CP-violation in $t\bar{t}\phi(125\ \text{GeV})$: asymmetries and interferences

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LHCHWG – WG2 and WG3 – CP-violation and Extended Higgs Sectors

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Karlsruhe Institute of Technology

Overview

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- Potential channel for probing BSM CP-violation: $pp \to t\bar{t}\phi$
- **Goal: Simulate an LHC-like analysis and draw C.L. exclusion limits on SM-like Higgs (all results are preliminary)**

Analysis

$t\bar{t}\phi$ and CP-observables

We can parameterize the general $t\bar{t}\phi$ interaction as

$$\mathcal{L} = k_t y_t \bar{t}\left(\cos\alpha + i\gamma_5 \sin\alpha\right) t\phi = y_t \bar{t}\left(\kappa + i\gamma_5\tilde{\kappa}\right) t\phi$$

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- CP-even: $\cos\alpha = 1, k_t = \kappa$
- CP-odd : $\sin\alpha = 1, k_t = \tilde{\kappa}$

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Several proposed observables in the literature Bernreuther et al. (1994), Gunion et al. (1996), Ellis et al. (2014),..., we choose:

- Angular varibles: $a_1 = \sin\theta_{\phi}^{t\bar{t}\phi} * \sin\theta_{\bar{t}}^{t\bar{t}}$, $\quad a_2 = \sin\theta_{\phi}^{t\bar{t}\phi} * \sin\theta_{b_{\bar{t}}}^{\bar{t}}$ (seq. boost)
- Gunion-He: $b_2 = (\vec{p}_t \times \hat{k}_z)\cdot(\vec{p}_{\bar{t}} \times \hat{k}_z)/(|\vec{p}_t||\vec{p}_{\bar{t}}|)$, $\quad b_4 = (p_t^z \cdot p_{\bar{t}}^z)/(|\vec{p}_t||\vec{p}_{\bar{t}}|)$

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→ Discriminate between signal/irreducible background Amor dos Santos et al. (2015)
→ Sensitive to different scalar mass values $m_\phi \in [10, 500]$ GeV DA et al. (2021)
→ Observables are CP-even → not sensitive to relative sign of the phase

Event generation and reconstruction

Event generation

→ MadGraph5_aMC

- Signal: $pp \to t\bar{t}\phi$ ($\alpha = 0°; 22.5°; 45°; 67.5°; 90°; 135°; 180°$)@NLO@13TeV
  - Higgs Characterization Model P. Artoisenet et al., JHEP 11, 043 (2013)
  - Dileptonic channel and $\phi \to b\bar{b}$ final state
- All relevant backgrounds
- Parton shower (Pythia) and detector simulation (Delphes)

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- $\#$ jets ≥ 4 ($\#$ b-tagged ≥ 3)
- Two oppositely charged leptons.
- Pseudo-rapidity $\eta < 2.5$ and transverse momenta $p_T > 20$ GeV

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Event reconstruction

- Several kinematical variables related with $t\bar{t}$ system used for BDTD $\rightarrow$ jet permutation with best score chosen DA et al. (2021)
- Implemented a new ϕ reconstruction

Reconstruction of ϕ

- Jet pair with closest invariant mass to 125 GeV

$$m_{\phi}^{\text{inv}} = \sqrt{(p_1 + p_2)^2}$$

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- New method for low mass regime

$$m_\phi^{(i)} = |\vec{p}_1| \sqrt{2 \frac{\sin\theta_1}{\sin\theta_2} \left[1 - \cos(\theta_1 + \theta_2)\right]}$$

  - Uses only one momentum and two angles

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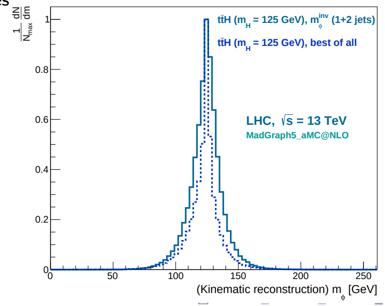
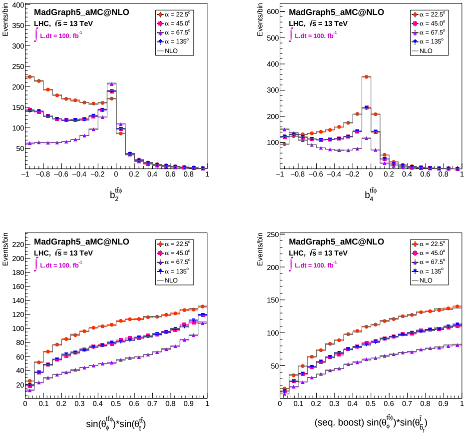
- Choose permutation and method with closest value to 125 GeV
- Very good improvement on the low mass region, also improves for $m_\phi = 125$ GeV



