Machine Learning the Higgs-top CP Measurement

Rahool Barman
Oklahoma State University

In Collaboration with:
Dr. Dorival Gonçalves (Oklahoma State Univ.), **Dr. Felix Kling** (DESY)

based on **PRD 105, 035023 (2022)**

Phenomenology 2022 Symposium

May 9 - 11, 2022

CP-violation in Higgs sector

- New sources of CP violating interactions are instrumental to explain the matter antimatter symmetry in the universe.
- One such exciting scenario is CP violation in the Higgs sector $\sim$ mixing of CP-even and odd states.
- Pure CP-odd hypothesis excluded at 95% CL at the LHC, however a CP-mixed hypothesis is still allowed.
- CPV in hZZ/hWW interactions extensively studied at the LHC using $h \to Z^{(*)}Z^{(*)}/W^{+(*)}W^{-(*)}$ decays $\to$ loop suppressed since no tree-level coupling between CP-odd Higgs component and gauge bosons.
  [CMS: 1411.3441; Ellis, Fok, Hwang, Sanz, You (2013); Englert, Goncalves, Mawatari, Plehn (2013)]
- Feasible alternative: CPV in $hf\bar{f}$ couplings can directly manifest at the tree-level $\to$ more sensitive probes compared to hVV interaction.

CP-violation in Higgs sector

- The largest among the Higgs-to-fermion couplings: $ht\bar{t}$, is the most desirable choice.
- Higgs-top interaction can be parametrized as:

$$\mathcal{L} = -\frac{m_t}{v}\kappa_t h\bar{t}(\cos\alpha + i\gamma_5 \sin\alpha)t \qquad (1)$$

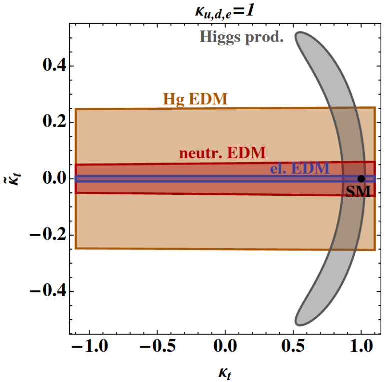
SM: $(\kappa_t, \alpha) = (1, 0)$, pure CP-odd interaction: $\alpha = \pm\pi/2$.

- A precise measurement of the CP-structure of this coupling could unravel clues for new physics.

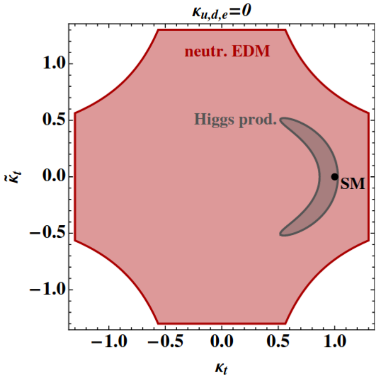
Indirect constraints

- Electron Dipole Moment probes can exert strong constraints on CP-violating Higgs-top couplings.

- Assuming $\kappa_e = 1$, constrains $|\kappa_t \sin\alpha| < 0.01$.



- Very sensitive to minor modifications.

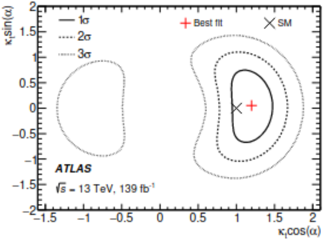


[Brod, Haisch, Zupan (2013)]

Direct probes

- Although, GF Higgs production at the LHC are sensitive to κ_t and α, however, loop-induced new physics effects can significantly deteriorate the prospects. [Grojean, Salvioni, Schlaffer, Weiler (2013); Dolan, Harris, Jankowiak, Spannowsky (2014)]

- $pp \to t\bar{t}h$ stands out as the viable direct probe to α as well as κ_t.
  - **Drawbacks:** Small rate at the current LHC and complex final states.
  - **Silver linings:** Observation for $t\bar{t}h$ at 5.2 σ [ATLAS: 2004.04545] and 6.6 σ [CMS: 2003.10866].
  - Current limits: $|\alpha| < 43^\circ$ (ATLAS) and $|\alpha| < 55^\circ$ (CMS) at 95% CL



[ATLAS: 2004.04545]

- Improved rates at the HL-LHC coupled with efficient top reconstruction and event information extraction techniques can lead to large sensitivity.

