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

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based on 2110.10177

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Constraining the CP nature of the Higgs boson

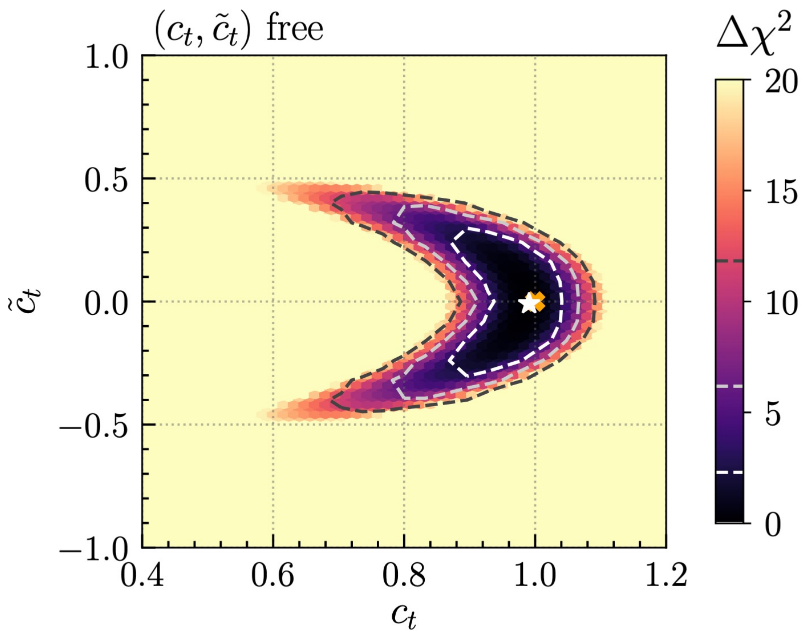
- New sources of CP violation are necessary to explain the baryon asymmetry of the Universe.
- One possibility: CP violation in the Higgs sector with Higgs boson being CP-admixed state.
- Most BSM theories predict largest CP violation in Higgs–fermion couplings.
- CP violation in the Higgs sector can be constrained by
  - demanding successful explanation of the baryon asymmetry (BAU)
  - electric dipole measurements,
  - collider measurements.

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

See also talks by Morgan Cassidy, Yanzhe Zhang, and Rahool Kumar Barman.

Constraining CP violation

- Pure CP-even observables:
    - Unambiguous markers for CP violation: e.g.
        - EDM measurements,
        - decay angle in $H \to \tau^+\tau^-$ [CMS, 2110.04836].
    - Experimentally difficult for top-Yukawa interaction.
- 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.



[HB et al., 2007.08542]

- Exploit kinematic information effectively mixing CP-even and CP-odd observables:
    - High sensitivity expected.

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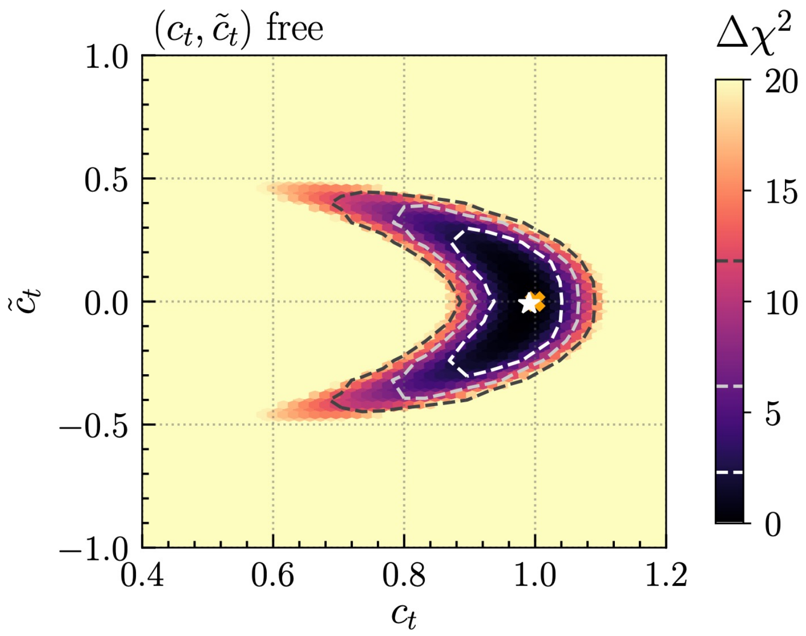

