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Top LHC France

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Probing the CP nature of the top Yukawa coupling in $t\bar{t}H$ multi-lepton final states with the ATLAS experiment at LHC

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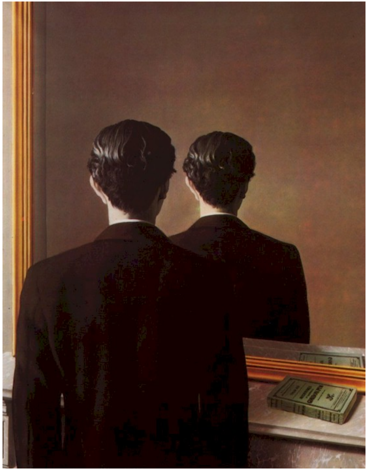
CP violation

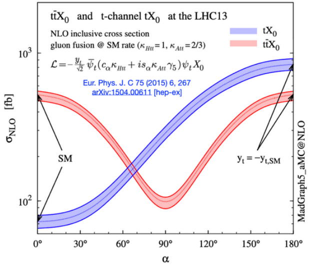
- The asymmetry between matter and antimatter in the Universe is a long-standing mystery
- *CP* violation, which could lead to such an asymmetry, has already been observed in the *K* and *B* meson systems
- It is not enough to explain the observed matter-antimatter asymmetry
- Since 2012, the Higgs sector is a new candidate source for *CP* violation



Magritte, *La reproduction interdite*, 1937

The top Yukawa coupling

- The top quark has the largest mass $m_t \simeq 172.5$ GeV
- The top Yukawa coupling is the strongest coupling in the Standard Model
- It makes it the perfect candidate to study the structure of the coupling

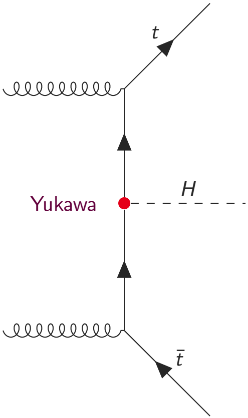


- The *CP* violating nature of the coupling is introduced through the modified Lagrangian

$$\mathcal{L}_{\text{Yukawa}} = -y_t \boldsymbol{\kappa_t'} \bar{t} e^{i\boldsymbol{\alpha}\gamma_5} t h$$

- The phase α accounts for *CP* violation while the parameter κ_t' accounts for the strength of the coupling
- The $(\alpha, \kappa_t') = (0^\circ, 1)$ corresponds to the Standard Model scenario

The $t\bar{t}H$ process



- $t\bar{t}H$ is a rare process ($\sigma \sim 0.5$ pb)
- It can be studied in its different final states, $H \to \gamma\gamma$, $H \to b\bar{b}$ and the multileptonic final states
- Previous analyses using $H \to \gamma\gamma$ and $H \to b\bar{b}$ have been carried in ATLAS and CMS
- Confidence Intervals (CI) and *CP*-odd exclusion are shown in the table below

Channel	α CI	*CP*-odd excl.	Ref.
ATLAS $H \to \gamma\gamma$	$[-43°, 43°]$	3.9σ	[1]
ATLAS $H \to b\bar{b}$	$[-73°, 53°]$	1.2σ	[2]
CMS $H \to \gamma\gamma$	–	3.2σ	[3]

Plan

1. Analysis strategy

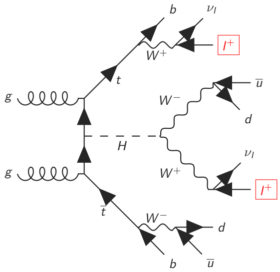
2. Parametrization of the signals

3. Results

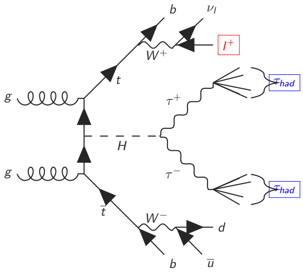
I - Introduction

Targetted events

- 2 kind of multilepton final states are sensitive to the CP nature of the top Yukawa coupling
- These are discriminated by the number of hadronic τ in the final state



0τ event



2τ event

- We will give an overview of these 2 channels separately

0τ channel

- The 0τ channel focuses on $H \to WW/\tau\tau$ and leptonic decays of the τ
- It has 2 subchannels differing in their number of final state leptons
- $2lSS$ channel with 2 same charge leptons in the final state
- $3l$ channel with 3 leptons in the final state

$2lSS$

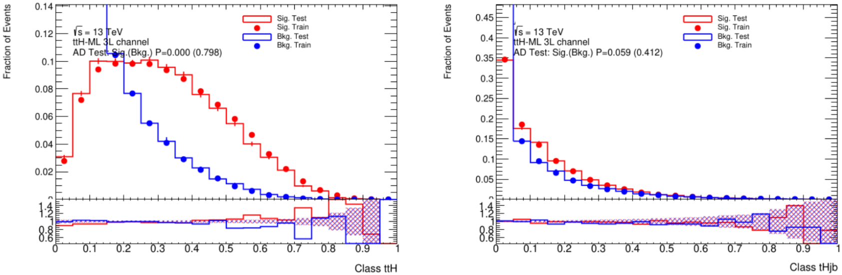
- Targetting semileptonic decay of $t\bar{t}$ pair
- The same sign condition forces one lepton to come from the $t\bar{t}$ decay
- The other one must come from the Higgs boson decay products
- 2 tight leptons of same sign with $p_T > 15$ GeV
- ≥ 3 jets, ≥ 1 b-jet

