New ways for CP violation studies in $t\bar{t}H$ events

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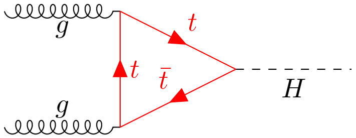
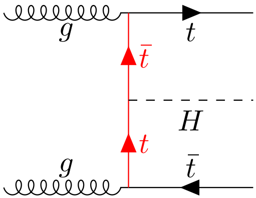
$t\bar{t}H$ channel & CP nature of the Higgs

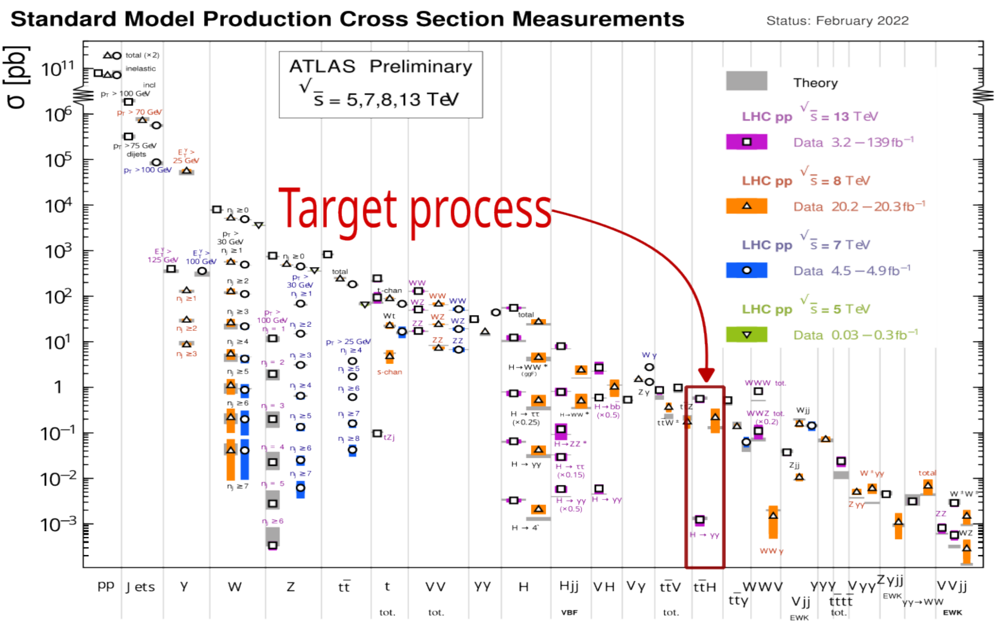
Motivations

- Yukawa interactions account for fermion masses in the SM
- Measurement of Yukawa coupling of Higgs to fermions important probe for new physics
- Coupling proportional to mass, of the order of unity for the top quark
- Only $t\bar{t}H$ can directly probe the top-Higgs coupling at tree level
- Sensitive to effects beyond the SM i.e CP violation





$t\bar{t}H$ in the Standard Model

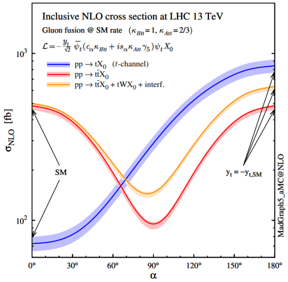


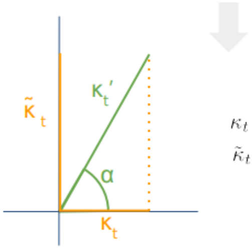
CP violation in the top Yukawa coupling

- CP structure in $t\bar{t}H$ can be parametrized as a complex phase in SM Lagrangian:

$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + i\sin(\alpha)\gamma_5\right]\psi_t\right\} H$$

- In this model $\alpha = 0$ implies no CP-violation



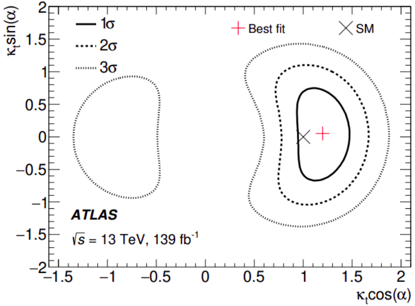


$$\kappa_t \equiv \kappa_t' \cos\alpha$$
$$\tilde{\kappa}_t \equiv \kappa_t' \sin\alpha$$

