
| observable | condition |
|---|---|
| $N_\gamma$ | $\geq 2$ (with $\|\eta\| < 2.5$ and $p_T > 25$ GeV) |
| $(p^\gamma_{T,1}, p^\gamma_{T,2})$ | $\geq (35, 25)$ GeV |
| $m_{\gamma\gamma}$ | $[105 - 160]$ GeV |
| $(p^\gamma_{T,1}/m_{\gamma\gamma}, p^\gamma_{T,2}/m_{\gamma\gamma})$ | $\geq (0.35, 0.25)$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

**Table 1:** Summary of preselection cuts.

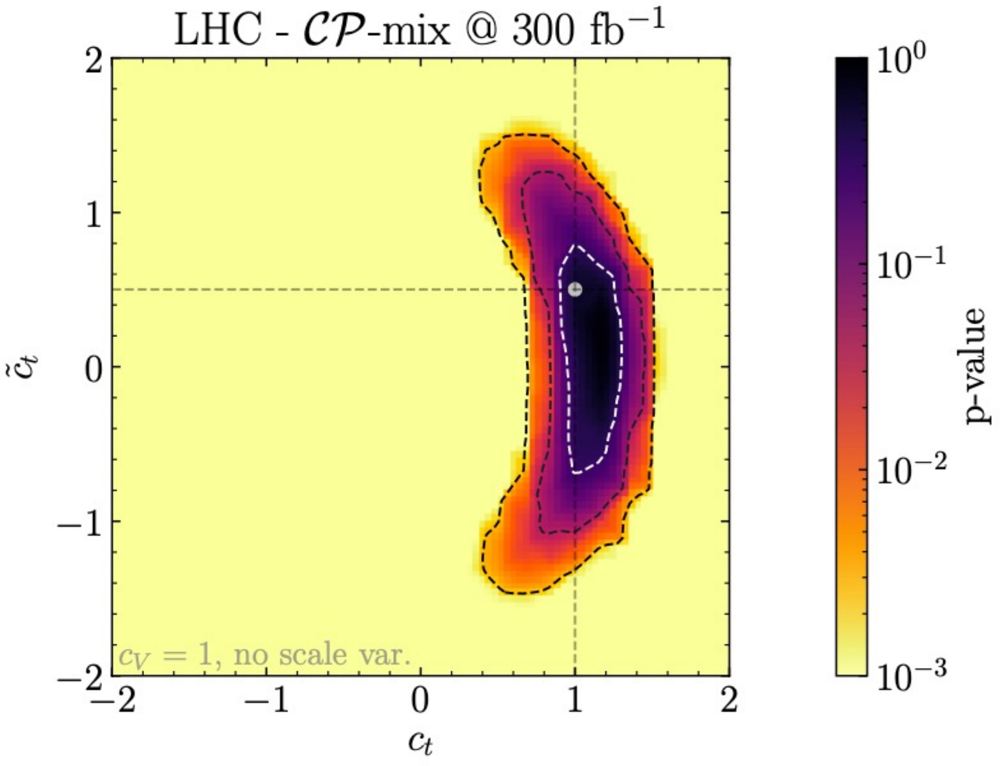
# Interpretation in terms of CP-violating angle

