Machine Learning the Higgs-top CP Measurement

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CP-violation in Higgs sector

- New sources of CP violating interactions can play a crucial role in explaining the baryon asymmetry.
- CP-violation in the Higgs sector realized through mixing of CP-even and odd states offer one such exciting scenario.
- 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:

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

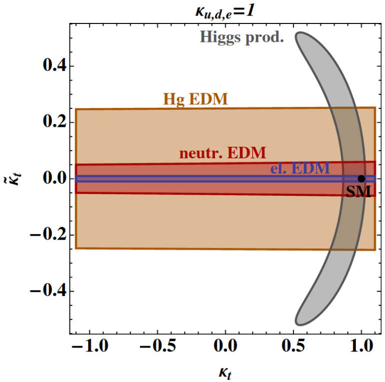
SM: $(\kappa_t, \alpha) = (1, 0)$, pure CP-odd interaction: $\alpha = \pm\pi/2$.

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

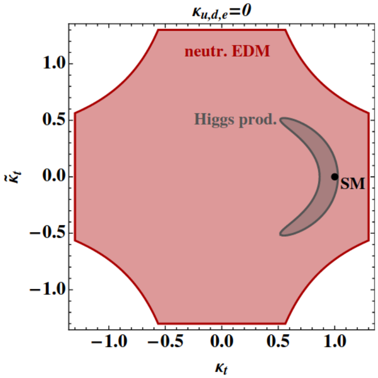
Indirect constraints

- 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.

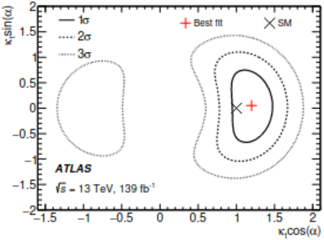


[Brod, Haisch, Zupan (2013)]

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].

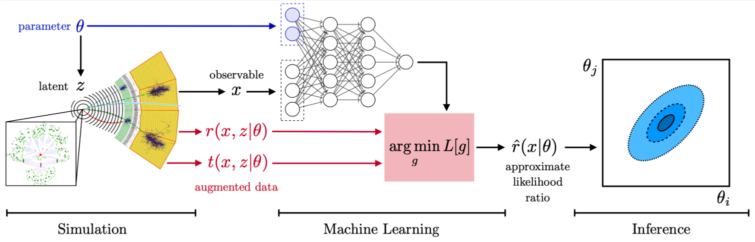


[ATLAS: 2004.04545]

- Improved rates at the HL-LHC coupled with efficient top reconstruction and event information extraction techniques can lead to large sensitivity.
- Aim: evaluate the projected capability of the HL-LHC in probing the Higgs-top CP structure via $t\bar{t}(h \to \gamma\gamma)$ channel through a robust machine learning analysis using the MadMiner framework.

Analysis

- The probability of observing a set of events characterized by observables x and theory parameters θ is quantified by a likelihood function $\sim p(x, \theta)$.
- An event likelihood $p(x, \theta)$ is an almost intractable function.
- The intractability has been circumvented through "likelihood-free inference" techniques $\rightarrow$ may miss out on some important information.
- MadMiner resolves this intractability by employing machine-learning based inference techniques. [Brehmer, Kling, Espejo, Cranner (2019)]



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

MadMiner overview

- Extracts information related to the ME from MC events while also modelling the detector and shower effects.
- Uses the extracted information to train a neural network that estimates the likelihood as a function of theory parameters.
- The estimated kinematic likelihood can be then translated into limits/projections.

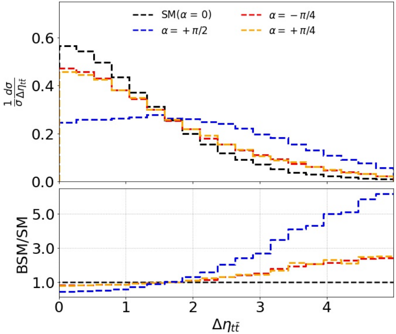
Network architecture:

- We train a fully connected NN with 3 hidden layers ($100 \times 100 \times 100$) is trained.
- The NN is an estimator of the likelihood function over the (α, κ_t) parameter space $\rightarrow$ accounts for the squared NP terms as well as the interference effects.
- The training is performed with 10^6 signal and background events before event selection.