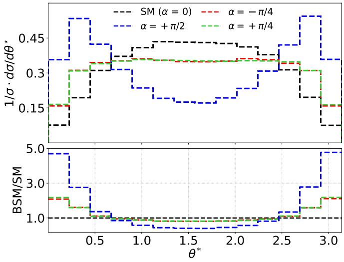
CP observables

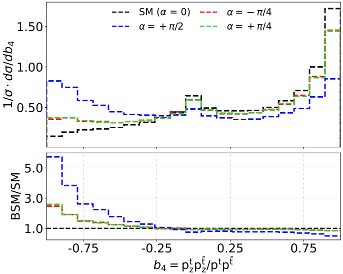
Numerous well-motivated observables have been explored in the literature

- θ^*: angle between t and beam direction in the $t\bar{t}$ CM frame.
- $b_4 = p_t^z p_{\bar{t}}^z / p_t p_{\bar{t}}$
- $m_{t\bar{t}}$: invariant mass of t and $\bar{t}$.
- $p_{T,h}$: transverse momentum of h
- $\Delta\eta_{t\bar{t}}$: pseudorapidity difference between t and $\bar{t}$.
- m_{th}: invariant mass of the t and h.

[Gunion, He (1996), Demartin, Maltoni, Mawatari, Zaro (2015), Demartin, Maltoni, Mawatari, Page Zaro (2014), Gonçalves, Kong, Kim (2018)]

Illustrative distributions at parton-level:





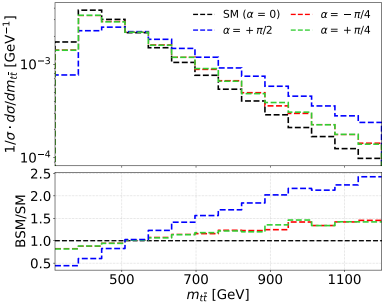
CP observables

Numerous well-motivated observables have been explored in the literature

- θ^*: angle between t and beam direction in the $t\bar{t}$ CM frame.
- $b_4 = p_t^z p_{\bar{t}}^z / p_t p_{\bar{t}}$
- $m_{t\bar{t}}$: invariant mass of t and $\bar{t}$.
- $p_{T,h}$: transverse momentum of h
- $\Delta\eta_{t\bar{t}}$: pseudorapidity difference between t and $\bar{t}$.
- m_{th}: invariant mass of the t and h.

[Gunion, He (1996), Demartin, Maltoni, Mawatari, Zaro (2015), Demartin, Maltoni, Mawatari, Page Zaro (2014), Gonçalves, Kong, Kim (2018)]

- Result in distinct profiles for different values of α.
- Sensitive to non-linear NP effects only $\propto \cos^2\alpha$ and $\sin^2\alpha$.



CP observables

- Observables sensitive to interference terms $\propto \sin\alpha\cos\alpha$ can be constructed from antisymmetric tensor products involving t, $\bar{t}$ and their decay products $\{i, j\}$: $\epsilon(p_t, p_{\bar{t}}, p_i, p_j) \sim \epsilon_{\mu\nu\rho\sigma} p_t^\mu p_{\bar{t}}^\nu p_i^\rho p_j^\sigma$,
[Boudjema, Godbole, Guadagnoli, Mohan (2015), Mileo, Kiers, Szynkman, Crane, Gegner (2016), Gonçalves, Kong, Kim (2018)]

$$\simeq E_t \vec{p}_{\bar{t}} \cdot (\vec{p}_i \times \vec{p}_j) - E_{\bar{t}} \vec{p}_i \cdot (\vec{p}_j \times \vec{p}_t) + E_i \vec{p}_j \times (\vec{p}_t \times \vec{p}_{\bar{t}}) - E_j \vec{p}_t \cdot (\vec{p}_{\bar{t}} \times \vec{p}_i)$$

- In $t\bar{t}$ rest frame, it simplifies to $\propto p_t \cdot (p_i \times p_j)$.
- Using these relations, genuine CP sensitive observables can be defined: [Gonçalves, Kong, Kim (2018)]

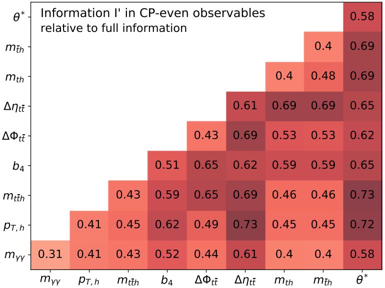
$$\Delta\phi_{ij}^{t\bar{t}} = \text{sgn}\left[\vec{p}_t \cdot (\vec{p}_i \times \vec{p}_j)\right] \arccos\left[\frac{\vec{p}_t \times \vec{p}_i}{|\vec{p}_t \times \vec{p}_i|} \cdot \frac{\vec{p}_t \times \vec{p}_j}{|\vec{p}_t \times \vec{p}_j|}\right].$$

