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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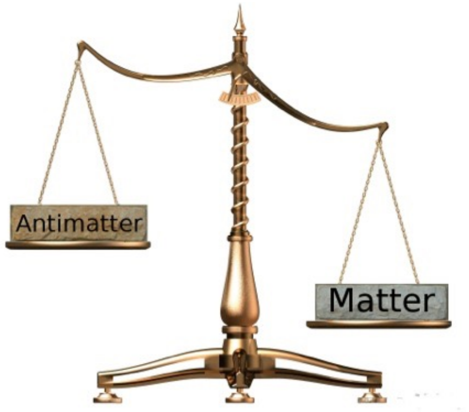
THE UNIVERSITY OF CHICAGO

LHC Top WG meeting, June 17th, 2022

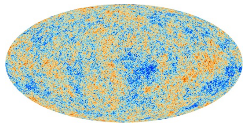
CP violation in the Higgs sector

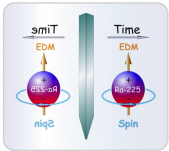


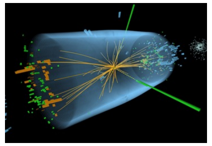
- New sources of CP violation are necessary to explain the baryon asymmetry of the Universe.
- One possibility: CP violation in the Higgs sector.

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.

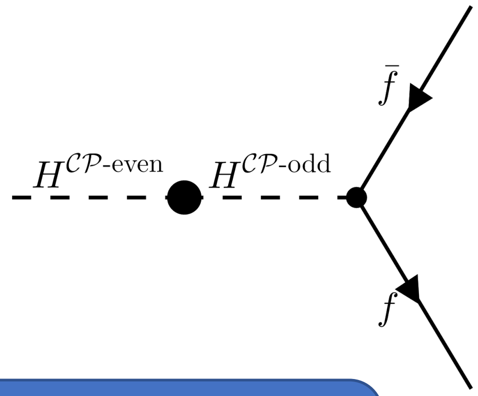






The CP nature of the Higgs boson

- 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.

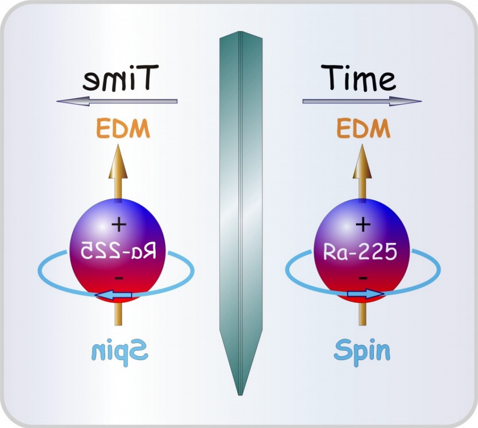


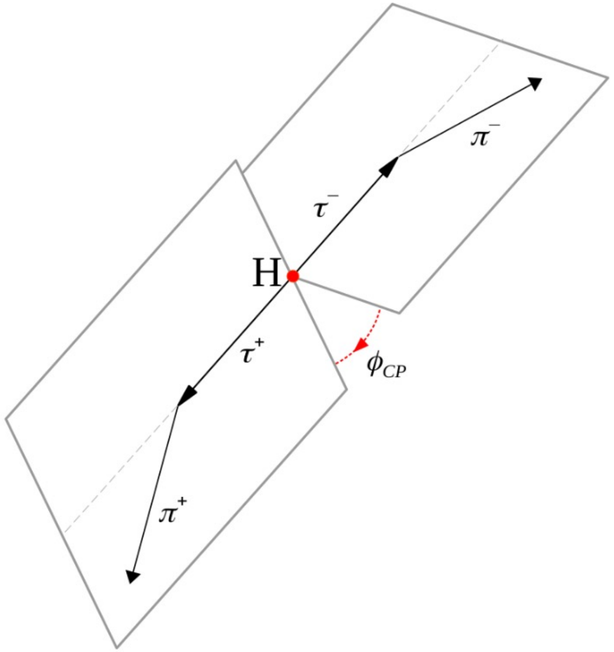
Focus of this talk: Constraining CP violation in the Higgs–top-quark interaction.

Constraining CP violation

CP violation in the Higgs sector can be constrained using:

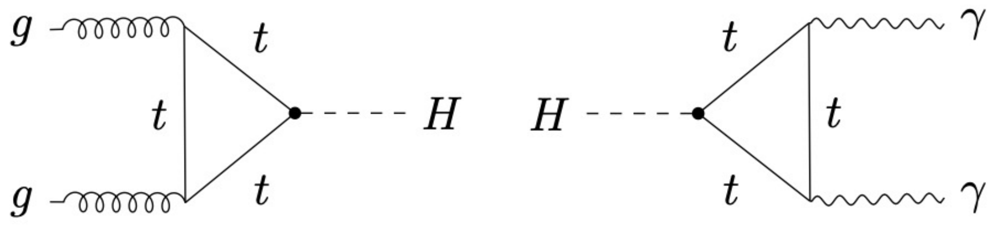
- **Pure CP-odd observables**:
  - Unambiguous markers for CP violation: e.g.
    - EDM measurements,
    - decay angle in $H \to \tau^+\tau^-$.
  - Experimentally difficult for top-Yukawa coupling since top-quarks need to be reconstructed.