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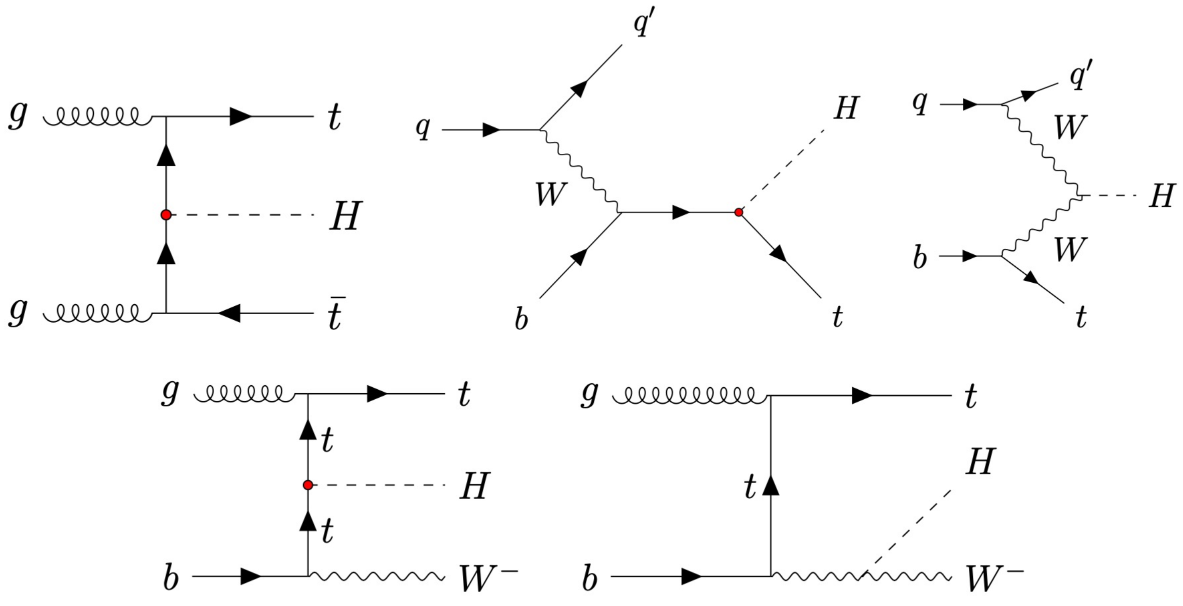
Top associated Higgs production

- Prime probe of the top-Yukawa interaction.
- Three sub channels contribute:
  - $\bar{t}tH$,
  - tH (or tHq),
  - tWH.
- Effective model:

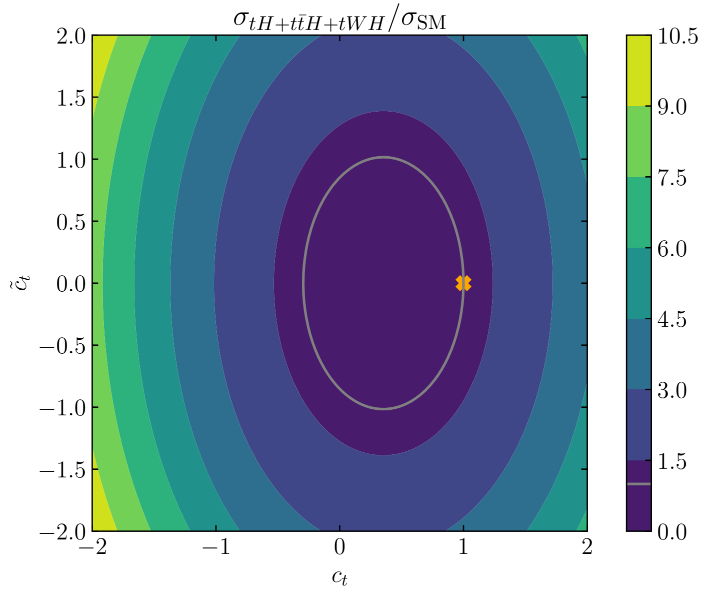
$$\mathcal{L}_{\text{top-yuk}} = -\frac{y_t^{\text{SM}}}{\sqrt{2}}\bar{t}\left(c_t + i\gamma_5\tilde{c}_t\right)tH.$$



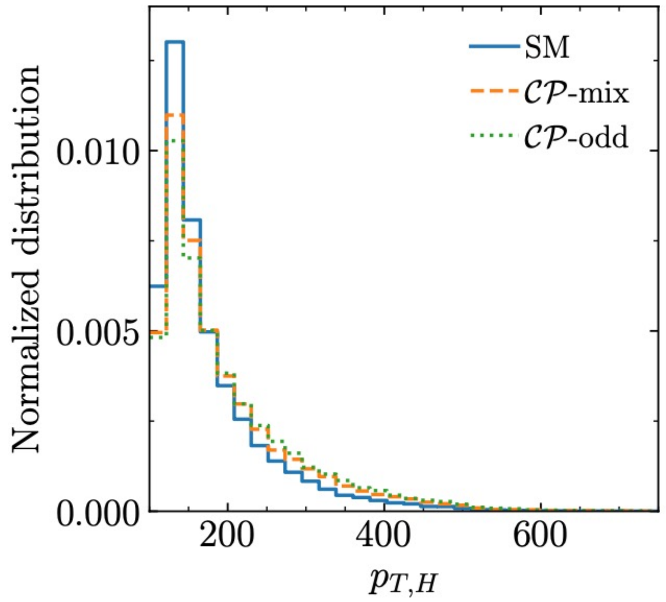
- Additional vary HZZ, HWW couplings (modifier c_V).
- We focus on $H \to \gamma\gamma$ and require at least one lepton.
- ZH and WH production as backgrounds.
- Standard acceptances cuts.