$3l$

- Two options
- Either a dileptonic decay of the Higgs
- Or a dileptonic decay of the $t\bar{t}$ pair
- Opposite sign pair invariant mass incompatible with the Z mass within 10 GeV
- ≥ 2 jets, ≥ 1 b-jet

Signal-background discrimination

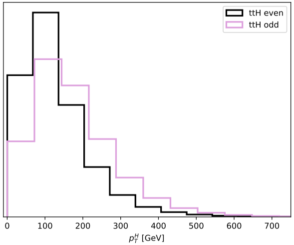
- The $t\bar{t}H$ and tH processes are very rare and various background can mimic the signal
- The most important ones are $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$ and VV
- 2 BDTs are used for $2lSS$ and $3l$ channels, relying on kinematics of the leptons, angular variables and tagging of the b-jets
- The different processes are classified using BDT distributions that are fitted
- The BDT outputs a score for $t\bar{t}H$, $tHjb$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$ and VV



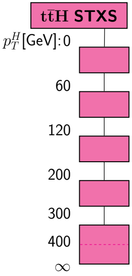
BDT output distributions discrimination

STXS framework

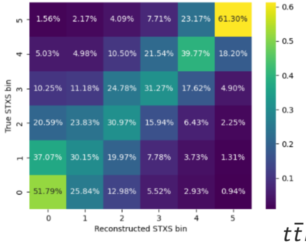
- An enhanced sensitivity to *CP* has been observed when splitting the analysis in Higgs p_T bins
- This is the STXS framework
- It will be used in the 0τ channel

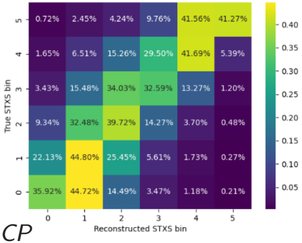


Higgs p_T distribution

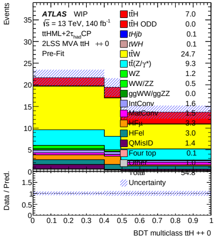


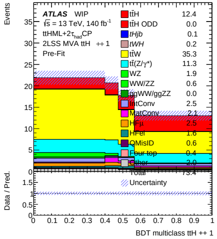
Confusion matrices of the GNN. $2lSS$ on the left and $3l$ on the right