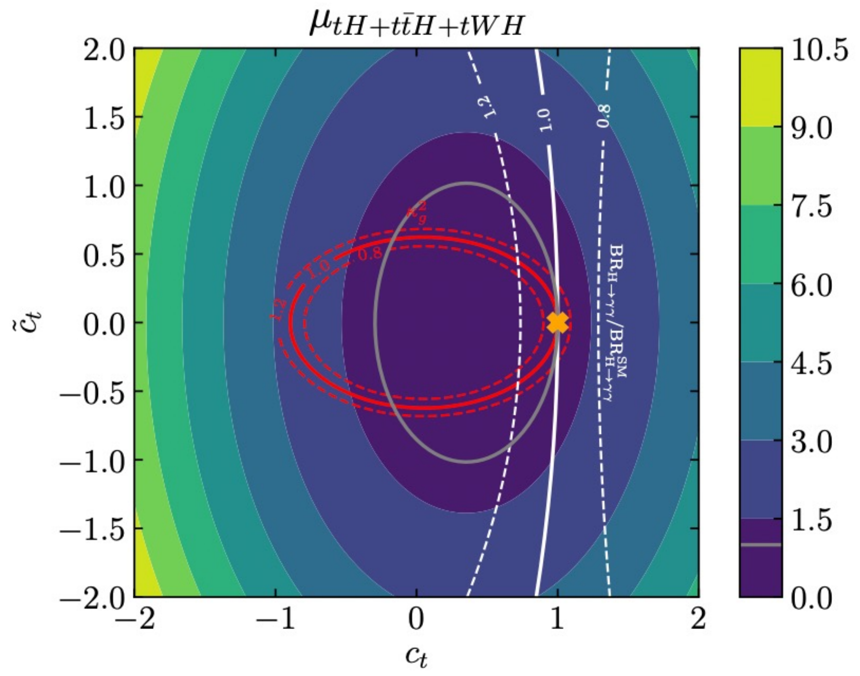


Constraining CP violation

CP violation in the Higgs sector can be constrained using:



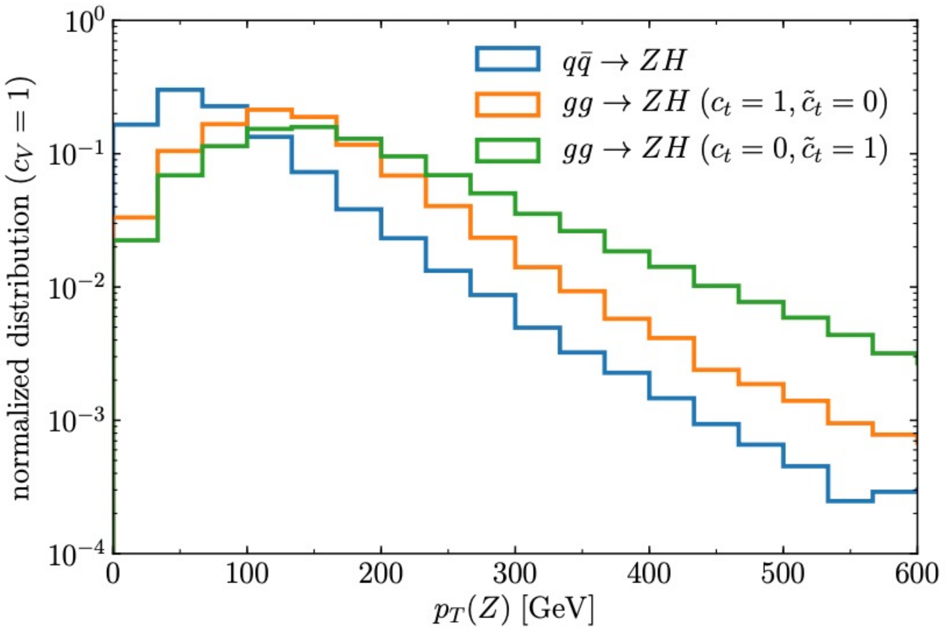
- **Pure CP-even observables**:
  - Many rate measurements are indirectly sensitive: e.g.
    - Higgs production via gluon fusion,
    - $H \to \gamma\gamma$,
    - Top-associated Higgs production.
  - Deviations from SM need not be due to CP violation.



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!

This talk: kinematic analysis of top-associated Higgs production.

Effective model

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

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

- Allow moreover for CP-conserving modification of HVV couplings (relevant for tH and tWH)

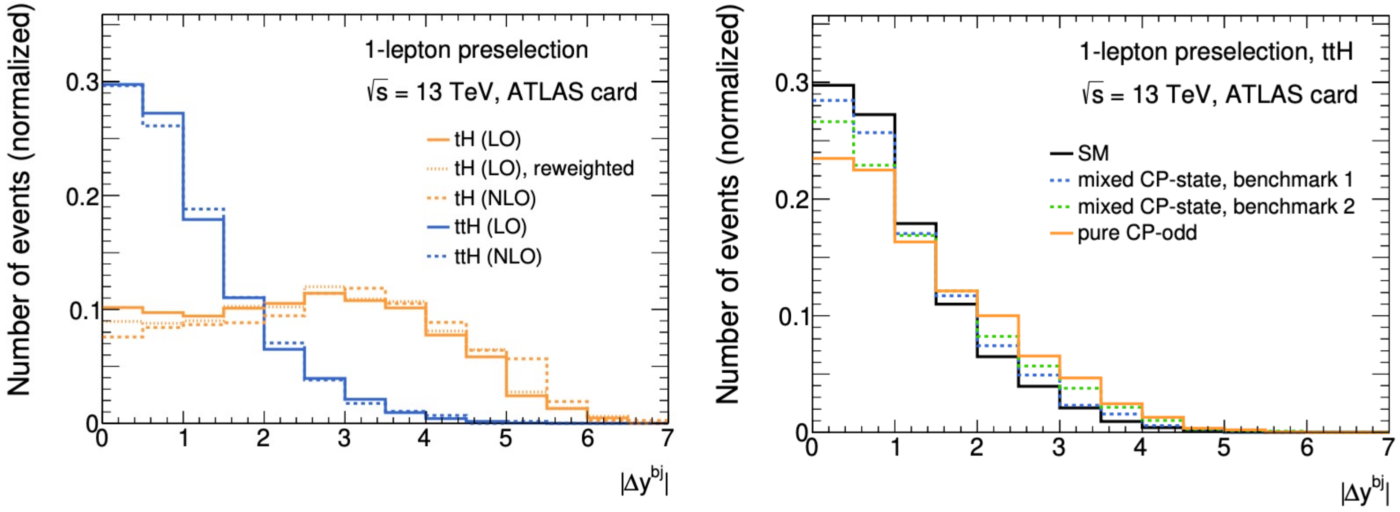
$$\mathcal{L}_V = c_V H\left(\frac{M_Z^2}{v}Z_\mu Z^\mu + 2\frac{M_W^2}{v}W_\mu^+ W^{-\mu}\right)$$

- SM: $c_t = 1$, $\tilde{c}_t = 0$, $c_V = 1$.