Asymmetries

Observables



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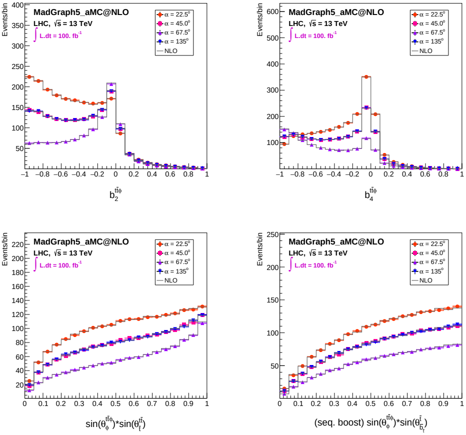

- Shapes change smoothly with angle
- Non-normalized, number of total events will change

Forward-Backward asymmetries

Criteria for defining quantitatively the sensitivity of observable

$$A_C[Y] = \frac{\sigma(Y > x_c) - \sigma(Y < x_c)}{\sigma(Y > x_c) + \sigma(Y < x_c)}$$

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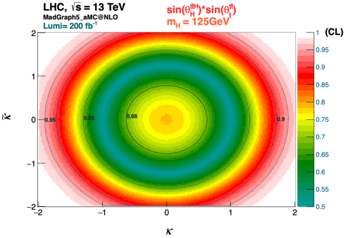
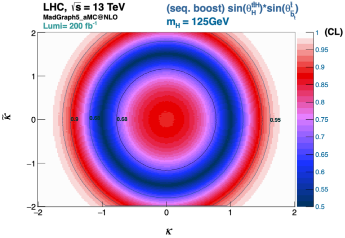
Asymmetries	x_c	$t\bar{t}\phi$ @ NLO+Shower (no cuts applied)		$t\bar{t}\phi$ after selection and reconstruction	
		scalar/pseudo	$t\bar{t}b\bar{b}$	scalar/pseudo	$t\bar{t}b\bar{b}$
$A_c[b_2]$	-0.30	$-0.35/+0.34$	-0.17	$-0.12/+0.24$	-0.03
$A_c[b_4]$	-0.50	$+0.41/-0.22$	$+0.33$	$+0.30/-0.06$	$+0.26$
$A_c[a_1]$	$+0.70$	$-0.27/-0.03$	-0.56	$-0.26/-0.19$	-0.37
$A_c[a_2]$	$+0.60$	$+0.05/+0.11$	-0.38	$+0.01/-0.01$	-0.22

$\rightarrow$ **We can use the asymmetries themselves to draw exclusion limits**

Limits from asymmetries

$\propto \kappa^2 + \tilde{\kappa}^2$





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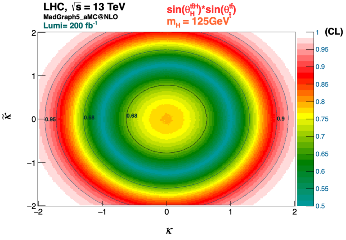
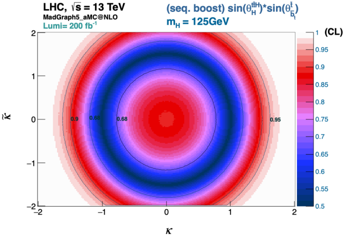
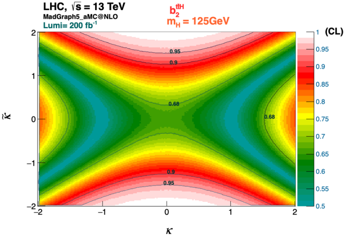
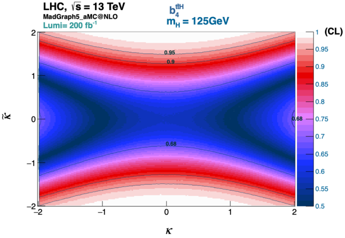


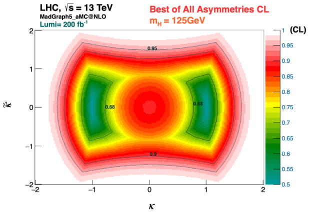


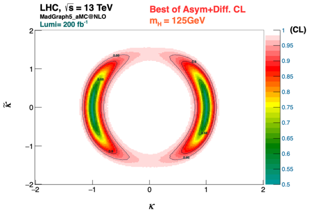
$\propto \kappa^2 - \tilde{\kappa}^2$





Limits from asymmetries (combination)





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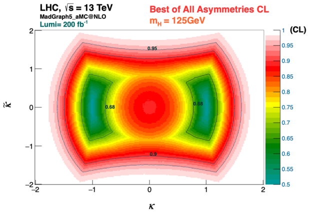

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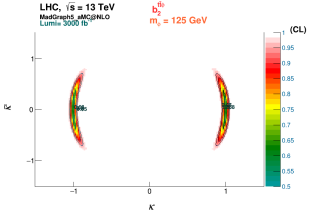
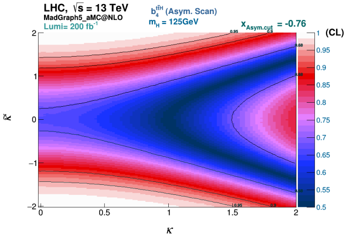
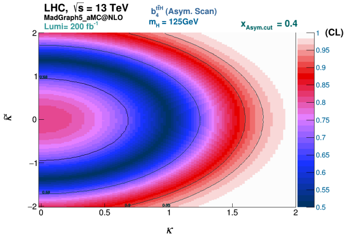


→ Expected at end of LHC lifetime: $|\alpha| < 40^\circ$ (95% C.L.)