Observable Information

- Due to limited $t\bar{t}(h \to \gamma\gamma)$ statistics we expect the non-linear NP effects to dominate over the linear effects at the detector level $\rightarrow$ Most of the sensitivity arises from CP-even observables.
- Relative sensitivity of CP-even observables on non-linear terms could also be quantified through Fisher information.

$$I' = \mathbb{E}\left[\frac{\partial \log p(x|\kappa_t^2,\alpha^2)}{d\alpha^2}\frac{\partial \log p(x|\kappa_t^2,\alpha^2)}{d\alpha^2}\right]$$

$p(x|\kappa_t, \alpha)$ is the event likelihood, $\mathbb{E}[.]$ is the expectation value at SM.



[$\rightarrow$ Talk by Dorival Gonçalves]

- $\Delta\eta_{t\bar{t}}$ and θ^* carry the most information ($\sim 60\%$).
- Most promising pairs: $\{\Delta\eta_{t\bar{t}}, p_{T,h}\}$ and $\{\theta^*, m_{t\bar{t}h}\}$

Information increases with successive addition of observables $\rightarrow$ illustrates the necessity of a multivariate analysis.

Top reconstruction

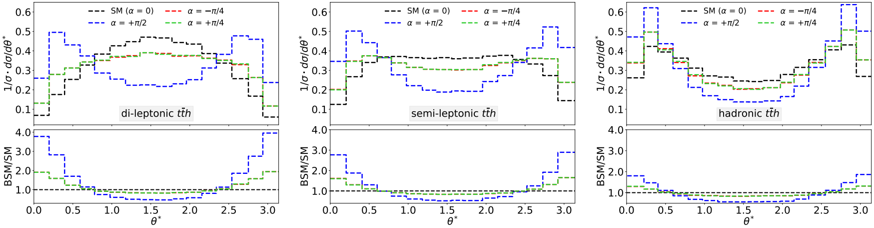
- Full reconstruction of the $t\bar{t}$ system is required at the detector level in order to access the full potential of these observables at the LHC.
- **Combinatorial ambiguities** and **presence of neutrinos** makes the reconstruction a challenging task.

Reconstruction strategy

1. **Semi-leptonic channel**: p_{z,ν_l} is computed by constraining $m_{l\nu_l}$ to W mass. $(m_{jjb} - m_t)^2 + (m_{\ell\nu b} - m_t)^2$ is minimized.
2. **Hadronic channel**: Similar mass minimization.
3. **Di-leptonic channel**: More complex. Top pairs are reconstructed through Recursive Jigsaw Reconstruction technique. [Jackson, Rogan (2017)]

Fully reconstructed $t\bar{t}h$

Detector-level distributions: θ^*



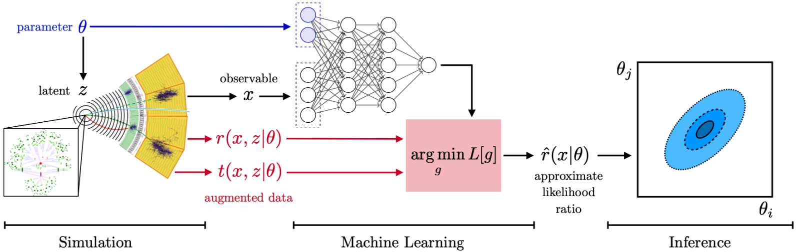
$\mathcal{O}(20\%)$ $\mathcal{O}(40\%)$ $\mathcal{O}(50\%)$

reduction in sensitivity compared to parton-level

The reduction in sensitivity reflects the efficiency of the reconstruction techniques in the respective channels.

Analysis strategy

- likelihood ratio $r\left(x|\theta,\theta_{SM}\right)$ is an excellent test statistic to discriminate NP effects parameterized by $\theta=(\kappa_t,\alpha)$ from SM $\theta_{SM}=(1,0)$.
- $r\left(x|\theta,\theta_{SM}\right)$ is intractable at the detector-level.
- MadMiner resolves this intractability by employing ML based inference techniques. [Brehmer, Kling, Espejo, Cranner (2019)]



(taken from [Brehmer, Cranner, Louppe, Pavez (2018)])

[→ Talk by Henning Bahl]