Top-associated Higgs production

- Top-associated Higgs production unique tree-level probe of top-Yukawa coupling.
- Three subchannels: $t\bar{t}H$, tH, tWH.
- tH and tWH negligible in the SM.
- Non-zero CP-odd top-Yukawa coupling can significantly enhance tH and tWH production.
- Non-zero CP-odd top-Yukawa coupling significantly affects kinematics.

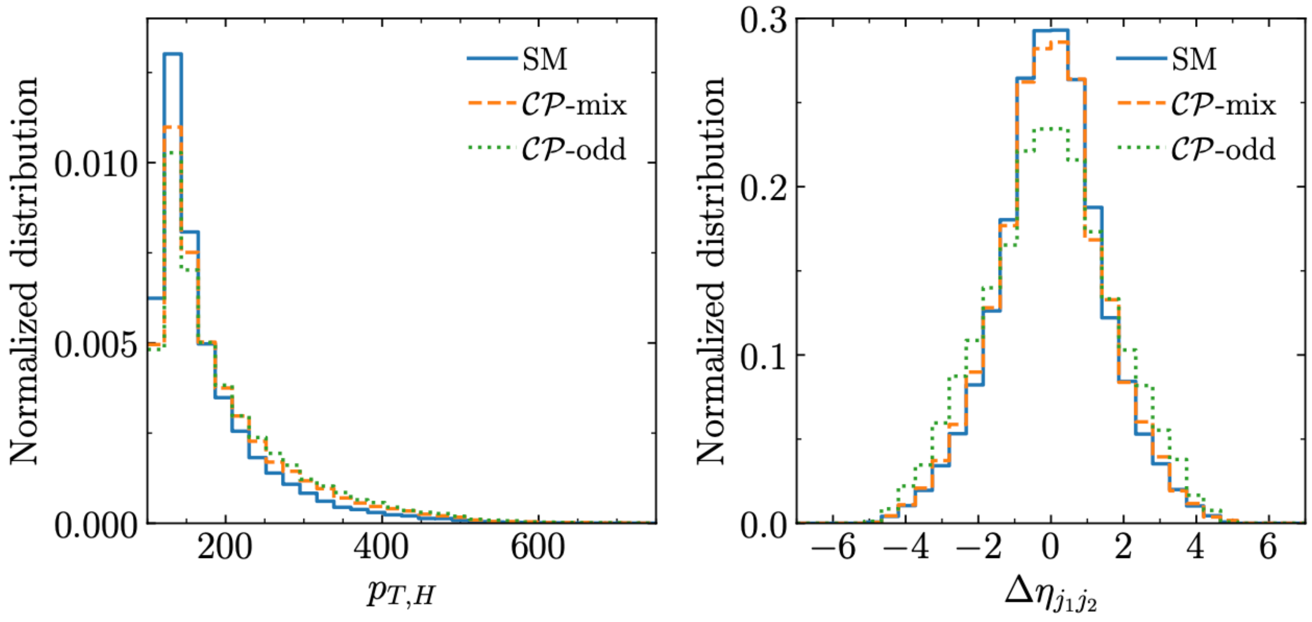
[HB et al.,2007.08542]



Model-independent separation of sub-channels difficult. → Combined analysis!

Kinematic analysis of top-associated Higgs prod.

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

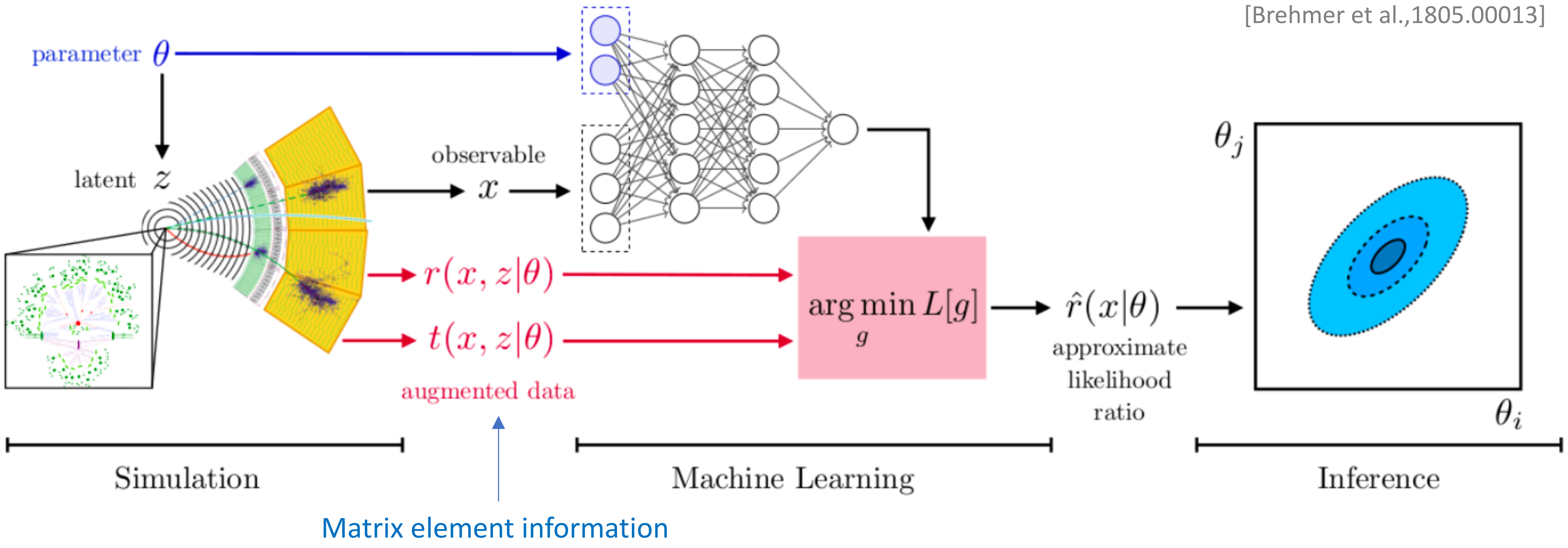


How to best exploit the full available information to constraint top-Yukawa interaction?