- Need to isolate $t\bar{t}H$ coupling (i.e tree-level)
- includes not only $t\bar{t}H$ but also tWH, tHq
- For a pure CP-odd coupling $t\bar{t}H$ is suppressed while tHq is enhanced
- The analyses need to include all these 3 processes together

Latest CP measurements in $t\bar{t}H$

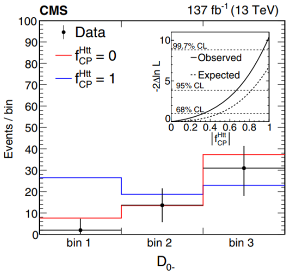
$t\bar{t}H$, $H \to \gamma\gamma$ results

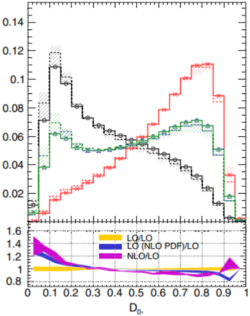


ATLAS analysis (PRL 125, 061802):

1. train BDT to separate $t\bar{t}H$ from background (BKG Discriminant)
2. BDT trained to separate CP-even from CP-odd couplings (CP Discriminant)

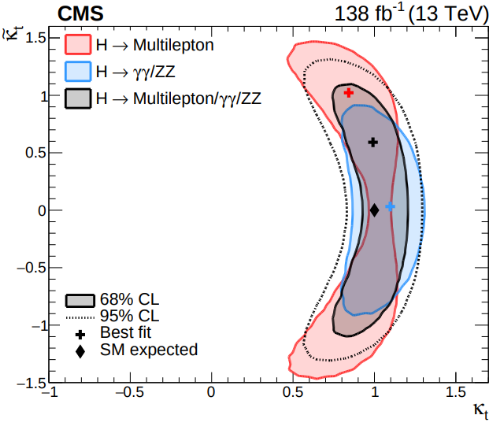
CP-odd excluded with 3.9σ, $|\alpha| > 43$ at 95% CL





CMS analysis (PRL 125, 061801):

- Same strategy using MVAs to separate BKGs and CP-odd from CP-even
- Use of the parametrization: $f_{CP}^{tt\bar{t}H} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2+|\tilde{\kappa}_t|^2}\ \mathrm{sign}\left(\tilde{\kappa}_t/\kappa_t\right).$
- Observed $f_{CP}^{tt\bar{t}H} = 0.00 \pm 0.33$ at 95% and pure CP-odd coupling excluded at 3.2σ.

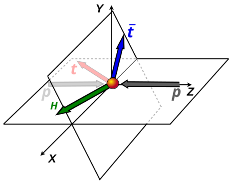


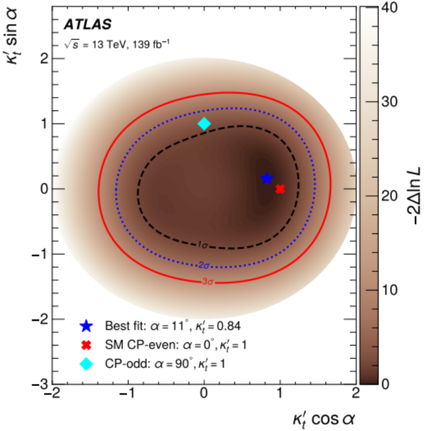
- Similar methodology in multi-lepton (CP-odd excluded at $> 2\sigma$) and H→VV→4ℓ channels (CP-odd excluded at 3.1σ) (arXiv:2208.02686 and PRD 104, 052004)
- Observed combined result of $|f_{CP}^{t\bar{t}H}| < 0.55$ at 68% and pure CP-odd scenario excluded at 3.7σ.

Alternative ways to study CP violation

Alternative way: direct CP observables

- Any deviation would be directly linked to CP violation
- Drawback: Might be less sensitive
- In the following we will present our studies of these relevant observables.