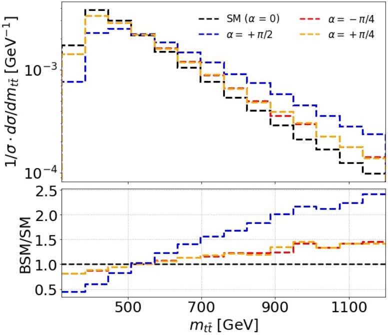
Some important observables

- 65 well-motivated observables are used to describe the signal and background.

- Difference of the top and anti-top pseudorapidity, $\Delta\eta_{t\bar{t}}$.



- Invariant mass of the $t\bar{t}$ pair, $m_{t\bar{t}}$.



Top reconstruction

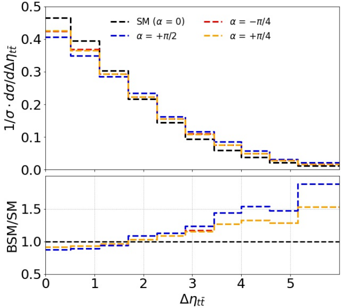
- Full reconstruction of the $t\bar{t}$ system is required at the detector level in order to access the full potential of these observables at the LHC.
- **Combinatorial ambiguities** and **presence of neutrinos** makes the reconstruction a challenging task.

Reconstruction strategy

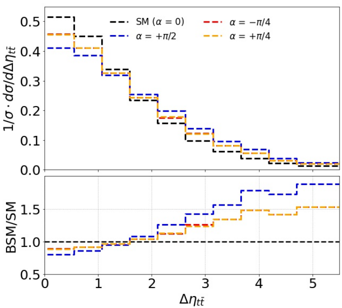
1. **Semi-leptonic channel**: p_{z,ν_l} is computed by constraining $m_{l\nu_l}$ to W mass. $(m_{jjb} - m_t)^2 + (m_{\ell\nu b} - m_t)^2$ is minimized.
2. **Hadronic channel**: Similar mass minimization.
3. **Di-leptonic channel**: More complex. Top pairs are reconstructed through Recursive Jigsaw Reconstruction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

Fully reconstructed $t\bar{t}h$

Detector-level distributions



Semi-leptonic channel

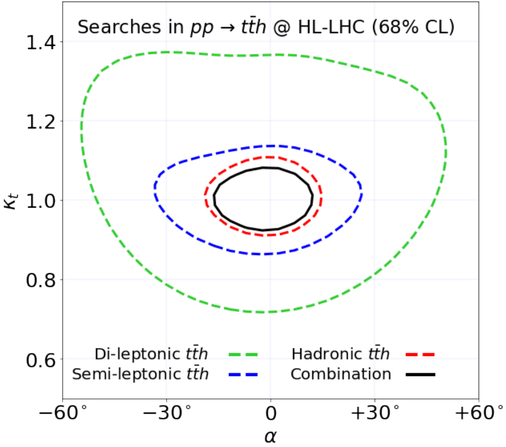


Di-leptonic channel

The distributions retain the sensitivity at the detector level albeit $\mathcal{O}(60)\%$ reduction compared to the parton level.

Preliminary results

Projected reach at 14 TeV LHC with $\mathcal{L} = 3000\ \mathrm{fb}^{-1}$



- Assuming $\kappa_t = 1$, the Higgs-top CP-phase could be probed up to $|\alpha| \sim 16^\circ$ at 68% CL.
- Sensitivity for κ_t is $\mathcal{O}(8\%)$ at 68% CL.

Conclusion

- A comprehensive list of well-motivated observables are included to probe the Higgs-top CP-structure.
- The goal was to harness their maximal potential via the full reconstruction of the top and the anti-top, and by using machine learning based inference techniques.
- The observables are found to retain a sizeable fraction of spin correlation information even at the detector level.
- The $t\bar{t}(h \to \gamma\gamma)$ channel at the HL-LHC has the potential to provide a rather strong sensitivity to the CP-phase.

Thank you for your attention!