Machine-learning based inference

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

[Brehmer et al.,1805.00013]



- 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.
- Works with MadGraph + Pythia + Delphes but other tools could also be interfaced.

[Brehmer,Kling,Espejo,Cranmer,1907.10621]

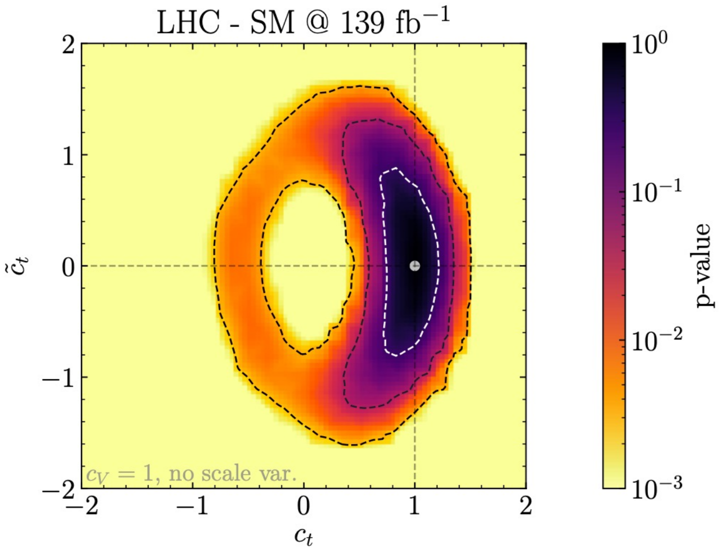
ML-based inference: setup

- 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.

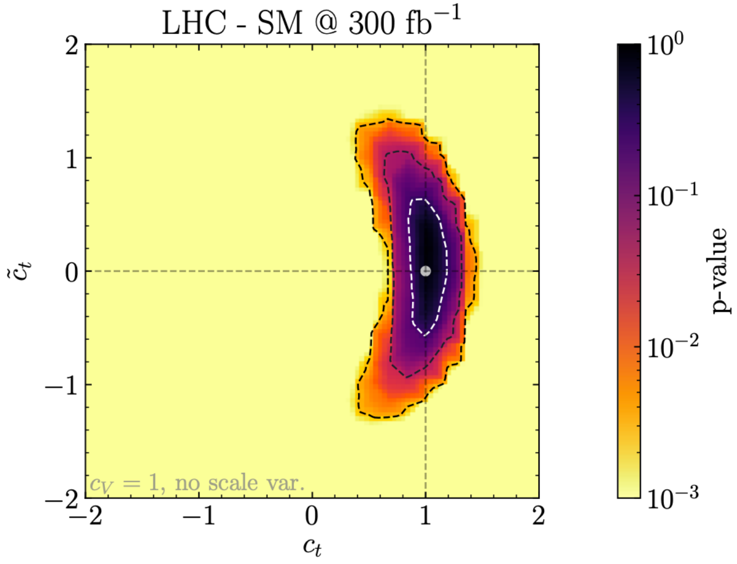
⇒ Evaluate likelihoods for different luminosities at the LHC + HL-LHC.

Expected limits at the (HL-)LHC

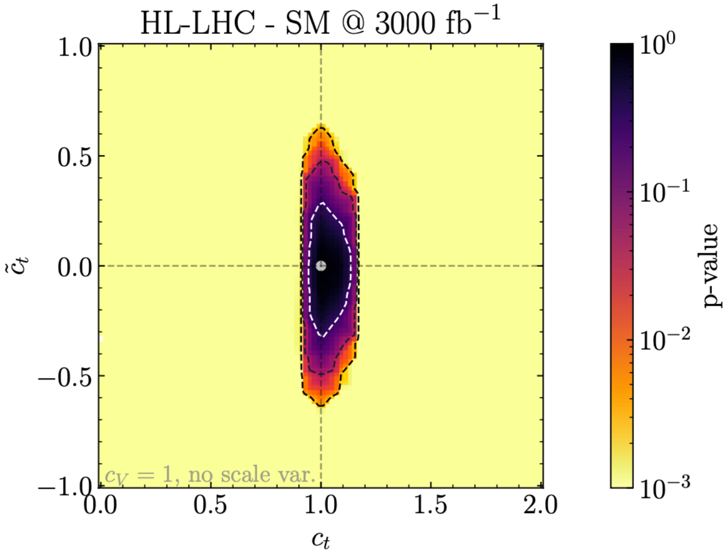
[HB&Brass,2110.10177]