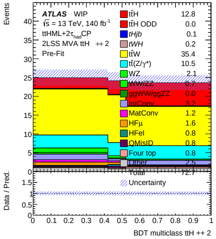


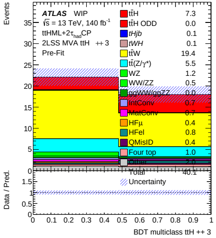


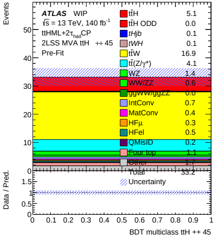
2lSS signal regions, $t\bar{t}H++$



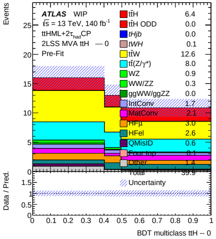


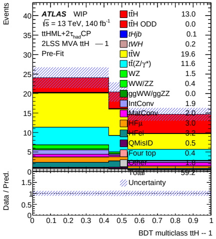


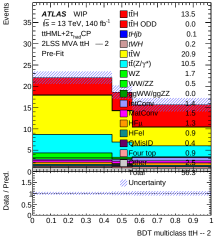


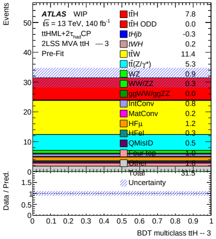


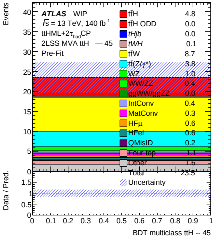
2*lSS* signal regions, $t\bar{t}H$ — —



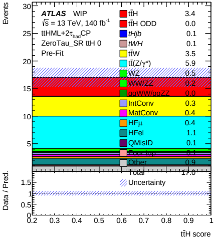


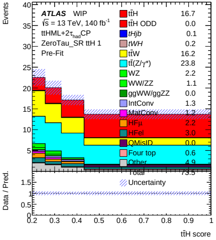


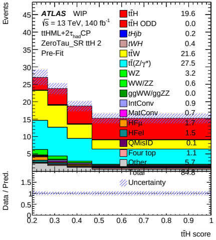


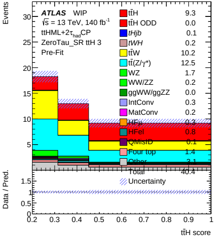


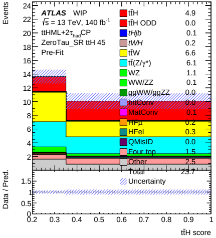
3/ signal regions





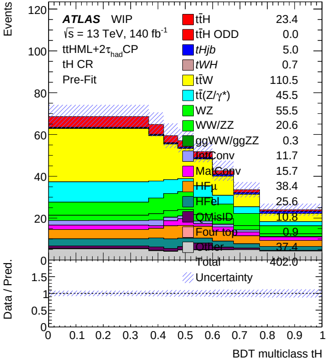




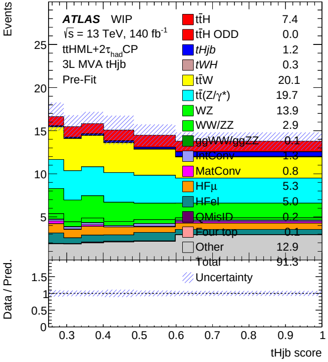


tH regions

- *tH* may also be sensitive to the *CP* nature of the top Yukawa coupling
- 2 *tH* signal regions are included in the analysis, one for 2*lSS* and one for 3*l*



tH 2*lSS*



tH 3*l*

Control regions

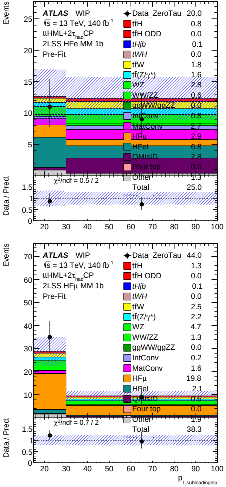
Background processes

- The $t\bar{t}H$ and tH processes are very rare and various background can mimic the signal
- The most important ones are $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$ and VV
- Control Regions (CR) are included for each of these processes to adjust their normalisation
- Another CR is included to control other minor backgrounds

Fakes and conversions

- Control regions are also included to control the rates of fake leptons (specific to the multilepton channel)
- These can be heavy flavor leptons HFe $HF\mu$, for which 6 regions are included in total
- Conversion of photons into leptons close to the interaction vertex (Internal Conversion) and in the detector material (External Conversion) are also controlled

Heavy flavor control regions

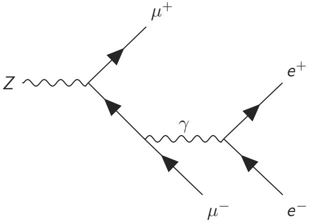


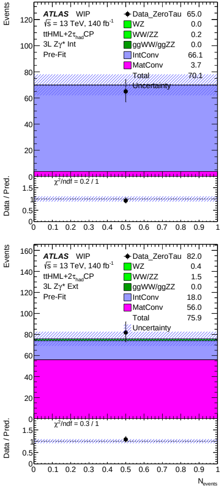
HFe/μ 2lSS MM

- Control electrons coming from heavy flavor decays
- Require 2 jets and a *b*-jets (decays are mostly from *b*-hadrons)
- Include every combination of lepton definition
- Leptons are selecected as tight in the signal regions
- Here they are either both medium, or one of them is tight

Conversion control regions

- The internal conversions regions require to identify decays of the Z boson into 2 muons
- They are built by tagging no b-jet
- Additionnally, 2 muons are required and an internal or material conversion candidate is required
- The invariant mass of the three leptons is required to be compatible with the Z mass within 10 GeV
- Evaluated using $Z \to \mu\mu$ bremstrahlung events



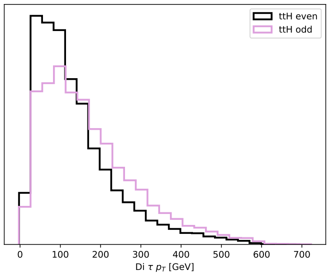


$Z\gamma$ internal and external conversion

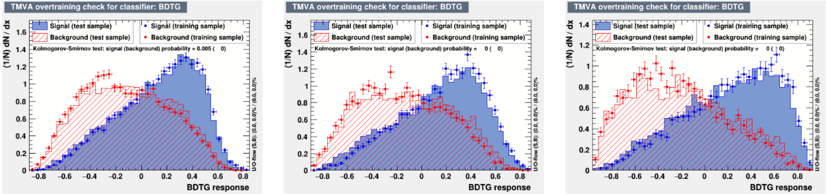
2τ channel

- Targets specifically $H \to \tau_{\text{had}}\tau_{\text{had}}$
- In such cases, the $t\bar{t}$ pair decays in 1 or 2 leptons
- The tH process is also sensitive to the CP nature of the top Yukawa coupling and makes another signal region