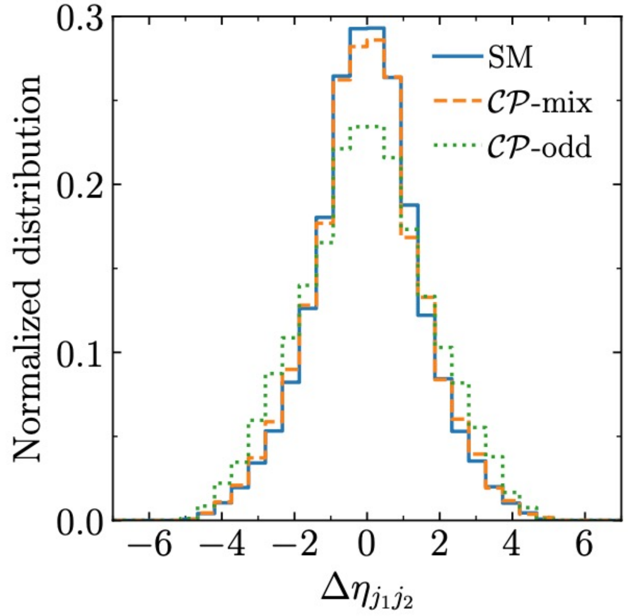
Constraints on effective model

Total rate



Exemplary kinematic distributions

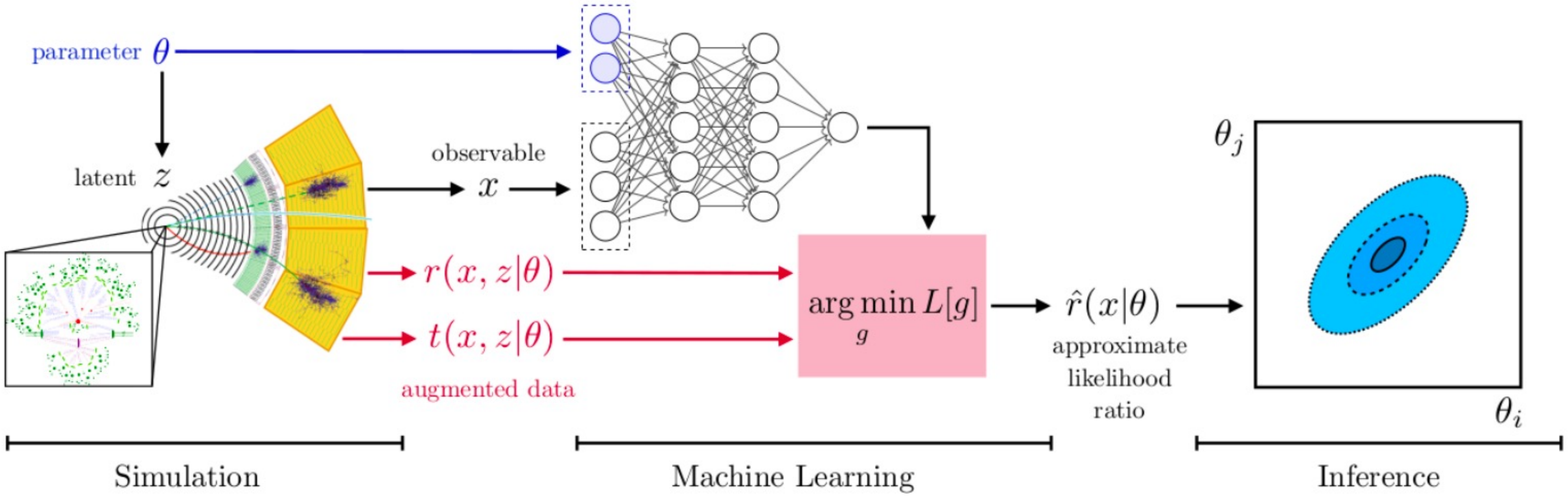




How to best exploit the full available information to constraint top-Yukawa interaction?

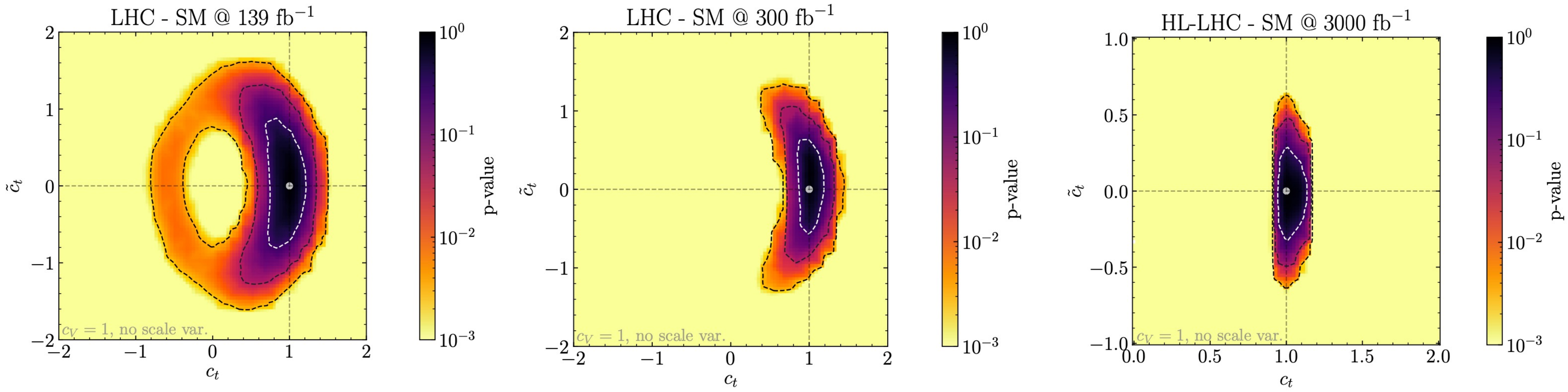
Machine-learning based inference

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



- Allows to extract the full available information (maximal sensitivity).
- 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 $c_V = 1$.
- Additional variation of c_V (and of the renormalization scale) only slightly weakens bounds.