$\alpha \leq 60°$ at 95% CL



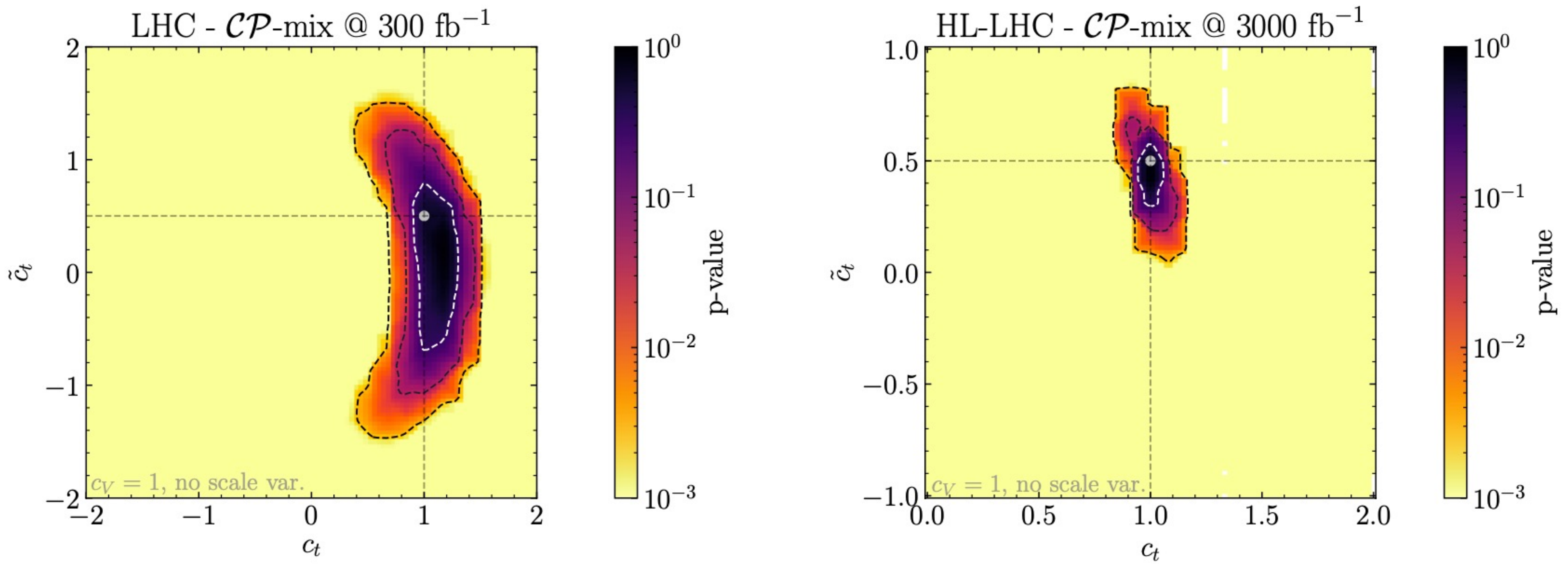
$\alpha \leq 40°$ at 95% CL



$\alpha \leq 22°$ 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 fb^{-1}).

