Probing the CP nature of the Higgs coupling in $t\bar{t}h$ events at the LHC

E. Gouveia (e.gouveia@cern.ch), S. Amor dos Santos, M. C. N. Fiolhais, R. Frederix, R. Gonçalo, R. Martins, A. Onofre, C. M. Pease, H. Peixoto, A. Reigoto, R. Santos, and J. Silva

Universidade do Minho · LIP

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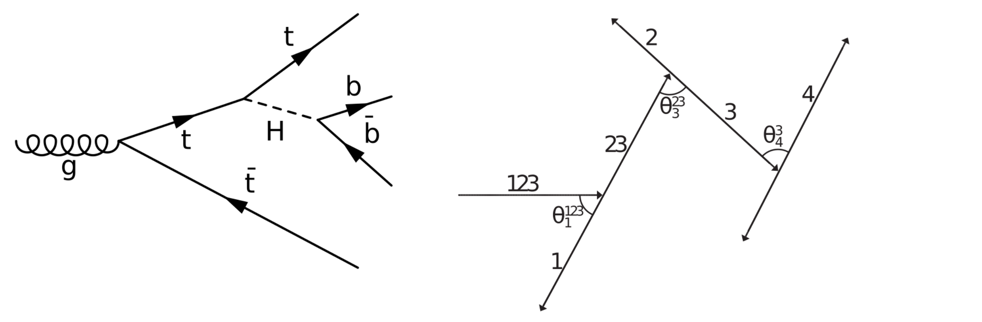
Introduction

- New sources of CP violation are required to account for the observed baryon asymmetry in the Universe [1]
- Some BSM theories, namely 2HDMs [2], predict Higgs bosons which are not CP eigenstates, leading to CP-violating Higgs interactions
- The top quark is the most massive fermion and $t\bar{t}h$ production will allow the first direct measurement of its Yukawa coupling
- **Can angular observables in $t\bar{t}h$ (dilepton) events at the LHC be used to measure the CP nature of the top quark Yukawa coupling?**

Angular observables

- With motivation from processes such as that on the left diagram, a generic chain of two-body decays (right diagram) was considered: $(123) \to 1 + (23)$, $(23) \to 2 + (3)$ and $(3) \to 4 + 5$



- θ^X_Y is the angle between the direction of Y, in the rest frame of X, and the direction of X, in the rest frame of its parent system
- Three families of observables: $f(\theta_1^{123})g(\theta_4^3)$, $f(\theta_1^{123})g(\theta_3^{23})$ and $f(\theta_3^{23})g(\theta_4^3)$, with $f, g = \{\sin, \cos\}$
- A set of observables was obtained by replacing 1, 2 and 3 with all permutations of $(t, \bar{t}, h)$ and replacing 4 with all the decay products of t, $\bar{t}$ or h
- Observables proposed in previous works were also studied. Two of the most compelling ones were b_4, from [11], and $\beta_{b\bar{b}}\Delta\theta^{\ell h}(\ell^+, \ell^-)$, from [12]

Asymmetries

- Asymmetries associated to each of the observables x_Y under study were defined according to (see [13])

$$A^Y = \frac{N(x_Y > 0) - N(x_Y < 0)}{N(x_Y > 0) + N(x_Y < 0)}$$

Observable x_Y	A^Y at gen.+PS level before cuts		A^Y after cuts and reconstruction	
	$t\bar{t}H/t\bar{t}A$	$t\bar{t}b\bar{b}$	$t\bar{t}H/t\bar{t}A$	$t\bar{t}b\bar{b}$
$\cos(\theta_h^{\bar{t}h})\cos(\theta_{\ell-}^h)$	$+0.37/+0.41$	$+0.17$	$\mathbf{+0.42/+0.39}$	$\mathbf{+0.24}$
$\sin(\theta_h^{t\bar{t}h})\sin(\theta_{b_{\bar{t}}}^{\bar{t}})$(seq.)	$+0.28/+0.33$	-0.17	$\mathbf{+0.25/+0.28}$	$\mathbf{+0.03}$
$\sin(\theta_h^{t\bar{t}h})\cos(\theta_{b_h}^{\bar{t}})$(seq.)	$-0.65/-0.77$	-0.62	$\mathbf{-0.78/-0.83}$	$\mathbf{-0.76}$
$\sin(\theta_t^{t\bar{t}h})\sin(\theta_{W+}^h)$(seq.)	$-0.03/-0.46$	-0.60	$\mathbf{+0.17/-0.06}$	$\mathbf{-0.04}$
$\sin(\theta_{\bar{t}}^{t\bar{t}h})\sin(\theta_{b_h}^h)$(seq.)	$+0.25/-0.08$	$+0.07$	$\mathbf{+0.37/+0.16}$	$\mathbf{+0.23}$
$\sin(\theta_h^{t\bar{t}h})\sin(\theta_t^{t\bar{t}})$	$+0.16/+0.37$	-0.21	$\mathbf{+0.23/+0.31}$	$\mathbf{+0.01}$
$b_4 = (p_t^z . p_{\bar{t}}^z)/(\lvert\vec{p}_t\rvert.\lvert\vec{p}_{\bar{t}}\rvert)$ [11]	$+0.35/-0.10$	$+0.33$	$\mathbf{+0.16/-0.17}$	$\mathbf{+0.12}$