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

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

- E.g., for SM point we have

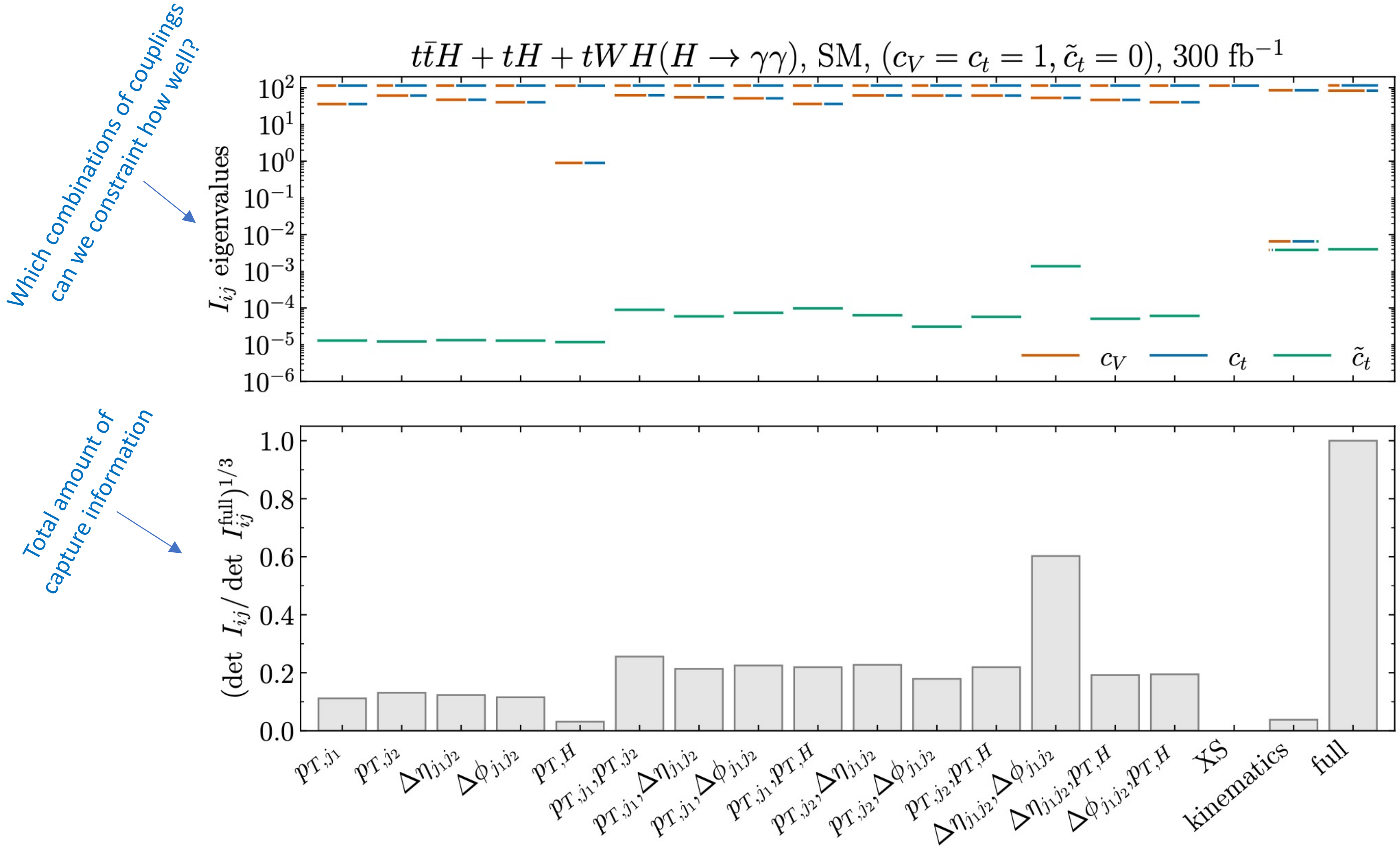
$$I^{\text{full}}_{ij}(\text{SM}) \simeq \begin{pmatrix} 91.4 & 13.7 & 0.1 \\ 13.7 & 108.2 & -0.1 \\ 0.1 & -0.1 & 0.004 \end{pmatrix},$$