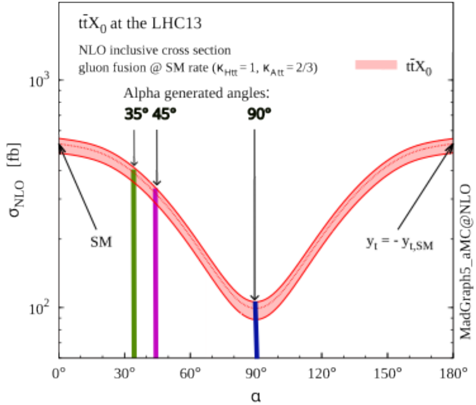
Tested in the ATLAS tt̄H → bb analysis (arXiv:2303.05974), Within the signal regions the following CP sensitive variables are fitted (arXiv:hep-ph/9602226):

- $b_2 = \frac{\left(\vec{p_t} \times \hat{n}\right) \cdot \left(\vec{p_{\bar{t}}} \times \hat{n}\right)}{\left|\vec{p_t}\right| \left|\vec{p_{\bar{t}}}\right|}$
- $b_4 = \frac{p_t^z \, p_{\bar{t}}^z}{\left|\vec{p_t}\right| \left|\vec{p_{\bar{t}}}\right|}$

Results point to $\alpha = 11^{\circ}{}^{+56^{\circ}}_{-77^{\circ}}$, with 1.2σ rejection of pure CP-odd hypothesis.

Study of these new observables

- We are generating $t\bar{t}H$ events in the "Higgs Characterization" (HC) model (JHEP11(2013)043), with $m_b = 0$ and in the 5 flavor scheme
- As the pure CP-odd scenario seems excluded we use new benchmarks
- Decided to focus on the 45 and 35 degrees scenarios
- Studied a series of possible discriminating variables, currently at parton level, without any reconstruction effect



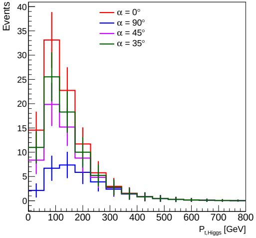
Variables considered

- Set of variables considered for the studies based on phenomenology and previous analysis works.
- Kinematics variables are still considered as can be used in combination with others to enhance the sensitivity

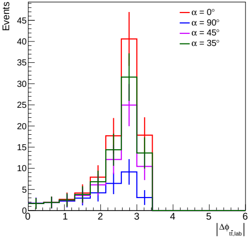
observable	definition	frame
p_{T}^{H}	-	lab, $t\bar{t}$, $t\bar{t}H$
$\lvert\Delta\eta_{t\bar{t}}\rvert$	$\lvert\eta_t - \eta_{\bar{t}}\rvert$	lab, H, $t\bar{t}H$
$\lvert\Delta\phi_{t\bar{t}}\rvert$	$\lvert\phi_t - \phi_{\bar{t}}\rvert$	lab, H, $t\bar{t}H$
$m_{t\bar{t}}$	$(p_t + p_{\bar{t}})^2$	all
$m_{t\bar{t}H}$	$(p_t + p_{\bar{t}} + p_H)^2$	all
θ^*	$\mathbf{p}_t \cdot \mathbf{n}$	$t\bar{t}$
b_1	$\frac{(\mathbf{p}_t \times \mathbf{n})\cdot(\mathbf{p}_{\bar{t}} \times \mathbf{n})}{p_{\mathrm{T}}^{t} p_{\mathrm{T}}^{t}}$	all
b_2	$\frac{(\mathbf{p}_t \times \mathbf{n})\cdot(\mathbf{p}_{\bar{t}} \times \mathbf{n})}{\lvert\mathbf{p}_t\rvert \ \lvert\mathbf{p}_{\bar{t}}\rvert}$	all
b_3	$\frac{p_t^x \ p_{\bar{t}}^x}{p_{\mathrm{T}}^{t} p_{\mathrm{T}}^{t}}$	all
b_4	$\frac{p_t^z \ p_{\bar{t}}^z}{\lvert\mathbf{p}_t\rvert \ \lvert\mathbf{p}_{\bar{t}}\rvert}$	all
$\cos(\phi_c)$	$\frac{\lvert(\mathbf{p}_{p_1} \times \mathbf{p}_{p_2})\cdot(\mathbf{p}_t \times \mathbf{p}_{\bar{t}})\rvert}{\lvert\mathbf{p}_{p_1} \times \mathbf{p}_{p_2}\rvert \ \lvert\mathbf{p}_t \times \mathbf{p}_{\bar{t}}\rvert}$	H
$\mathcal{A}(\phi_c)$	$\frac{N(0<\phi_c<\pi/4) - N(\pi/4<\phi_c<\pi/2)}{N(0<\phi_c<\pi/4) + N(\pi/4<\phi_c<\pi/2)})$	H

In depth look (kinematic variables)