A^Y values in $t\bar{t}H$, $t\bar{t}A$ and $t\bar{t}b\bar{b}$ events for a selection of observables with significant signal/background or $t\bar{t}H/t\bar{t}A$ separation, at generator+PS level (before selection cuts) and after full kinematic reconstruction (including cuts).

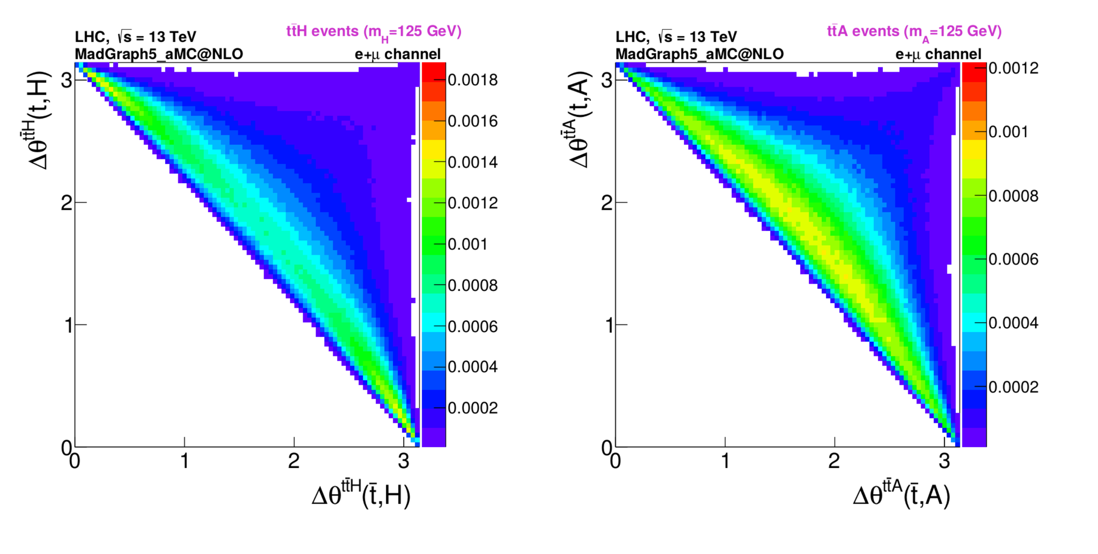
Event Generation and Simulation

- MadGraph5_aMC@NLO [3] with NNPDF2.3 PDF sets [4]
- UFO Model for signal: `HC_NLO_X0` [5]
- Top Yukawa interaction was parametrised as

$$\mathcal{L} = \kappa\, y_t\, \bar{t}\,(\cos\alpha + i\gamma_5 \sin\alpha)\, t\, h$$

- $t\bar{t}h$ signal: $m_h = 125$ GeV, $\cos\alpha$ from -1 to 1
  - $\cos\alpha = \pm 1 \Rightarrow$ **SM, pure CP-even Higgs boson ($h = H$)**
  - $\cos\alpha = 0 \Rightarrow$ **pure CP-odd Higgs boson ($h = A$)**
- pp collisions with $\sqrt{s}$ =13 TeV
- $t\bar{t}h$ and $t\bar{t}b\bar{b}$ were generated at NLO in QCD. $t\bar{t}$ + jets (c- and light) and other SM backgrounds generated at LO with additional jets
- MadSpin [6] used to decay h and the $t\bar{t}$ system (dileptonically)
- Parton shower (PS) and hadronization: Pythia6 [7]
- Fast detector simulation with Delphes [10].The b-tagging efficiency goes up to 50% (20%) for true b-jets (c-jets).