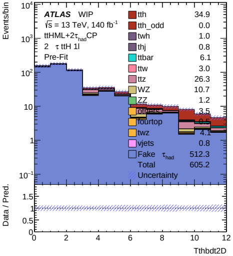
- A BDT has been trained to discriminate between CP-even and CP-odd tH and $t\bar{t}H$ events
- One of its main discriminative variable is $p_T^{\tau\tau} \sim p_T^H$
- Various angular variables between the different objects in the event are also used
- The STXS framework is not used in this case



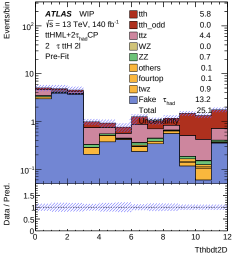
2τ signal regions



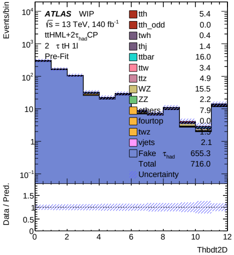
BDT discrimination



$t\bar{t}H\ 1L2\tau$



$t\bar{t}H\ 2L2\tau$



$tH\ 1L2\tau$

II - Parametrization

of the signals

Impact of the modified Yukawa

- The modified Yukawa coupling can be parametrized as,

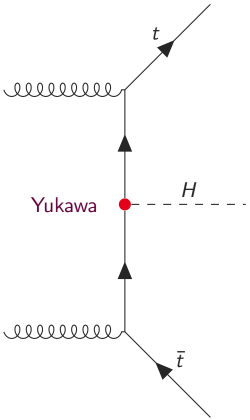
$$\mathcal{L}_{\text{Yukawa}} = -y_t \kappa'_t \bar{t}(\cos\alpha + i \sin\alpha\gamma_5)th$$

- How does the yield evolve in the SR *w.r.t* (α, κ'_t)?
- At first order in the coupling, the most general form must be,

$$\begin{aligned} y^{SR}(\alpha, \kappa'_t) \;&\propto A\kappa'^2_t \cos^2\alpha + B\kappa'^2_t \sin^2\alpha + E\kappa'^2_t \cos\alpha \sin\alpha && \text{2 diagrams w/ Yukawa} \\ &+ C\kappa'_t \cos\alpha + D\kappa'_t \sin\alpha && \text{1 w/ Yukawa and 1 w/o} \\ &+ F && \text{2 diagrams w/o Yukawa} \end{aligned}$$

- Parity considerations *w.r.t* $\alpha = 0$ leads to $E = D = 0$
- How to determine the coefficients A, B, C, F?

$t\bar{t}H$ parametrization



- There is only one main diagram for the production of the $t\bar{t}H$ process
- So that the parametrization is much simpler,

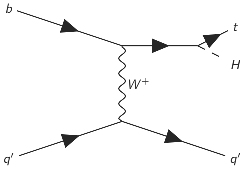
$$y^{SR}_{t\bar{t}H}(\alpha, \kappa'_t) = y^{SM}_{t\bar{t}H}\kappa'^2_t \cos^2\alpha + y^{CP}_{t\bar{t}H}\kappa'_t \sin\alpha$$

- where y^{SM} and y^{CP} are the yields for $(\alpha = 0, \kappa'_t = 1)$ and $(\alpha = 90^\circ, \kappa'_t = 1)$ respectively

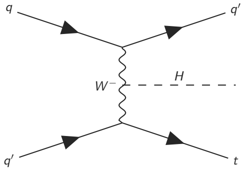
- It may come from these two diagrams
- Interferences between these diagrams lead to coefficient $\propto \kappa_t'$
- The parametrization cannot be further simplified,

$$
\begin{aligned}
y_{tH}^{SR}(\alpha, \kappa_t') = & A\kappa_t'^2 \cos^2 \alpha \\
& + B\kappa_t'^2 \sin^2 \alpha \\
& + C\kappa_t' \cos \alpha \\
& + F
\end{aligned}
$$

- Needs to fit the coefficients A, B, C, F in the tH process
- Procedure done for tHq and tWH events independently



Yukawa



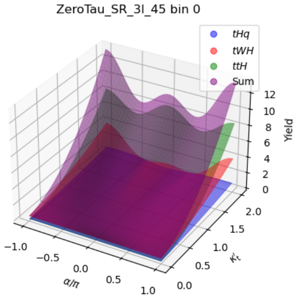
No Yukawa

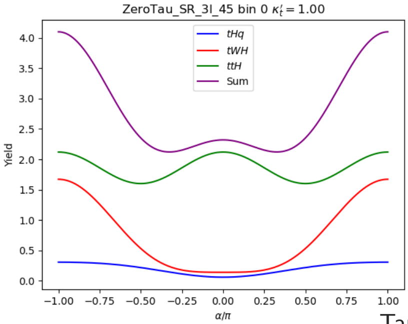
Determination of the tH parametrization

- Samples were generated with MG5_aMC@NLO for somes values of (α, κ_t')

$$(0^\circ,1),\ (15^\circ,1),\ (30^\circ,1),\ (45^\circ,1),\ (60^\circ,1),\ (75^\circ,1),\ (90^\circ,1),\ (180^\circ,1),\ (0^\circ,0.5),\ (0^\circ,2)$$