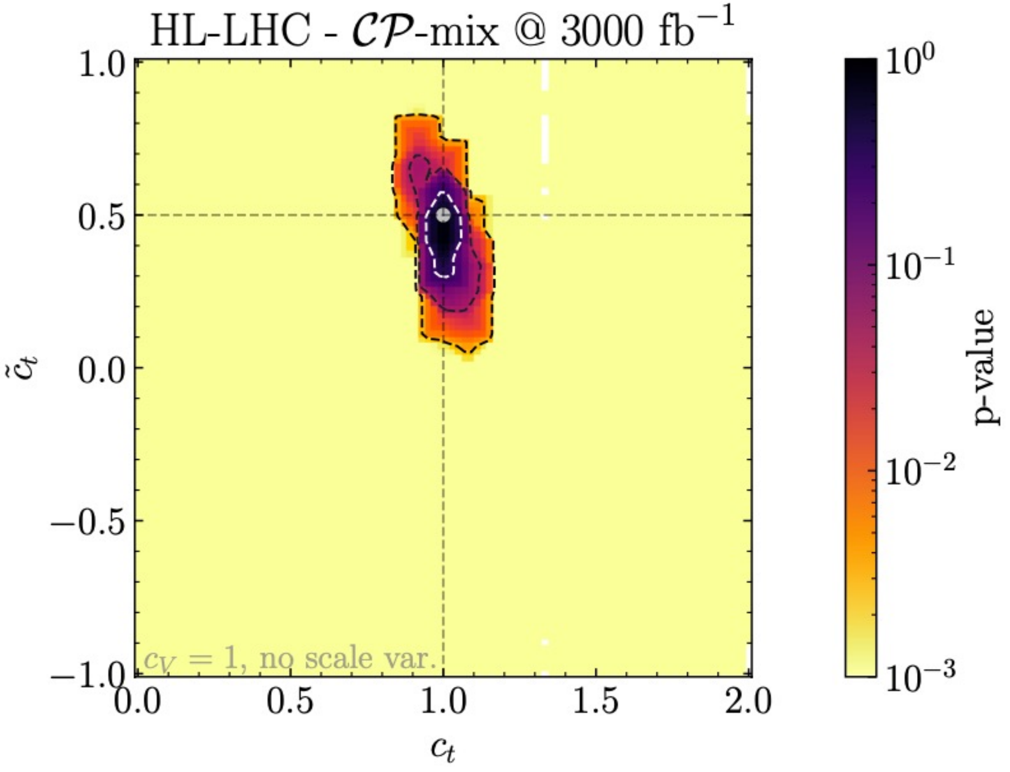


# Variation of $c_V$ and renormalization scale



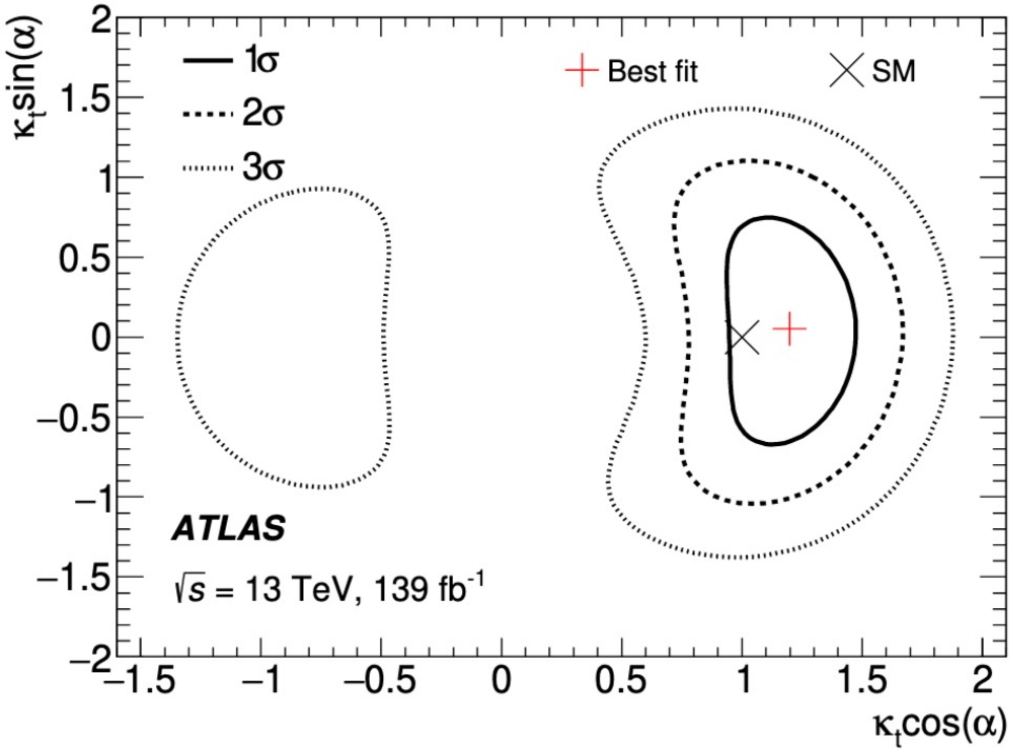
# Limits in case of deviation from SM

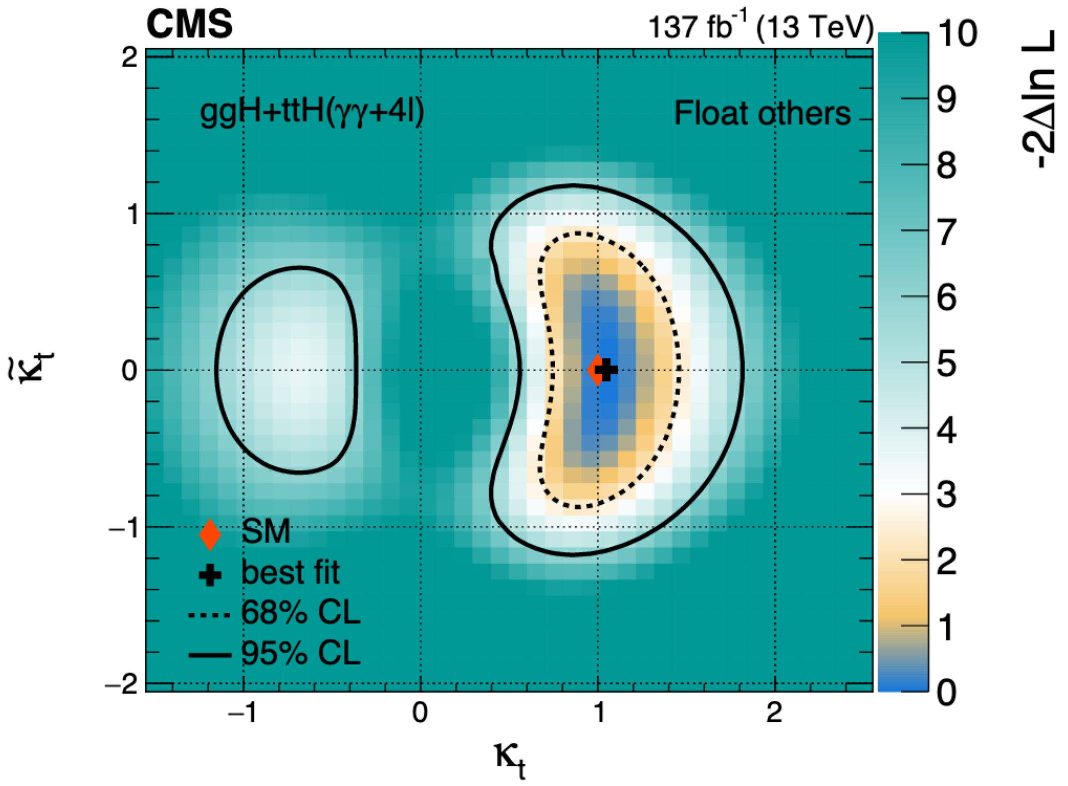


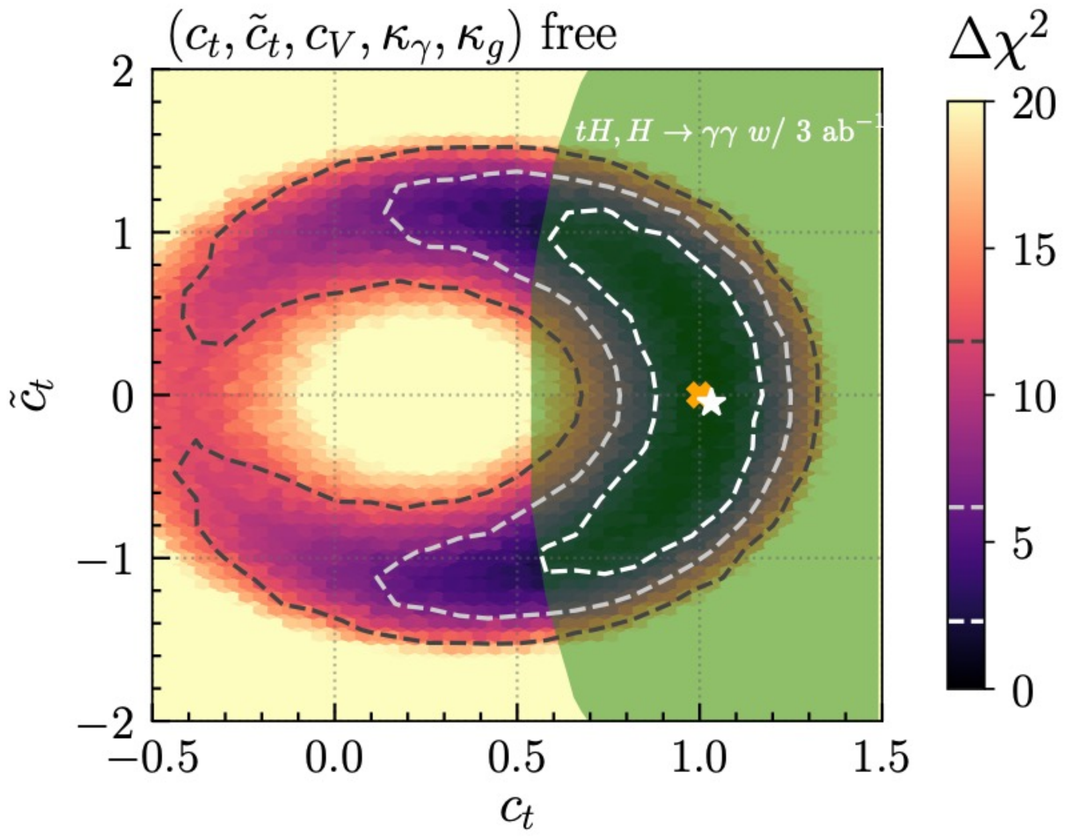




- CP-mix: $c_t = 1$, $c_{\tilde{t}} = 0.5$, $c_V = 1$.

# Experimental studies [ATLAS,2004.04545;CMS,2104.12152]




$(c_t, \tilde{c}_t, c_V, \kappa_\gamma, \kappa_g)$ free
$tH, H \to \gamma\gamma$ w/ 3 ab$^{-1}$
$\Delta\chi^2$
20
15
10
5
0
2
1
0
−1
−2
−0.5
0.0
0.5
1.0
1.5
$c_t$
$\tilde{c}_t$

# Which observables drive these constraints?

- Use Fisher matrix to evaluate information for different observables

$$I_{ij}(\theta) = \mathbb{E}\left[\frac{\partial \log p_{\text{full}}(\{x\}|\theta)}{\partial \theta_i}\frac{\partial \log p_{\text{full}}(\{x\}|\theta)}{\partial \theta_j}\bigg|_\theta\right],$$