Limits in case of deviation from SM



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

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

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

Information about c_V

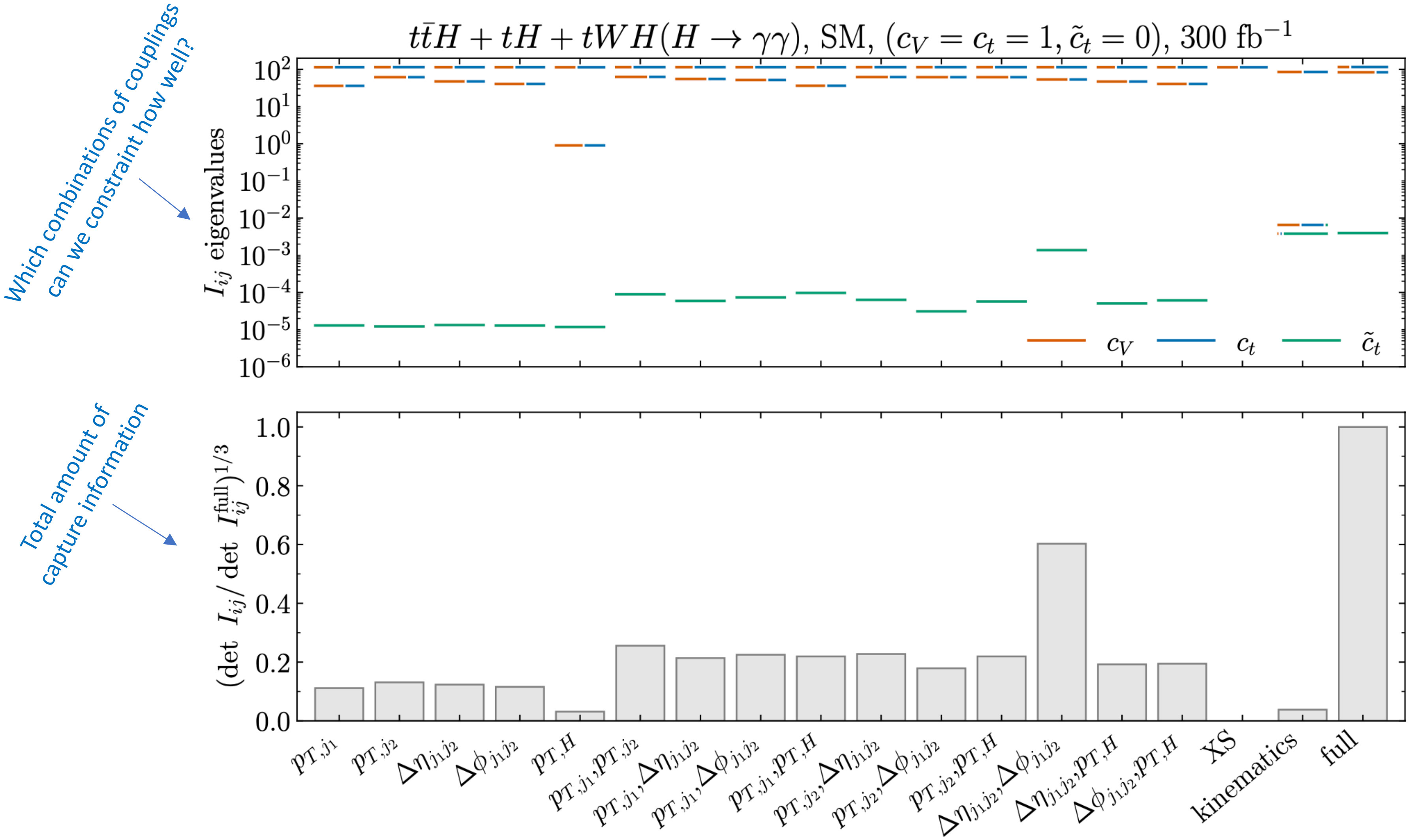
Information about c_t

Correlation of c_t and c_V

Information about $\tilde{c}_t$

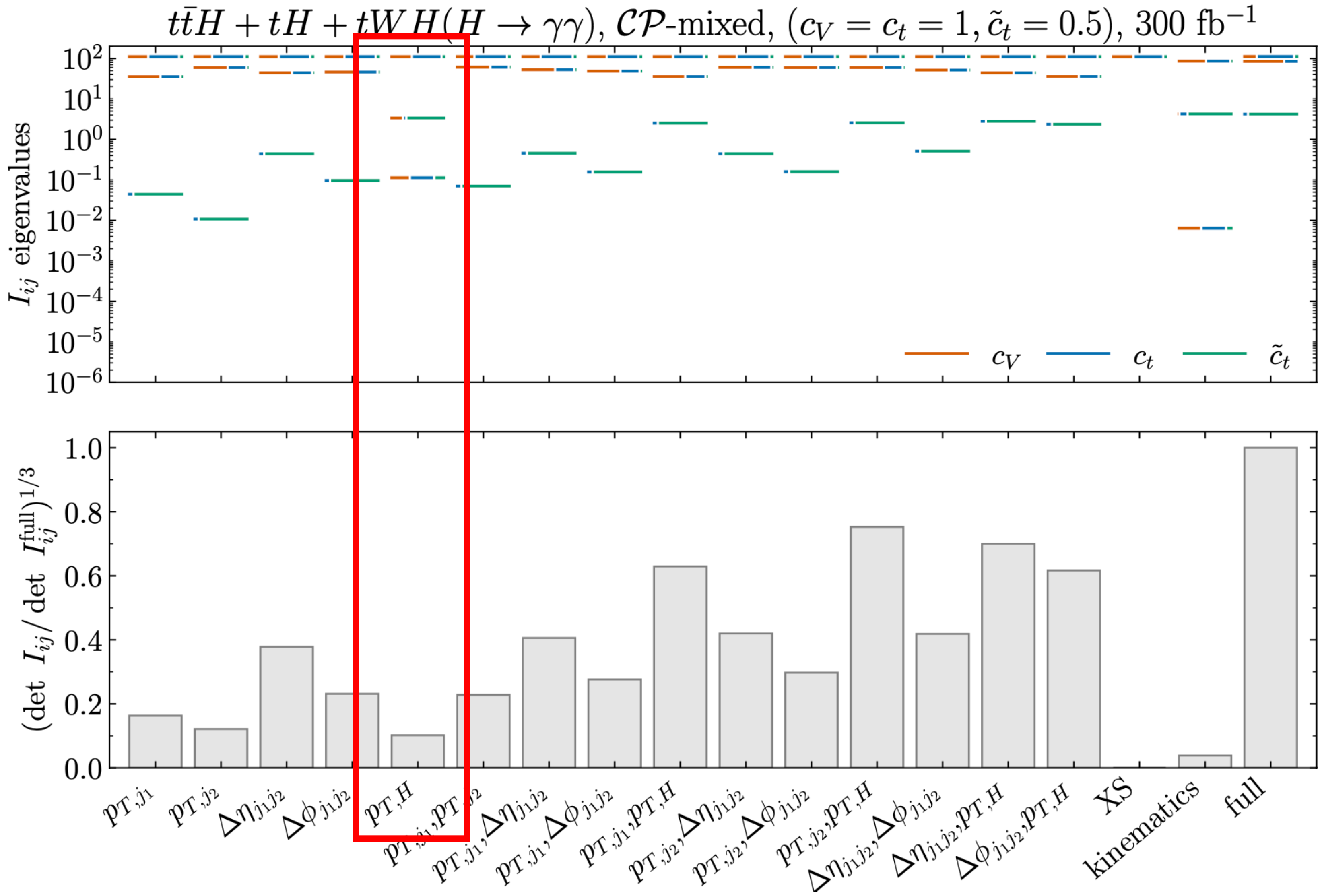
- Evaluate Fisher matrix for various 1D and 2D histograms, full likelihood, XS only, kinematics only.

Fisher information for SM scenario



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

Important:
Due not separate tH bin based on assumption of SM-like kinematics!

Conclusions

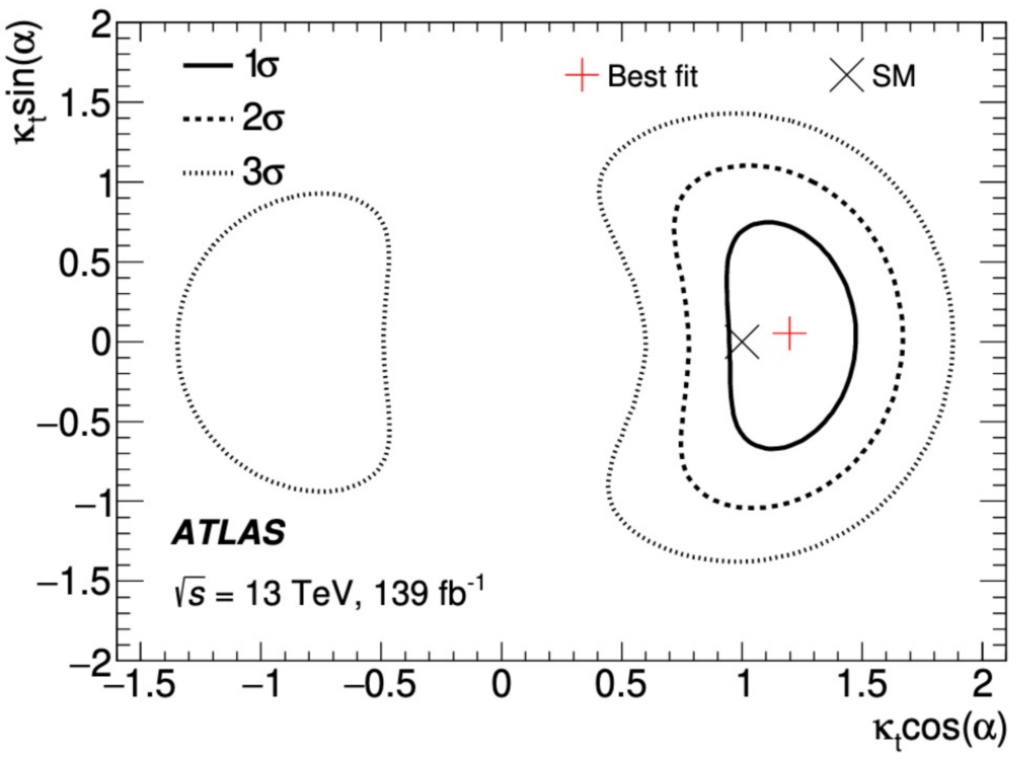
Initial question: What is the best way to CP violation in the top-Yukawa coupling at the LHC?