- A fit was performed to derive the coefficients A, B, C, F in the tH process for each bin of each region





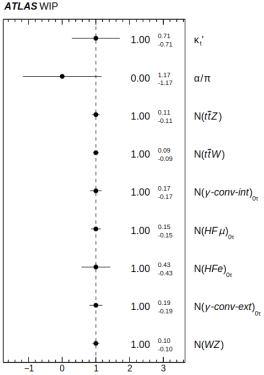
III - Results

and expected sensitivity

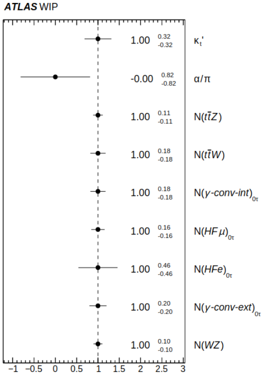
Measurement strategy

- A profile likelihood fit was performed to extract the values of the POIs κ_t' and α
- Along with these 2 POIs, the normalization factors of the main backgrounds are included, $t\bar{t}W$, $t\bar{t}Z$, WZ, HFe/μ and γ conversions
- In particular, the interval of α is derived
- The expected sensitivity of the analyses will be presented in each channel independently
- A combination is finally performed
- For each setup, an Asimov fit helps us derive the expected sensitivity under the SM hypothesis
- Another fit with data in the control region is performed to get a more data oriented estimation of the sensitivity

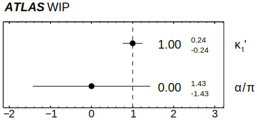
Individual channel Asimov results



$2LSS$ fit



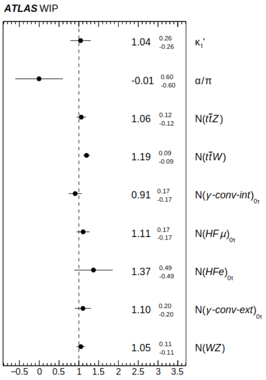
$3L$ fit



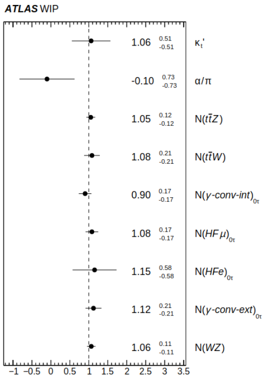
2τ fit

- All normalisation factors are fitted to their SM value as expected
- The errors on α are not to be trusted here

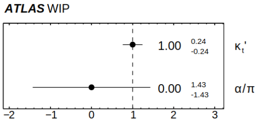
Individual channel Hybrid results



$2LSS$ fit



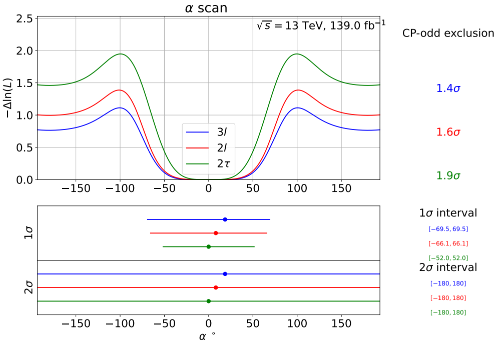
$3L$ fit



2τ fit

- All norm factors are compatible with the SM value apart from $N(t\bar{t}W)$

Likelihood scans Hybrid for individual channels

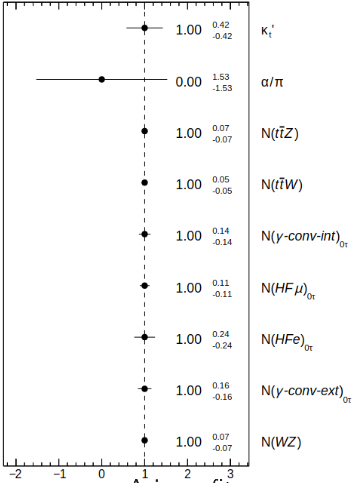


Hybrid α scans

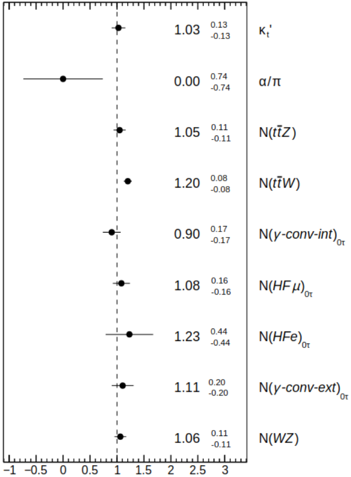
- Perform likelihood scans to determine the expected sensitivity of each channels
- Derive the interval for α
- Exclusion of *CP*-odd hypothesis is evaluated by the value of $-2\Delta \log \mathcal{L}$ at $\alpha = 90°$
- No 95% CI is expected in individual channels