with

$$\text{cov}(\hat{\theta}|\theta)_{ij} \geq I_{ij}^{-1}(\theta),$$

- E.g., for SM point we have

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

with the parameter space spanned by

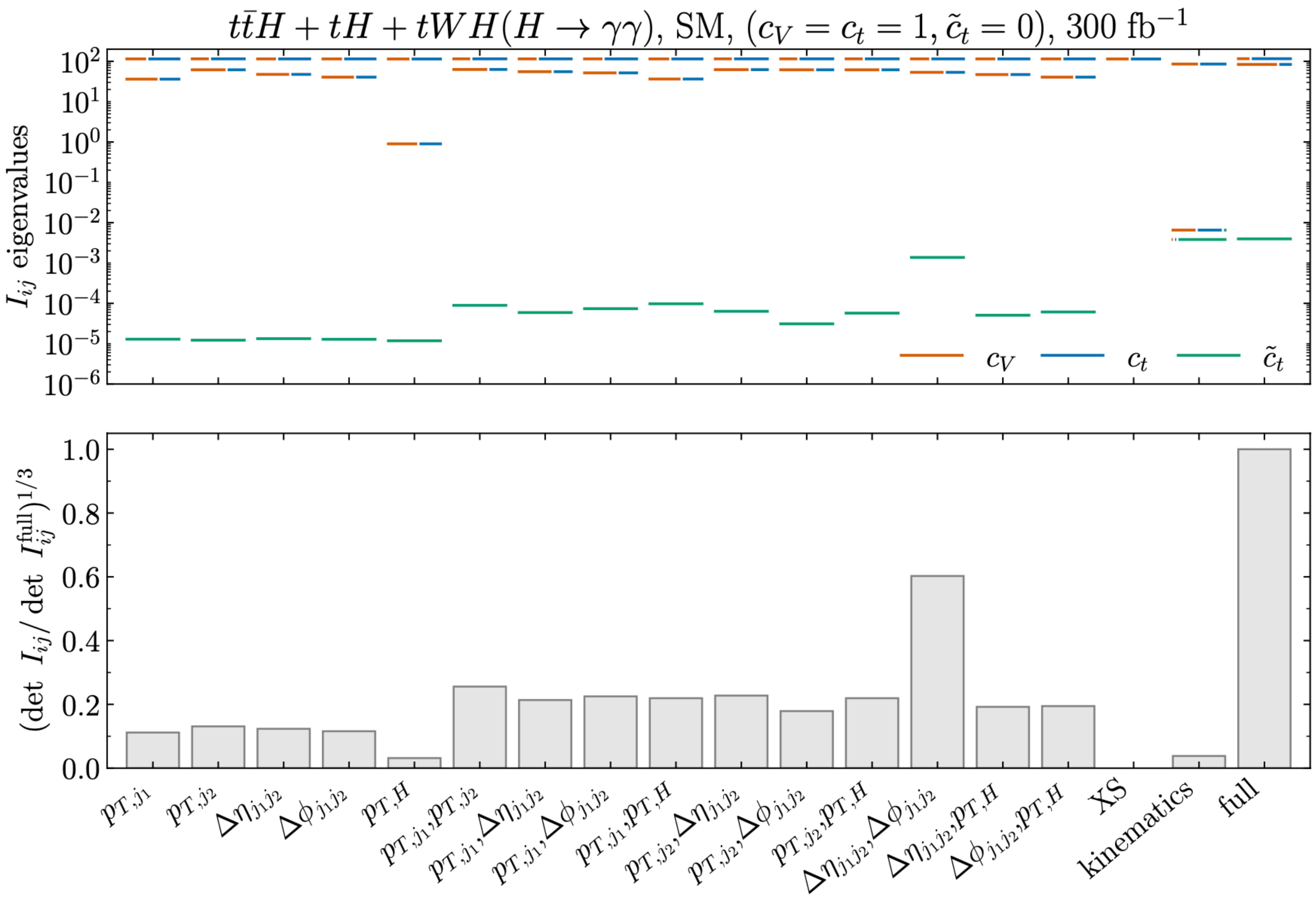
$$\begin{pmatrix} c_V \\ c_t \\ c_{\tilde{t}} \end{pmatrix}$$