→ **How does the asymmetry point affect the shape of the exclusions?**

Exploiting the asymmetry point





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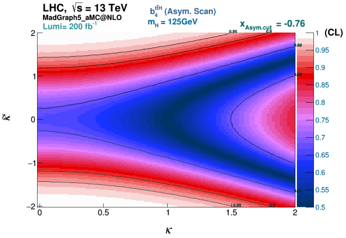

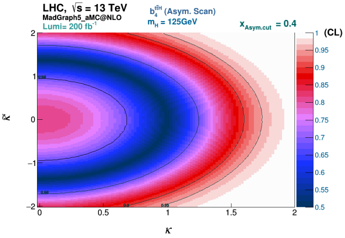

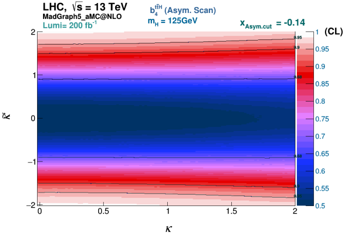

- Asymmetry point defines shape
- We can attain either κ or $\tilde{\kappa}$ independent limits (depending on observable)
- Dependence on κ^2 and/or $\tilde{\kappa}^2$
- What about a possible interference term $\propto \kappa\tilde{\kappa}$?

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- We used the CP-odd variable given in Ellis et al. (2014), Gonçalves et al. (2018)

$$\Delta\phi_{l^+l^-}^{t\bar{t}} = \mathrm{sgn}(\hat{p}_t \cdot (\hat{p}_{l^+} \times \hat{p}_{l^-})) \arccos\left[(\hat{p}_t \times \hat{p}_{l^+}) \cdot (\hat{p}_t \times \hat{p}_{l^-})\right]$$

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For any observable

$$\frac{d\sigma}{dX} = \kappa^2 \frac{d\sigma^{\text{even}}}{dX} + \tilde{\kappa}^2 \frac{d\sigma^{\text{odd}}}{dX} + \kappa\tilde{\kappa} \frac{d\sigma^{\text{int.}}}{dX}$$

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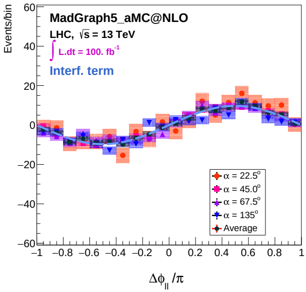

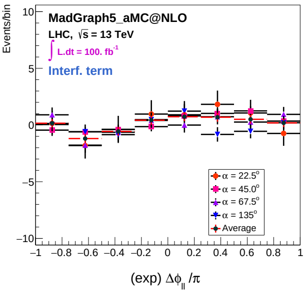

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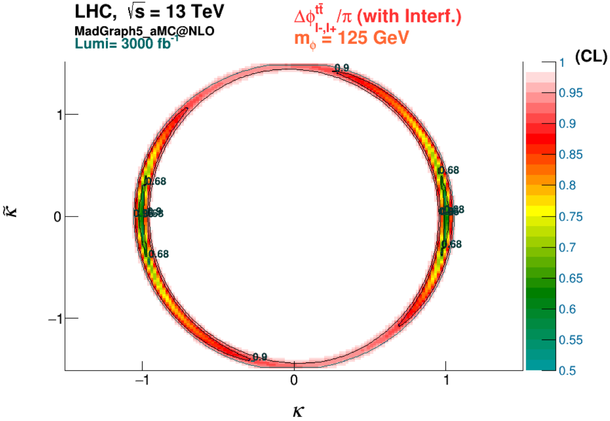

- Effects are minute → <u>not sensitive to int. term from this channel alone</u>

Conclusions

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- $pp \to t\bar{t}\phi$ events can be used for BSM CP-probing at the LHC
- New mass reconstruction method improves mass distribution in a large range of values, including $m_\phi = 125$ GeV
- Asymmetries (asymmetry point) should be exploited to increase sensitivities to different scenarios
- In particular, draw independent limits on CP-even/-odd components of the $t\bar{t}\phi$ coupling.
- Highly improbable that $t\bar{t}\phi$ alone can measure interference terms, even at end of LHC lifetime

Thank you!