Channel	*CP*-odd excl.
$3l$	1.4σ
$2lSS$	1.6σ
2τ	1.9σ

Results of combination Hybrid and Asimov

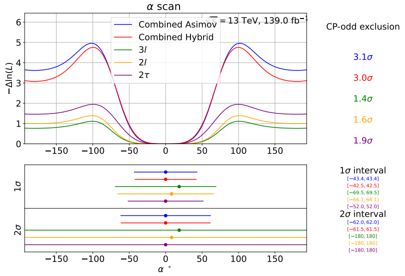


Asimov fit

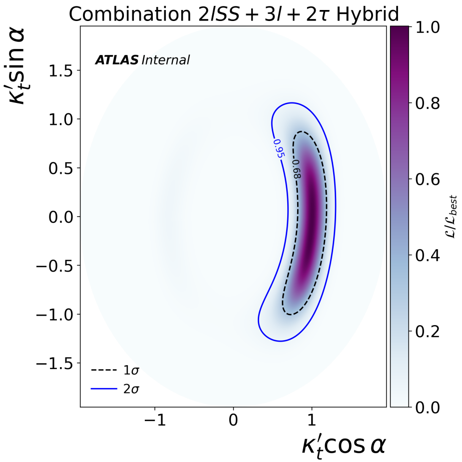


Hybrid fit

Combination improvements



α scans



2D contour

- Improved sensitivity when combining
- $|\alpha| \leq 43^\circ$ at 95% CI
- *CP*-odd hypothesis excluded at 3σ
- Similar expected results between Asimov and Hybrid setups

Conclusion

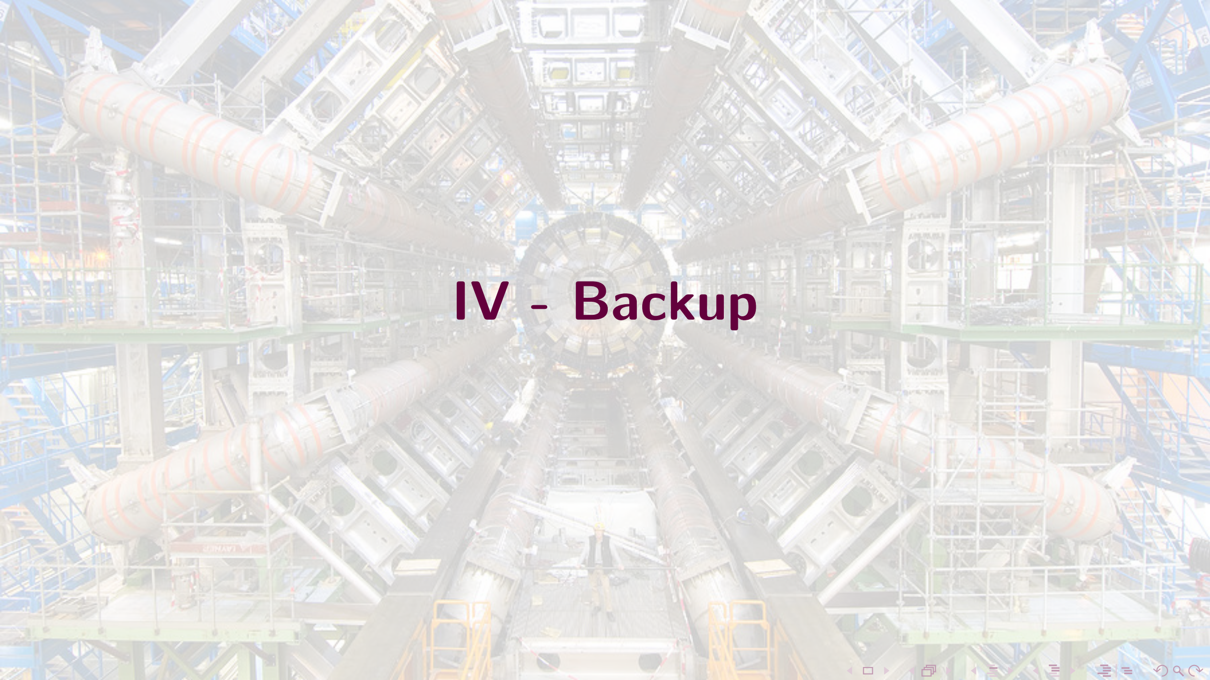
- The $t\bar{t}H$ CP analysis in the multilepton channel has an expected sensitivity comparable to the measurements in other Higgs decay channels
- The expected confidence region for α is at 43°
- The CP-odd hypothesis is excluded at 3σ
- The analysis is also perfoming the cross section measurement

Channel	CP-odd excl.
$2lSS$	1.6σ
$3l$	1.4σ
2τ	1.9σ
Combined	3σ

Further steps

- Analysis unblinded and approval in progress
- Expected publication soon

Thank you for your attention!