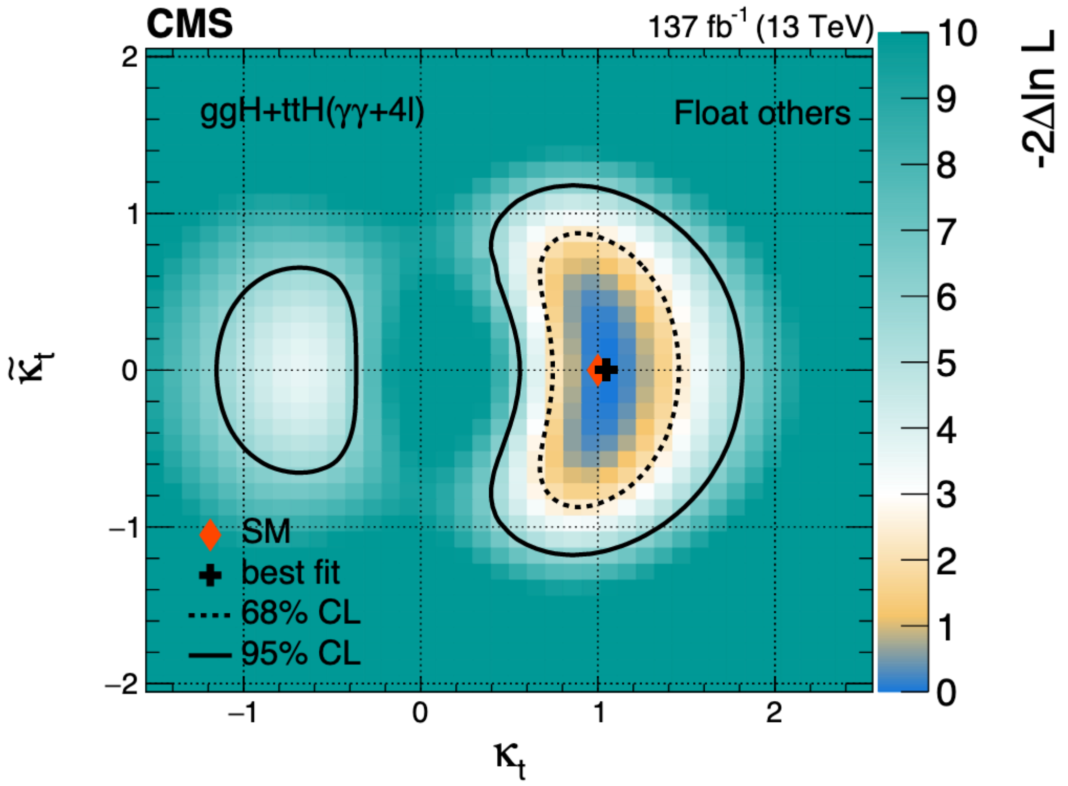
- Focused on top associated Higgs production with $H \to \gamma\gamma$.
- Used machine-learning based inference approach allowing to extract full available information.
- Strong bounds expected especially at HL-LHC.
- Used Fisher information to compare sensitivity of different observables.
- For establishing a deviation from the SM, the Higgs p_T shape is a promising observable.
- Method easily extendible to other production/decay modes.

Thanks for your attention!