with the parameter space spanned by

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

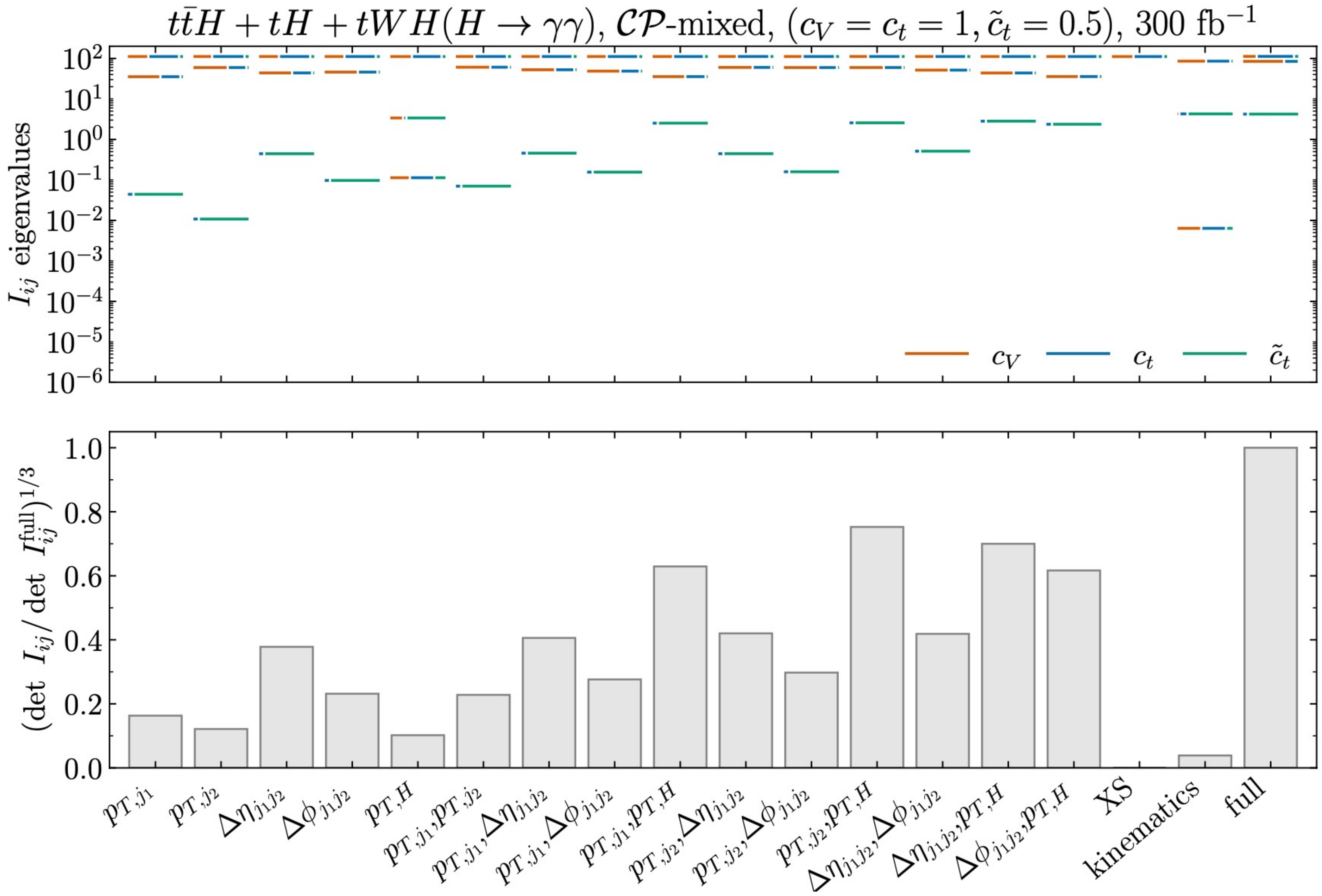
- Evaluate Fisher matrix for various 1D and 2D histograms, full likelihood, XS only, kinematics only.