IV - Backup

Lepton definitions

	e					μ				
	L	L'	M	M_{ex}	T	L	L'	M	M_{ex}	T
LooseVar_Rad isolation	Yes					Yes				
Non-prompt lepton BDT (PLIV)	No		*Tight*	*Tight-not-VeryTight*	*VeryTight*	No		*Tight*	*Tight-not-VeryTight*	*VeryTight*
Identification	Loose	Tight				Loose	Medium			
Charge mis-assignment veto (ECIDS)	No	Yes				N/A				
Conversion rejection	No	Yes				N/A				
Transverse impact parameter significance $\|d_0\|/\sigma_{d_0}$	< 5					< 3				
Lonzgitudinal impact parameter $\|z_0 \sin\theta\|$	< 0.5 mm									

Table 5: Loose (L or L'), Medium (M), Medium exclusive (M_{ex}), and Tight (T) light lepton definitions.

Conversion candidates

External conversion

- Reconstruction of a conversion vertex with $r > 20$ mm
- The invariant mass of the electron track and the closest track to the conversion vertex is required to be < 100 MeV

Internal conversion

- Not classified as *external conversion*
- The invariant mass of the electron track and the closest track to the primary vertex is required to be < 100 MeV

Lepton selection in the SRs

Channel	Cut-based Control Regions	Signal and MVA-based Control regions
2ℓSS	TM$_{ex}$,M$_{ex}$T, M$_{ex}$M$_{ex}$	TT
3ℓ	L'MM/LMM (L' for μ and L for e)	LTT (L for ℓ_0)
4ℓ	LLLL	
2ℓSS+1τ_{had}	L'L' and MM (for fake τ_{had} CR)	MM
1ℓ+2τ_{had} and 2ℓ+2τ_{had}	L[L]	

Table 6: Summary of the light lepton definitions used in the six analysis channels. The definition used for each of the leptons selected in a given channel is indicated e.g TT corresponds to the definition of the two leptons in the SR of the 2ℓSS channel while LLLL corresponds to the definition of the 4 leptons in the 4ℓ channel.

Signal regions definitions

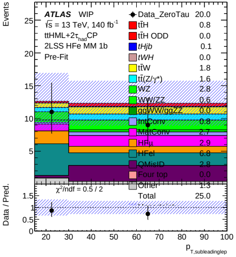
	2ℓSS+$0\tau_{had}$	3ℓ+$0\tau_{had}$	4ℓ
τ_{had} candidates	==0 M	==0 M	–
Leptons counting	==2 T: p_T >15 GeV	==3 (T,T,L): p_T > 15, 15, 10 GeV	==4 L: p_T > 10 GeV
Lepton details	SS	OS (to others): L p_T > 10 GeV SS pair: T p_T >15 GeV OS pair: $\lvert m(ll) - m_Z \rvert > 10$ GeV and $m(ll) > 12$ GeV	Sum charge = 0 OS pairs: $m(ll) > 12$ GeV $m(llll) \notin [115\text{ GeV}, 130\text{ GeV}]$
N_{jets}	≥ 3	≥ 2	≥ 2
N_{b-jets} (@ 85% WP)	≥ 1	≥ 1	≥ 1

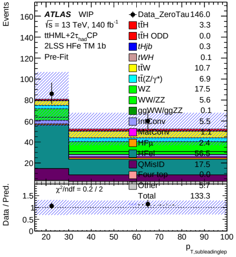
	2ℓSS+$1\tau_{had}$	1ℓ+$2\tau_{had}$	2ℓOS+$2\tau_{had}$
τ_{had} candidates	==1 M: p_T > 20 GeV	==2 OS M p_T > 20 GeV	==2 OS M p_T > 20 GeV
Leptons counting	==2 M: p_T >10 GeV	==1 L p_T > 27 GeV	==2 OS L p_T > 10 GeV
Lepton details	SS $\lvert m(ll) - m_Z \rvert > 10$		OS pair: $\lvert m(ll) - m_Z \rvert > 10$ GeV and $m(ll) > 12$ GeV
N_{jets}	≥ 3	≥ 3	–
N_{b-jets}	≥ 1 (@ 85% WP)	≥ 1 (@ 77% WP)	> 0 (@ 77% WP)