Angular distributions at generator+PS level



2D distributions of $t\bar{t}h$ events, at generator+PS level, over the angle between the t and h directions (y-axis) and the angle between the $\bar{t}$ and h directions (x-axis), all evaluated in the $t\bar{t}h$ rest frame. The plot on the left shows $t\bar{t}H$ events and the plot on the right shows $t\bar{t}A$ events.

- **CP nature of the Yukawa interaction significantly affects the kinematics of production**
- In $t\bar{t}H$, more events are produced in which t (or $\bar{t}$) recoils against the $\bar{t}h$ (th) system. In $t\bar{t}A$, events are more evenly spread

Event selection and kinematic reconstruction

- Event selection:
  - $\geq$4 jets and 2 opposite-sign leptons (e or μ), all with $p_T \geq 20$ GeV and $|\eta| \leq 2.5$
  - $|m_{\ell\ell} - m_Z| > 10$ GeV
  - At least 3 b-tagged jets
- 16% (17%) of $t\bar{t}H$ ($t\bar{t}A$) signal events are accepted
- For the reconstruction of t, $\bar{t}$ and h, **a jet assignment is picked using a BDT**:
  - Training on $t\bar{t}H$ events
  - Object-pair variables used as input: ΔR, $\Delta\Phi$, lab-frame angles $\Delta\theta$ and invariant masses
- **Neutrinos are reconstructed by imposing W and top mass constraints and that the $\vec{p_T}$ of ν and $\bar{\nu}$ add up to the $\vec{E}_T^{\text{miss}}$ in the detector**

$$\begin{aligned}(p_{\ell+} + p_\nu)^2 &= m^2_{W+},\\ (p_{\ell-} + p_{\bar{\nu}})^2 &= m^2_{W-},\\ (p_{W+} + p_b)^2 &= m^2_t,\\ (p_{W-} + p_{\bar{b}})^2 &= m^2_{\bar{t}},\\ p_x^\nu + p_x^{\bar{\nu}} &= E_x^{\text{miss}},\\ p_y^\nu + p_y^{\bar{\nu}} &= E_y^{\text{miss}}\end{aligned}$$

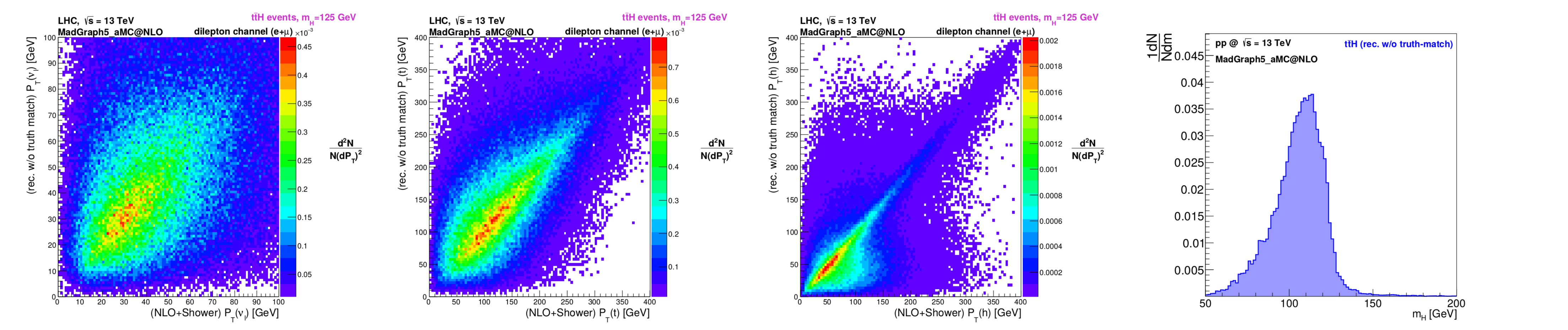
- **If multiple solutions are found, a likelihood is maximised to choose the most adequate one**:

$$L_{t\bar{t}h} \sim \frac{1}{p_{T\nu}p_{T\bar{\nu}}} P(p_{T\nu})P(p_{T\bar{\nu}})P(p_{Tt})P(p_{T\bar{t}})P(p_{Tt\bar{t}})P(m_t, m_{\bar{t}})P(m_h),$$

where $P(X)$ is the probability density function (p.d.f.) at generator+PS level of the observable X, evaluated at the reconstructed value of X