Appendix

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

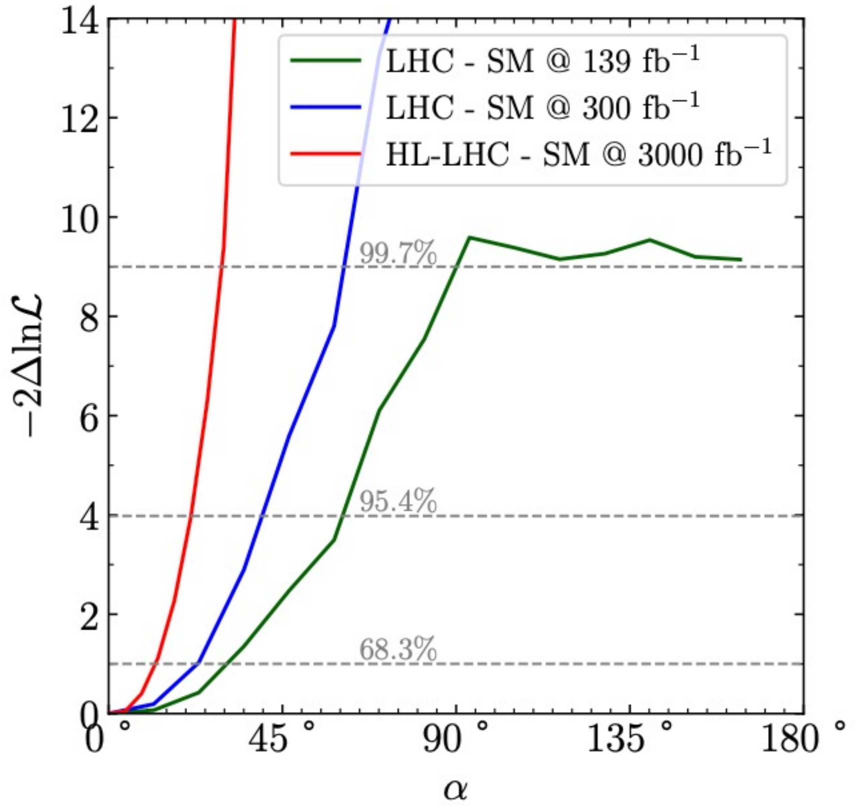




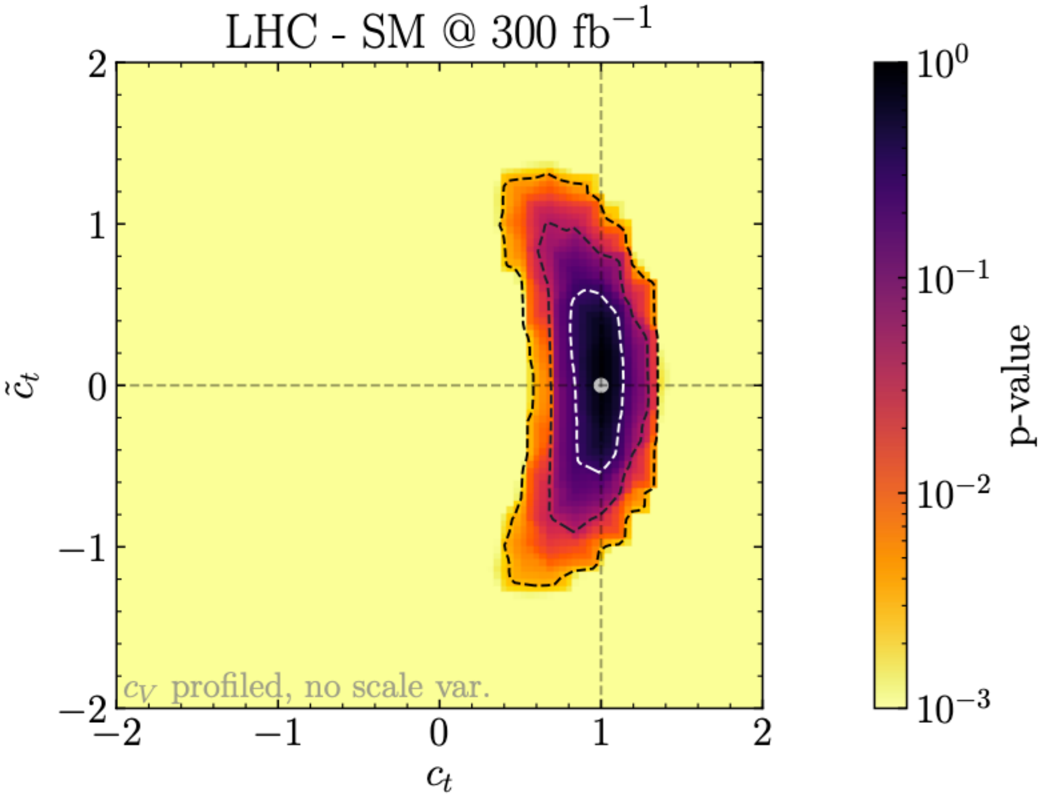
observable	condition
N_γ	≥ 2 (with $\lvert\eta\rvert < 2.5$ and $p_T > 25$ GeV)
$(p^\gamma_{T,1}, p^\gamma_{T,2})$	$\geq (35, 25)$ GeV
$m_{\gamma\gamma}$	$[105 - 160]$ GeV
$(p^\gamma_{T,1}/m_{\gamma\gamma}, p^\gamma_{T,2}/m_{\gamma\gamma})$	$\geq (0.35, 0.25)$
N_ℓ	≥ 1 (with $\lvert\eta\rvert < 2.5$ and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

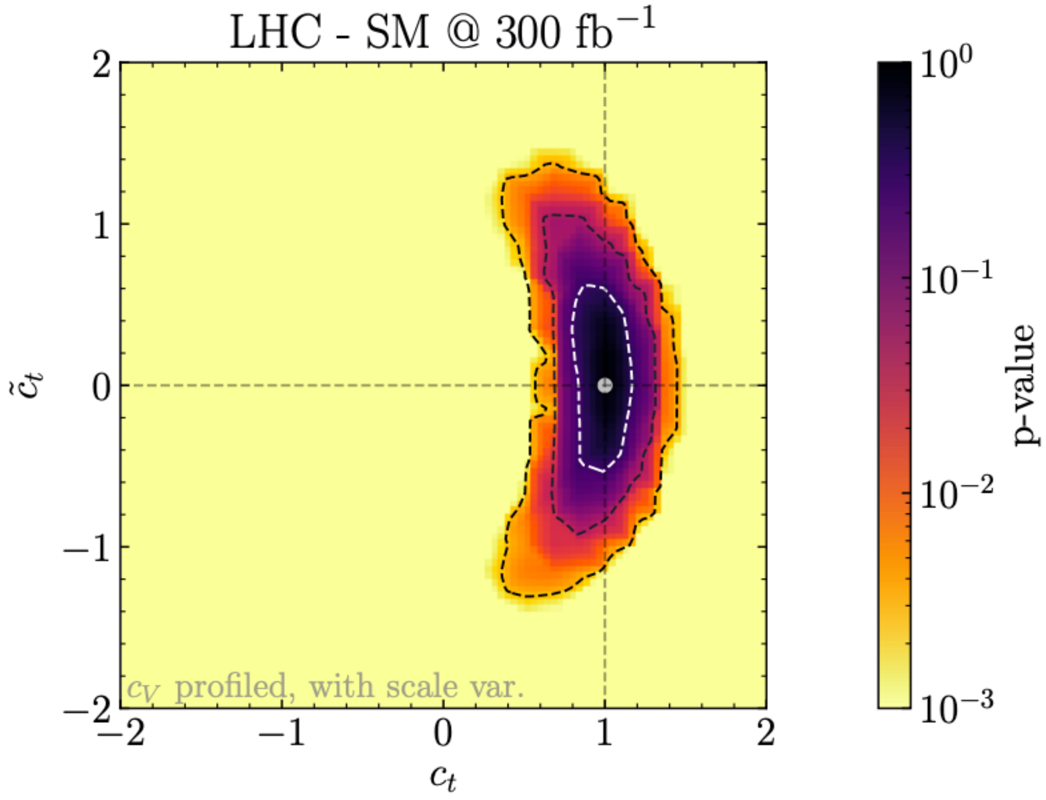
Table 1: Summary of preselection cuts.

Interpretation in terms of CP-violating angle



Variation of c_V and renormalization scale





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