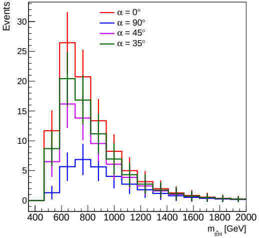
$p_t, p_{\bar{t}}, p_H$, Showing p_H



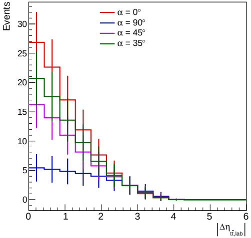
$|\Delta\phi_{t\bar{t}}| = |\phi_t - \phi_{\bar{t}}|$



$m_{t\bar{t}H} = (p_t + p_{\bar{t}} + p_H)^2$

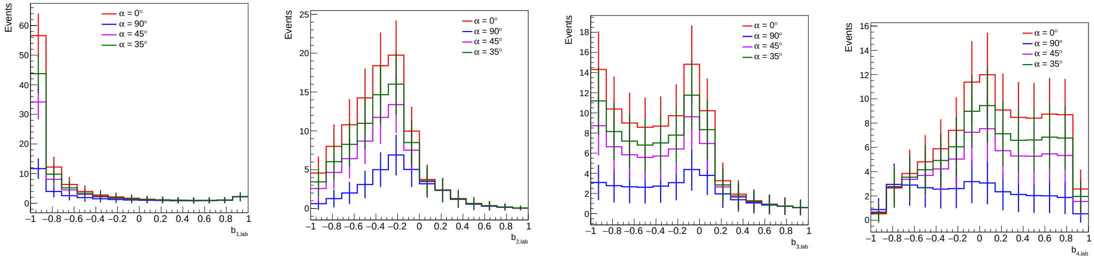


$|\Delta\eta_{t\bar{t}}| = |\eta_t - \eta_{\bar{t}}|$



- Kinematic variables show a good discrimination and are easier to measure and construct.
- Considering the 140 fb^{-1} and only the $H \rightarrow \gamma\gamma$ case, for showing a case example

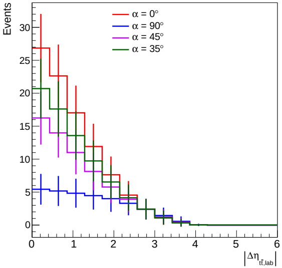
$$b_1 = \frac{\left(\overrightarrow{p_t} \times \hat{n}\right) \cdot \left(\overrightarrow{p_{\bar{t}}} \times \hat{n}\right)}{p_t^T \, p_{\bar{t}}^T} \qquad b_2 = \frac{\left(\overrightarrow{p_t} \times \hat{n}\right) \cdot \left(\overrightarrow{p_{\bar{t}}} \times \hat{n}\right)}{\left|\overrightarrow{p_t}\right| \left|\overrightarrow{p_{\bar{t}}}\right|} \qquad b_3 = \frac{p_t^x \, p_{\bar{t}}^x}{p_t^T \, p_{\bar{t}}^T} \qquad b_4 = \frac{p_t^z \, p_{\bar{t}}^z}{\left|\overrightarrow{p_t}\right| \left|\overrightarrow{p_{\bar{t}}}\right|}$$



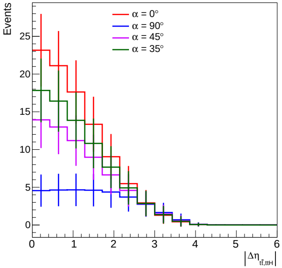
- b_i variables are constructed to be CP sensitive and have already been successfully used for CP discrimination.
- Considering the 140 fb^{-1} and only the $H \to \gamma\gamma$ case, for showing a case example

Reference frames

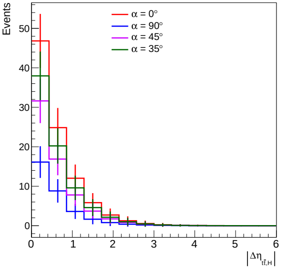
$|\Delta\eta_{t\bar{t}}|$ lab frame



$|\Delta\eta_{t\bar{t}}|$, ttH frame



$|\Delta\eta_{t\bar{t}}|$, H frame



We consider different rest-frames for our observables, to verify possible increase in sensitivity in other reference frames

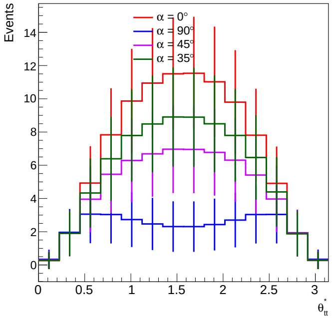
- the lab frame,
- the $t\bar{t}$ rest frame with $\mathbf{p}_t + \mathbf{p}_{\bar{t}} = \mathbf{0}$,
- the $t\bar{t}H$ rest frame with $\mathbf{p}_t + \mathbf{p}_{\bar{t}} + \mathbf{p}_H = \mathbf{0}$
- the H rest frame with $\mathbf{p}_H = \mathbf{0}$.