Reconstruction performance on $t\bar{t}H$ events

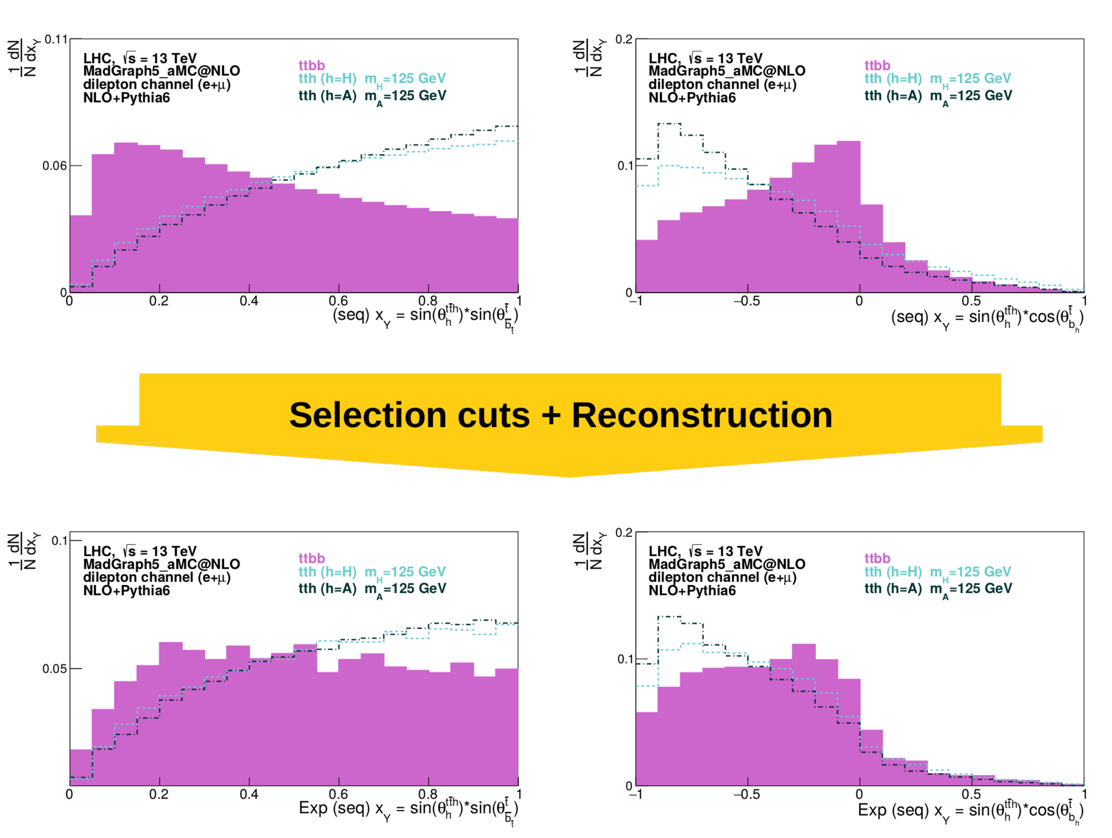
- **Solution is found in 62% (61%) of selected $t\bar{t}H$ ($t\bar{t}A$) signal events. In 31% (34%) of the $t\bar{t}H$ ($t\bar{t}A$) signal events, the reconstruction results in the same jet assignment as a ΔR truth-matching**