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

# Fisher information for SM scenario

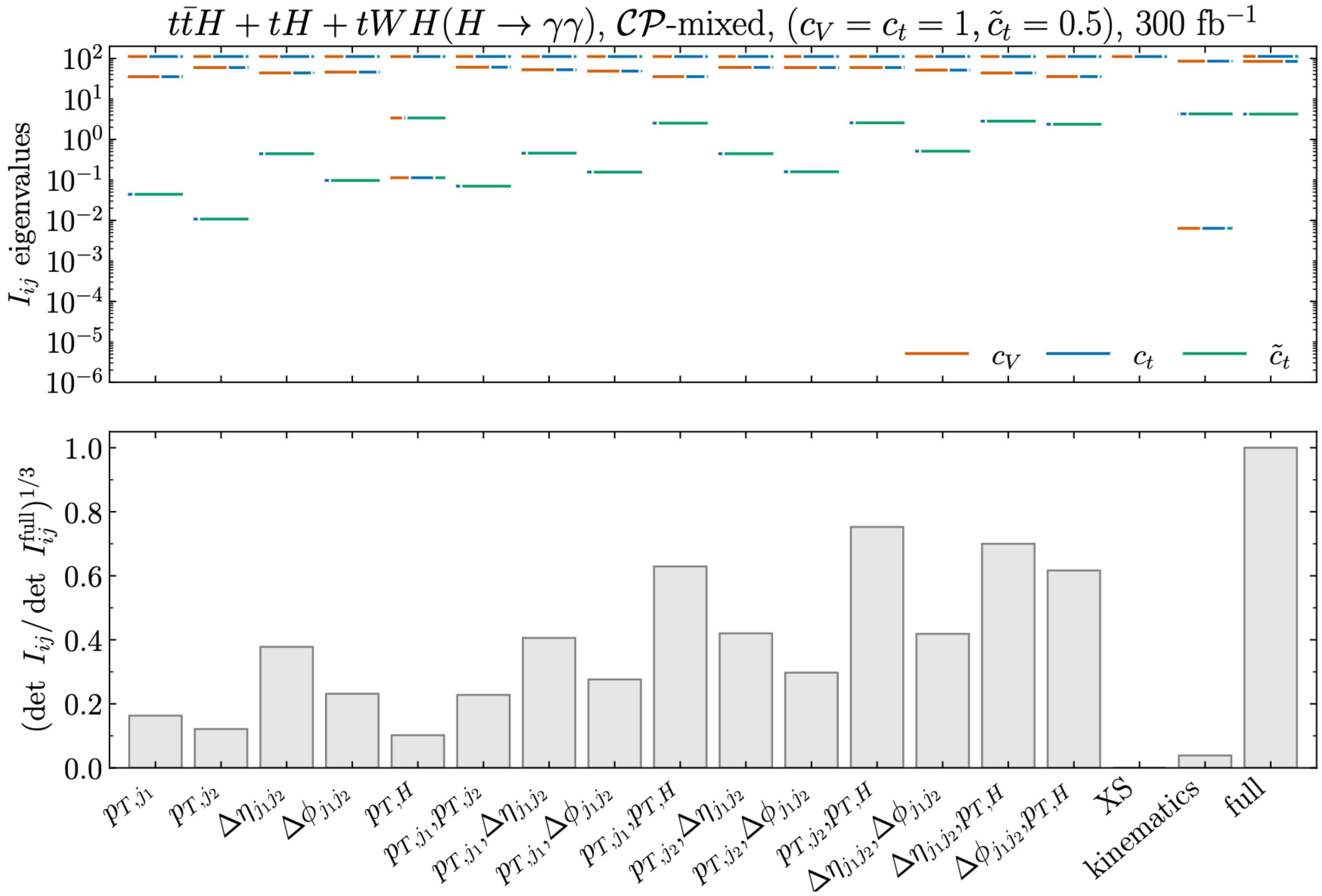
Which combinations of couplings can we constraint how well?