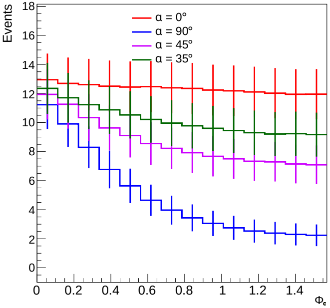
In depth look (Collin-Sopher angle, ϕ_C, asymmetry)

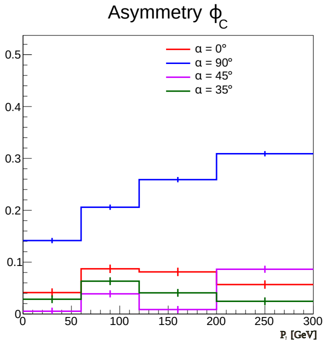
$$\boldsymbol{\theta}^* = \mathbf{p}_t \cdot \mathbf{n}$$

$$\cos(\phi_c) = \frac{|(\mathbf{p}_{p_1} \times \mathbf{p}_{p_2}) \cdot (\mathbf{p}_t \times \mathbf{p}_{\bar{t}})|}{|\mathbf{p}_{p_1} \times \mathbf{p}_{p_2}|\ |\mathbf{p}_t \times \mathbf{p}_{\bar{t}}|}$$

$$\mathcal{A}(\phi_c) = \frac{N(0<\phi_c<\frac{\pi}{4}) - N(\frac{\pi}{4}<\phi_c<\frac{\pi}{2})}{N(0<\phi_c<\frac{\pi}{4}) + N(\frac{\pi}{4}<\phi_c<\frac{\pi}{2})}$$





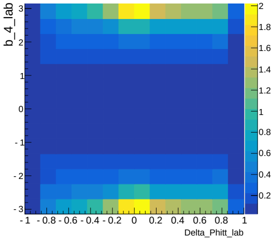


- CP sensitive variables introduced in other rest frames, as the Collin-Sopher angle (PRD 16, 2219), ϕ_c (arXiv:2008.13442v1) and an asymmetry variable build using the latter.
- Considering the 140 fb^{-1} and only the $H \to \gamma\gamma$ case, for showing a case example

Variables combination and ranking

- Studied possible combinations of two variables to increase the sensitivity
- Significance estimation as follow (ATL-PHYS-PUB-2020-025)

$$S = -2\sum_{i=1}^{N_{bins}}\left(N_i^{SM}\log\left(\frac{N_i^{BSM}}{N_i^{SM}}\right) - (N_i^{BSM} - N_i^{SM})\right)$$



- Defining BSM as samples with $\alpha = /0$ and SM as $\alpha = 0$

Significance summary table

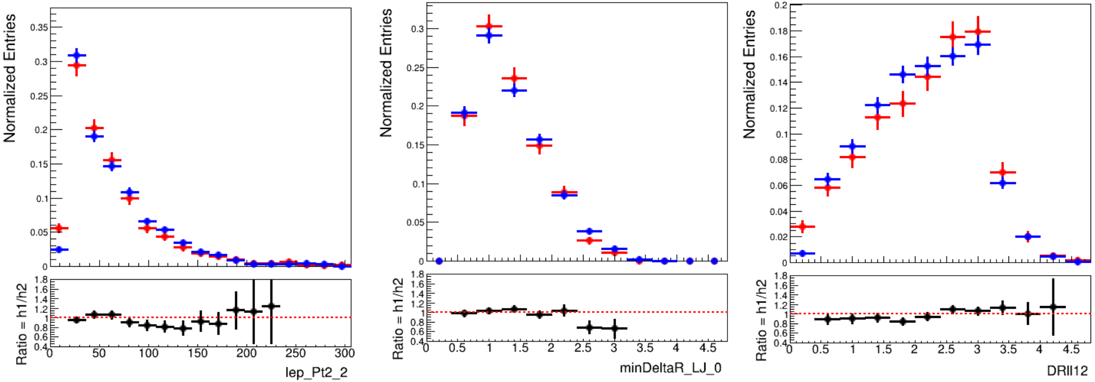
	Httbar_invm_lab	ttbar_invm_lab	Ht_invm_lab	Pt_higgs	Pt_top	Eta_higgs	Eta_top	b_1_lab	b_2_lab	b_3_lab	b_4_lab	Theta_star_lab	Delta_eta_half_lab	Delta_phi_half_lab
NORM, 90° lab	0.933	0.818	0.959	0.990	0.763	0.840	0.843	0.983	0.856	0.873	0.831	0.651	0.996	1.000
NORM, 45° lab	0.678	0.584	0.716	0.780	0.565	0.606	0.619	0.913	0.825	0.586	0.673	0.436	1.000	0.937
NORM, 35° lab	0.526	0.420	0.526	0.621	0.277	0.184	0.264	1.000	0.842	0.303	0.728	0.183	0.876	0.970