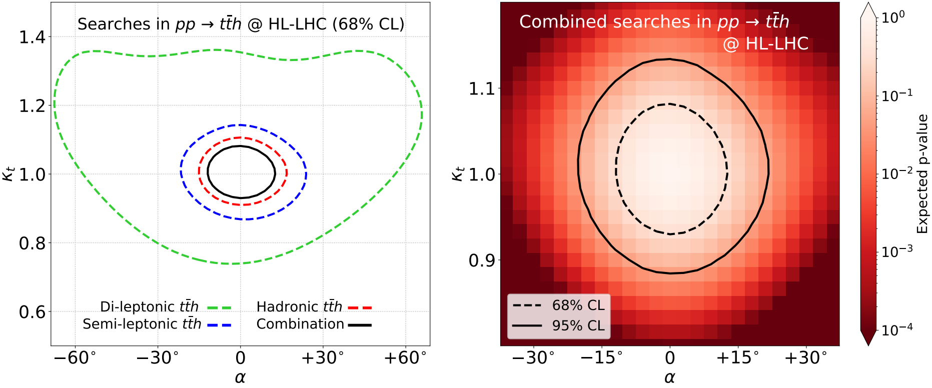
MadMiner overview

- Joint likelihood ratio, $r(x, z|\theta_0, \theta_1) = p(x, z|\theta_0)/p(x, z|\theta_1)$, and joint score $t(x, z|\theta_0) = \nabla_\theta \log\left(p(x, z|\theta)\right)\Big|_{\theta_0}$ can be computed for every event. [Brehmer, Kling, Espejo, Cranner (2019)]
- MadMiner uses loss functions that depend on $r(x, z|\theta_0, \theta_1)$ and $t(x, z|\theta_0)$, whose minimizing function is $r(x|\theta_0, \theta_1)$. [Brehmer, Louppe, Pavez, Cranmer (2018)]
- Uses reconstructed observables x + ME information in training
  $\rightarrow$ interpolates matrix element (ME) information from MC simulated events as a function of θ.
  $\rightarrow$ accounts for parton shower, hadronization and detector effects.
- Projected sensitivities are then extracted through likelihood ratio tests.

Network architecture:

- 80 observables are used to describe the signal and background in the multivariate analysis.
- Fully connected NN with 3 hidden layers ($100 \times 100 \times 100$) is trained.
- Training is performed with 10^6 signal and background events before event selection.

Projected reach at 14 TeV LHC ($\mathcal{L} = 3\ \mathrm{ab}^{-1}$)



- Higgs-top CP-phase could be probed up to $|\alpha| \lesssim 13^\circ$ at 68% CL.
- Sensitivity for top Yukawa is $\kappa_t \lesssim 8\%$ at 68% CL.

Summary

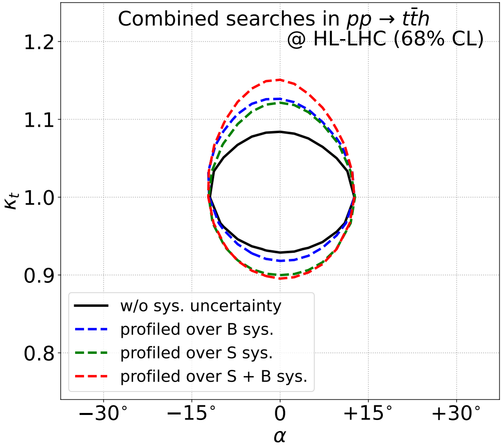
- We examine the prospects of directly measuring the Higgs top CP-structure in $t\bar{t}(h \to \gamma\gamma)$ channel at the HL-LHC.
- Several well-motivated observables that utilize the reconstructed $t\bar{t}$ system are included.
- The goal is to harness their maximal sensitivity through a combination of efficient $t\bar{t}$ reconstruction techniques and machine learning based inference techniques.
- The observables are found to retain a sizeable fraction of spin correlation information even at the detector level.
- The HL-LHC can directly probe κ_t and α up to $\kappa_t \lesssim 8\%$ and $|\alpha| \lesssim 13^\circ$ respectively at 68% CL through combined searches in the dileptonic, semileptonic and hadronic $t\bar{t}(h \to \gamma\gamma)$ channel.

See talks by

- Dorival Gonçalves: Probing CP-violation and thermal history of our Universe with Higgs physics
- Zhite Yu: Azimuthal Angular Correlation as a New Boosted Top Jet Substructure
- Henning Bahl: Constraining CP-violation in the Higgs-top-quark interaction using machine-learning-based inference
- Morgan Cassidy: CP Structure of the Top Yukawa at a Multi-TeV Muon Collider
- Yanzhe Zhang: CP Violating Top Yukawa Coupling at the Future Moun Collider

Thank you for your attention!

Backup slides



Effect of systematic uncertainties