Fisher information for SM scenario

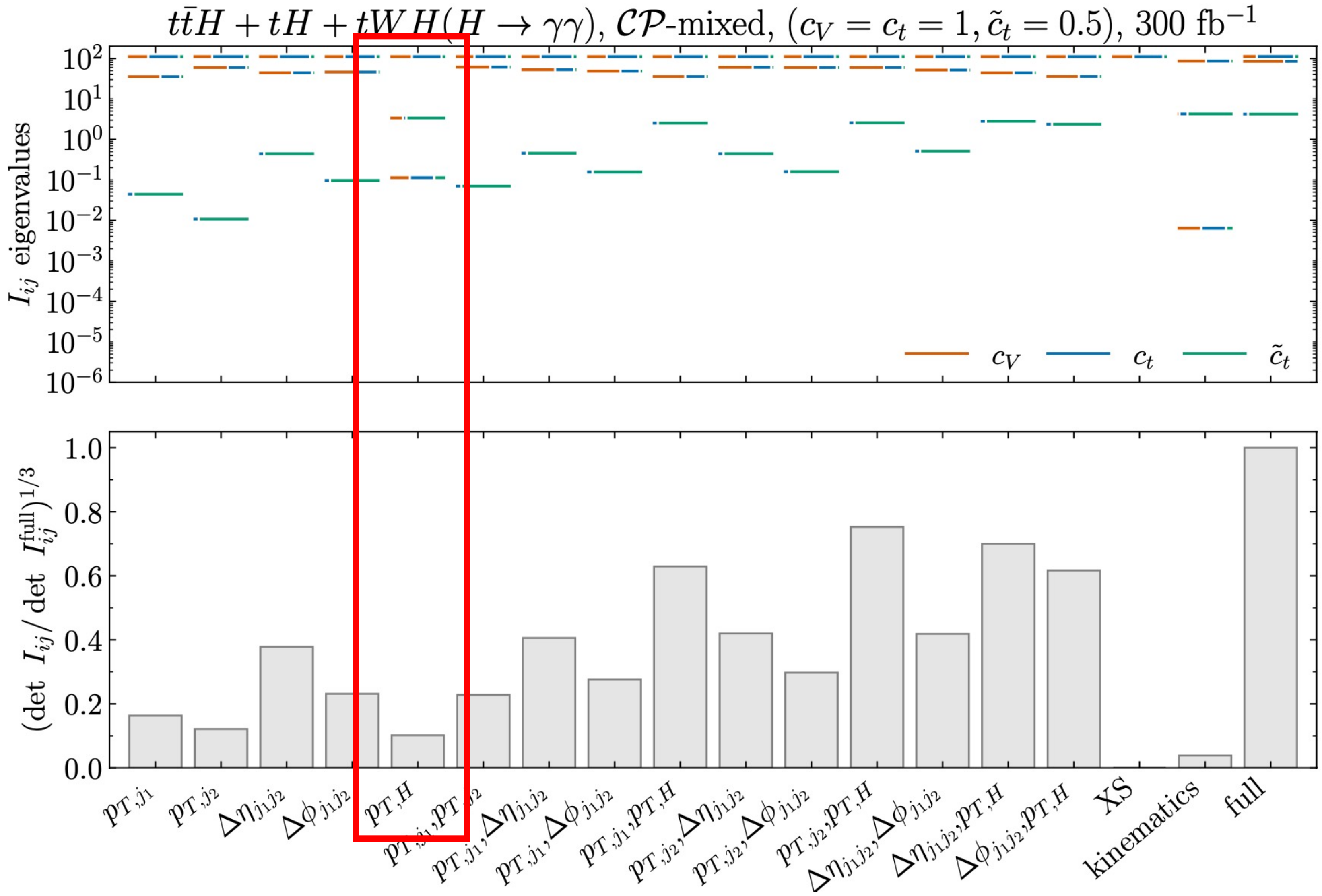


- $c_{\tilde{t}}$ not constrained by rate.
- Use of kinematic information mandatory.
- No single observable able to capture information about $c_{\tilde{t}}$.

Fisher information for CP-mixed scenario



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.

Conclusions

- Initial question: how well can we constrain CP violation in the top-Yukawa?
- Focused on top associated Higgs production with $H \to \gamma\gamma$.
- Used machine-learning based inference approach allowing to extract full available information.
- Strong bounds expected especially at HL-LHC.
- Used Fisher information to compare sensitivity of different observables.
- For establishing a deviation from the SM, the Higgs p_T shape is a promising observable.

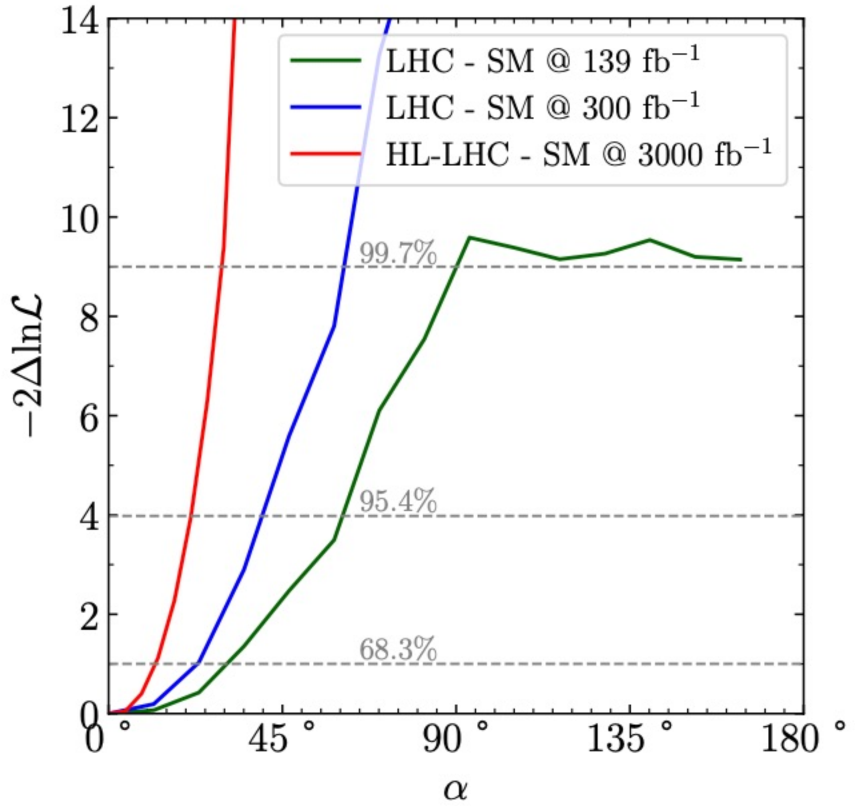
Thanks for your attention!