Poisson significance [14 bins]

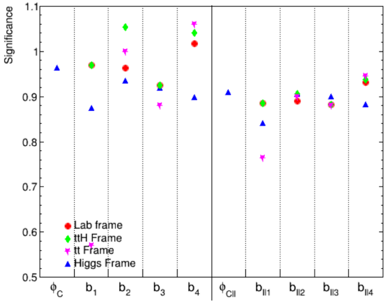
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2

Towards including decays and reconstruction effects

- Studies performed with $t\bar{t}H$ MC samples after applying a multilepton section. Delphes is used for detector simulation
- Matched the yields and object shapes distribution to the $t\bar{t}H$ multilepton 80 fb^{-1} analysis, (ATLAS-CONF-2019-045)



- Hard to reconstruct tops and Higgs in the multilepton analysis
- Test different re-definition of variables using decay products, for example the leptons in the leptonic top and Higgs decays



- Few examples of variables defined in the lepton same sign and 3 lepton final states

$$\cos\phi_{C\ell\ell} = \frac{|(\overrightarrow{n_{p_1}} \times \overrightarrow{n_{p_2}}) \cdot (\overrightarrow{n_{\ell+}} \times \overrightarrow{n_{\ell-}})|}{|\overrightarrow{n_{p_1}} \times \overrightarrow{n_{p_2}}|\,|\overrightarrow{n_{\ell+}} \times \overrightarrow{n_{\ell-}}|}$$

$$b_{\ell\ell,1} = \frac{(\overrightarrow{p_{\ell+}} \times \hat{n}) \cdot (\overrightarrow{p_{\ell-}} \times \hat{n})}{p^T_{\ell+} p^T_{\ell-}} \qquad b_{\ell\ell,2} = \frac{(\overrightarrow{p_{\ell+}} \times \hat{n}) \cdot (\overrightarrow{p_{\ell-}} \times \hat{n})}{|\overrightarrow{p_{\ell+}}|\,|\overrightarrow{p_{\ell-}}|}$$

$$b_{\ell\ell,3} = \frac{p^{\times}_{\ell+} p^{\times}_{\ell-}}{p^T_{\ell+} p^T_{\ell-}} \qquad b_{\ell\ell,4} = \frac{p^z_{\ell+} p^z_{\ell-}}{|\overrightarrow{p_{\ell+}}|\,|\overrightarrow{p_{\ell-}}|}$$

Summary and outlook

- Presented alternative ways to search for CP violation in the top Yukawa coupling using direct CP probes
- First attempt to take into account low mixing CP angles
- Studies at truth level and some initial reco studies performed
- Conclusions would be used in the $t\bar{t}H \rightarrow$ Multilepton CP ATLAS analysis

Thanks for your attention!

BACKUP

Inclusive Higgs decays, 140 fb^{-1} ($\mathrm{b_i}$ variables)

$$b_1 = \frac{\left(\overrightarrow{p_t} \times \hat{n}\right) \cdot \left(\overrightarrow{p_{\bar{t}}} \times \hat{n}\right)}{p_t^T \, p_{\bar{t}}^T} \qquad b_2 = \frac{\left(\overrightarrow{p_t} \times \hat{n}\right) \cdot \left(\overrightarrow{p_{\bar{t}}} \times \hat{n}\right)}{\left|\overrightarrow{p_t}\right| \left|\overrightarrow{p_{\bar{t}}}\right|} \qquad b_3 = \frac{p_t^x \, p_{\bar{t}}^x}{p_t^T \, p_{\bar{t}}^T} \qquad b_4 = \frac{p_t^z \, p_{\bar{t}}^z}{\left|\overrightarrow{p_t}\right| \left|\overrightarrow{p_{\bar{t}}}\right|}$$