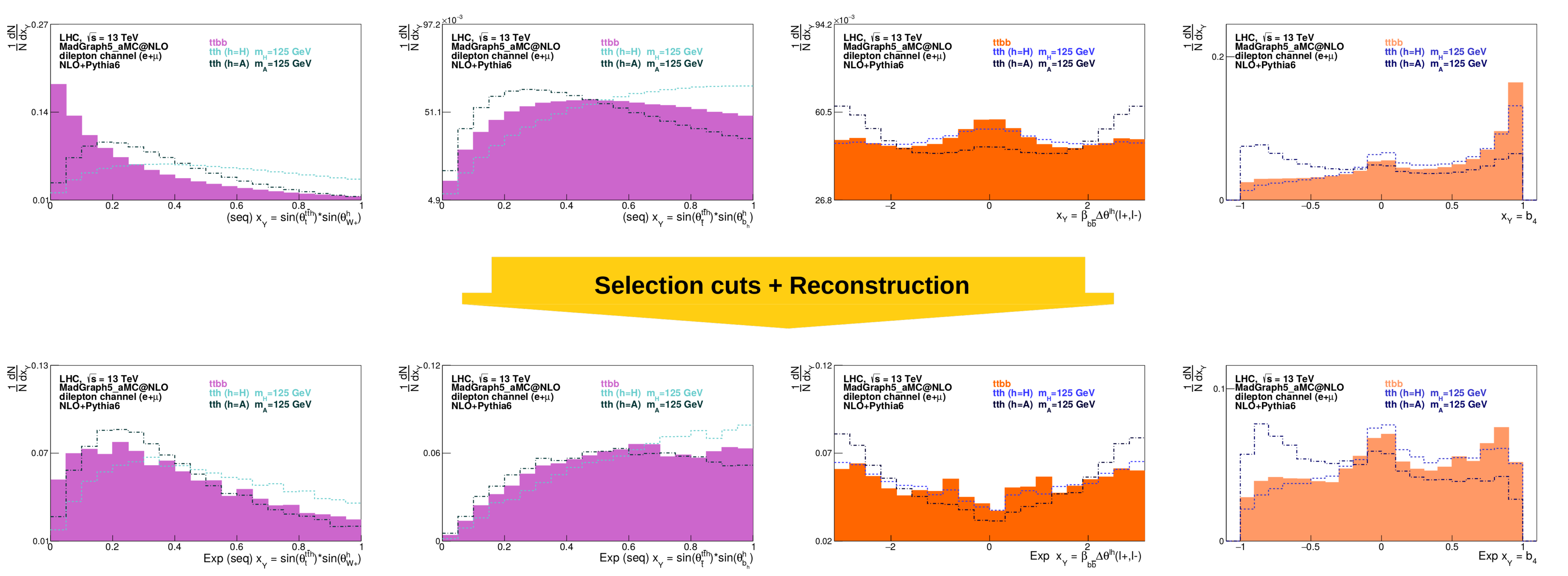
p_T distributions of ν (left), t (middle-left) and H (middle-right) after $t\bar{t}H$ reconstruction. On the x-axis is the generator+PS level p_T and on the y-axis is the reco-level p_T. On the right,reconstructed m_H.

- **Excess of high-p_T neutrinos $\to$ reconstruction uses their free momenta to compensate for radiation losses**

Signal/Background

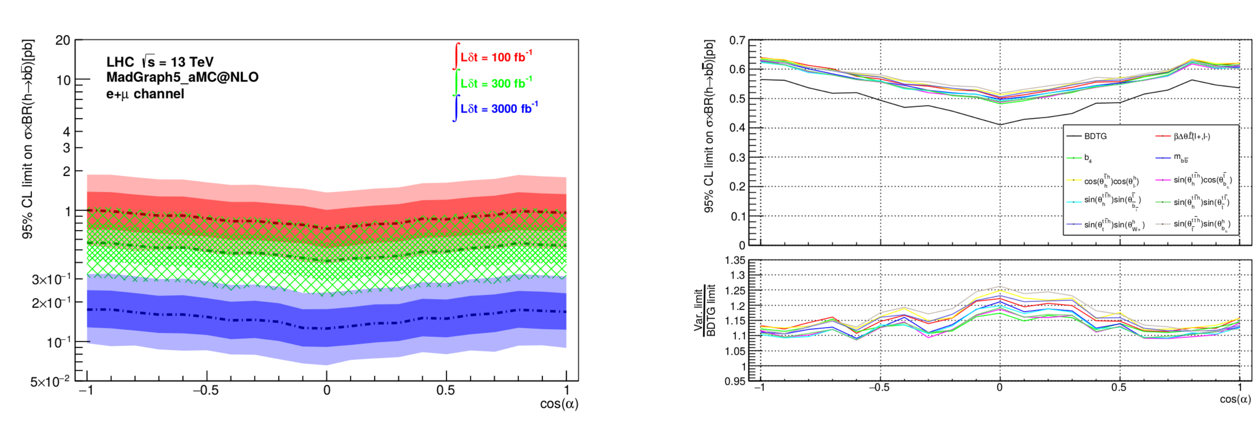


CP-even/CP-odd



Expected limits at 95% CL

- **A BDT was trained for signal/background classification for each value of $\cos\alpha$.** Input variables include the observables studied and variables used in the ATLAS 8 TeV search [14].
- **Expected limits at 95% CL were obtained using the BDT as a discriminant.** Limits were also extracted using instead each single input variable



Limits on $\sigma \times BR(h \to b\bar{b})$ obtained with the BDT discriminant for integrated luminosites of 100, 300 and 3000 fb^{-1} (left). Comparison, for 300 fb^{-1}, of limits obtained using each angular observable as discriminant (right).

Conclusions

- **Angular observables in $t\bar{t}h$ events keep information about the CP nature of the top-Higgs coupling, even after cuts, detector simulation and kinematic reconstruction**
- **Most powerful observables require $t\bar{t}h$ reconstruction**
- **Search is not too sensitive to the CP-phase α**

Acknowledgements

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