Appendix

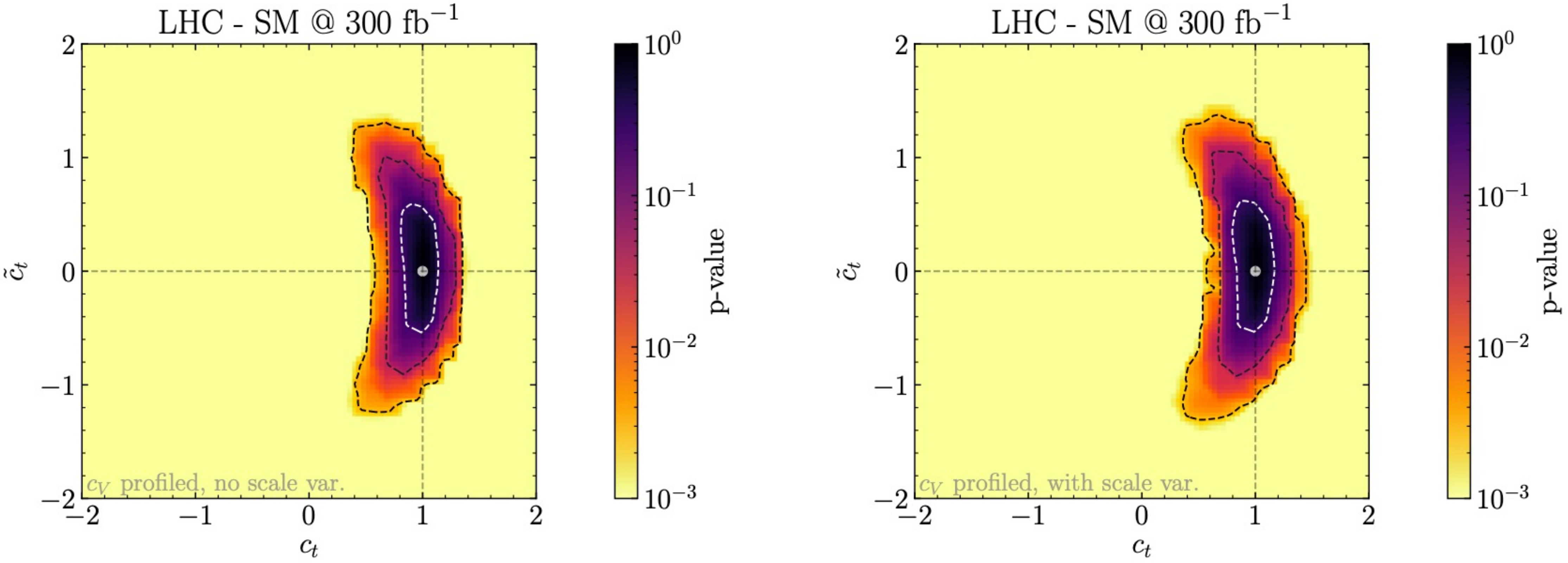
observable	condition
N_γ	≥ 2 (with $\lvert\eta\rvert < 2.5$ and $p_T > 25$ GeV)
$(p^\gamma_{T,1}, p^\gamma_{T,2})$	$\geq (35, 25)$ GeV
$m_{\gamma\gamma}$	$[105 - 160]$ GeV
$(p^\gamma_{T,1}/m_{\gamma\gamma}, p^\gamma_{T,2}/m_{\gamma\gamma})$	$\geq (0.35, 0.25)$
N_ℓ	≥ 1 (with $\lvert\eta\rvert < 2.5$ and $p_T > 15$ 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.

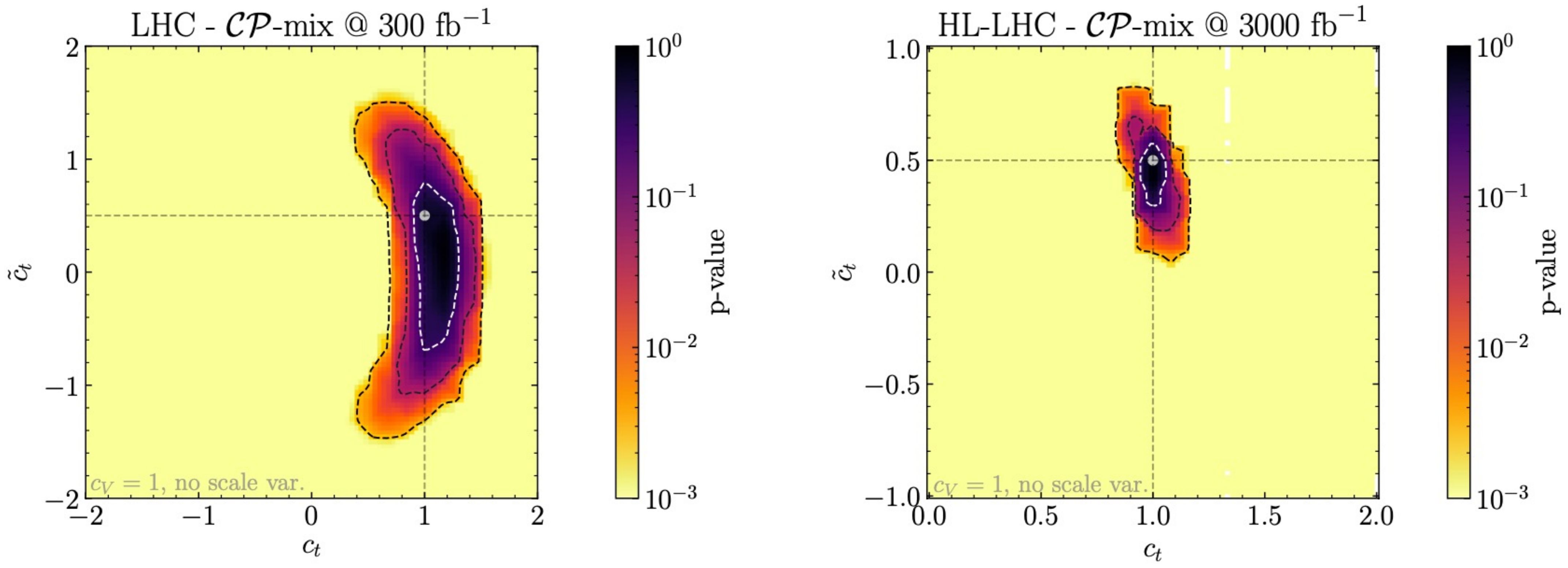
Interpretation in terms of CP-violating angle