Total amount of capture information




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

# Fisher information for CP-mixed scenario



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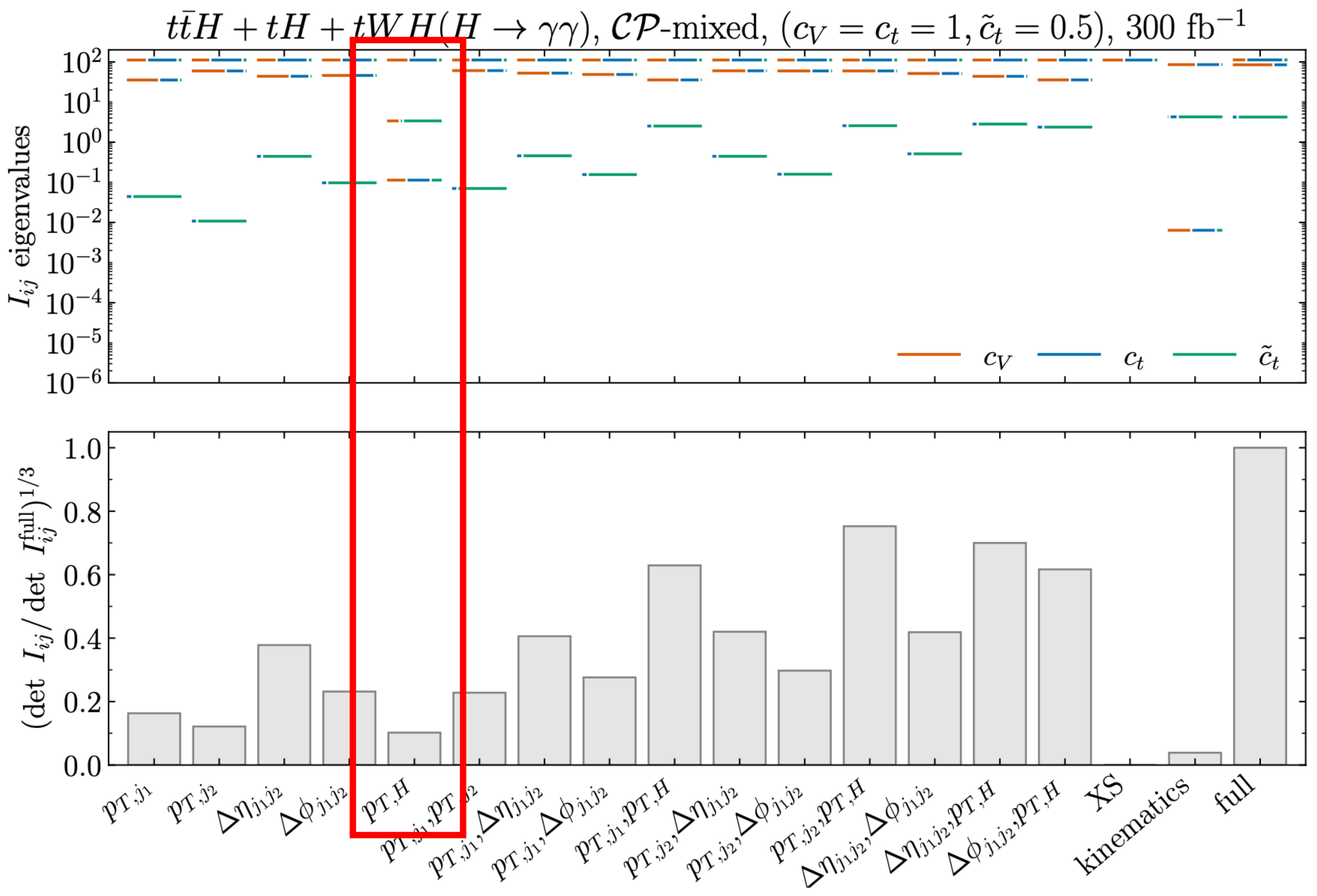


- For CP-mixed scenario, Higgs $p_T$ captures sizeable amount of information on $c_{\tilde{t}}$.

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