Variation of c_V and renormalization scale

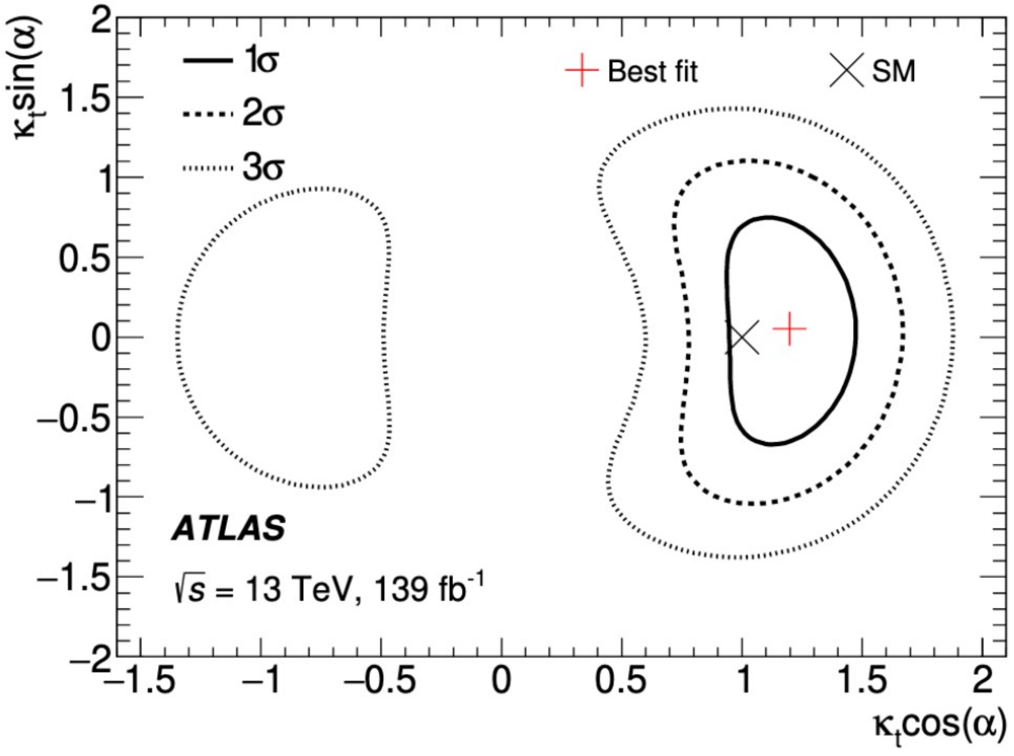


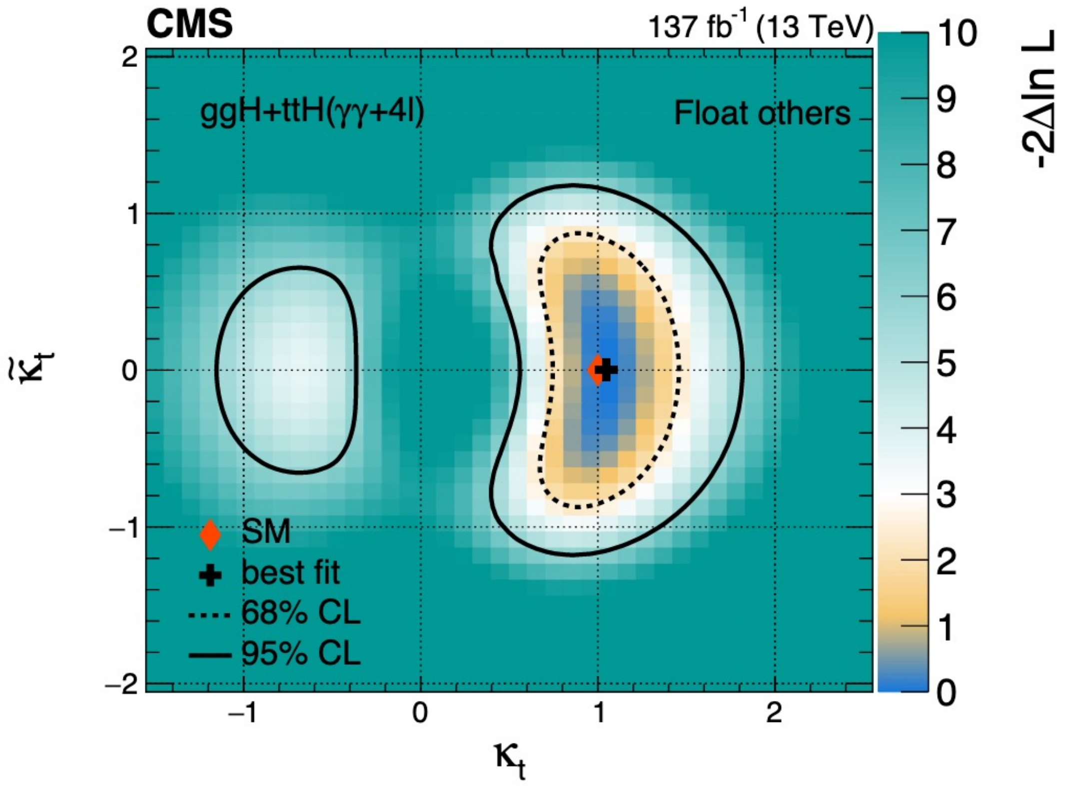
Limits in case of deviation from SM



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

Experimental studies [ATLAS,2004.04545;CMS,2104.12152]





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