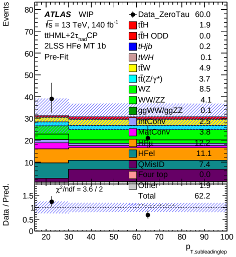
Control regions definitions

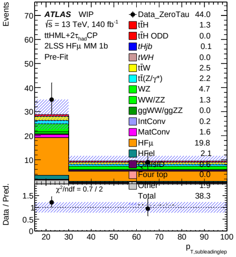
Control regions for:	Diboson	$t\bar{t}Z$	Conversions	HF non-prompt
N_{jets}	2 or 3	≥ 4	≥ 0	≥ 2
$N_{b-\text{jets}}$	$1\ b^{85\%}$		$0\ b^{85\%}$	$1\ b^{85\%}$
Lepton requirement	3ℓ		$\mu\mu e^*$	2ℓSS
Lepton definition	(L, M, M)			$(T, M_{\text{ex}}) \parallel (M_{\text{ex}}, T) \parallel (M_{\text{ex}}, M_{\text{ex}})$
Lepton p_{T} [GeV]	(10, 15, 15)			(15, 15)
$\lvert m^{\text{SF}}_{\ell^+\ell^-} - m_Z \rvert$ [GeV]	< 10		> 10	–
$\lvert m_{\ell\ell\ell} - m_Z \rvert$ [GeV]	>10		< 10	–
$m_T(\ell_0, E_{\text{T}}^{\text{miss}})$ [GeV]	–			< 250 for TM_{ex} and $M_{\text{ex}}T$ pairs
τ_{had} candidates (Medium)	0			0
Region split	–	–	internal / material	subleading $e/\mu \times (TM_{\text{ex}}, M_{\text{ex}}T, M_{\text{ex}}M_{\text{ex}})$
Region naming	3ℓVV	3ℓttZ	3ℓIntC	$2\ell\text{tt(e)}_{TM_{\text{ex}}}$, $2\ell\text{tt(e)}_{M_{\text{ex}}T}$, $2\ell\text{tt(e)}_{M_{\text{ex}}M_{\text{ex}}}$
			3ℓMatC	$2\ell\text{tt}(\mu)_{TM_{\text{ex}}}$, $2\ell\text{tt}(\mu)_{M_{\text{ex}}T}$, $2\ell\text{tt}(\mu)_{M_{\text{ex}}M_{\text{ex}}}$

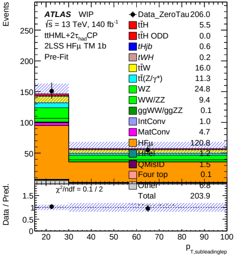
Heavy flavor control regions

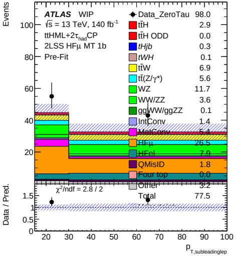




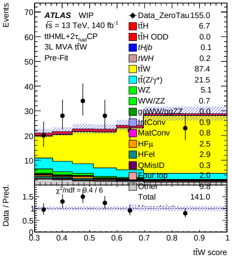


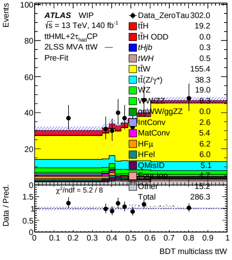


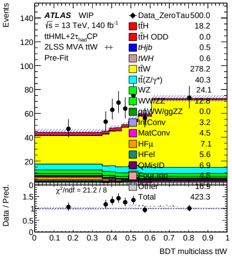


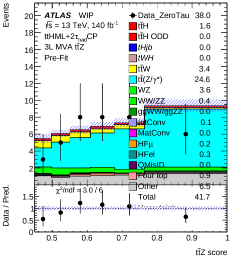


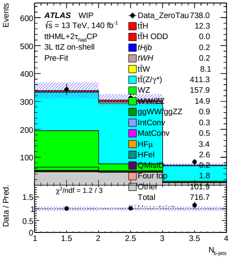
CR $t\bar{t}W$, $t\bar{t}Z$



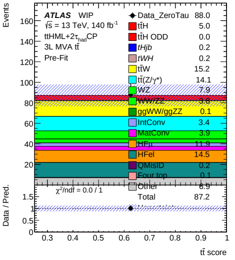


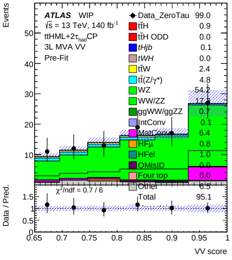


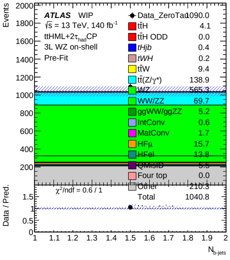


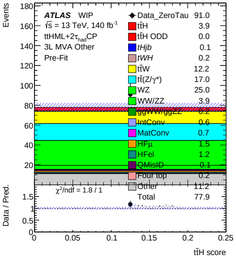


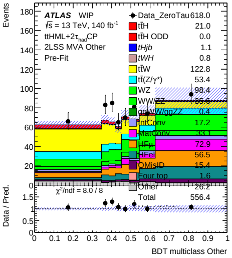
CR $t\bar{t}$, VV and others



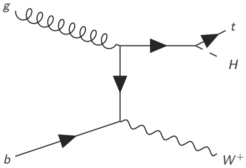




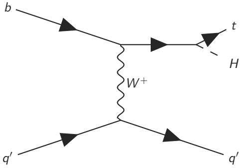




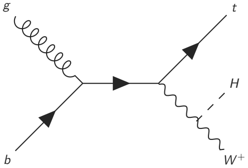
tHq and tWH diagrams



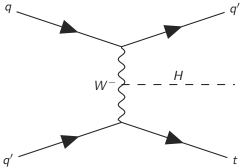
(a) tWH with tH Yukawa coupling



(b) tHq with tH Yukawa coupling



(c) tWH w/o Yukawa tH coupling

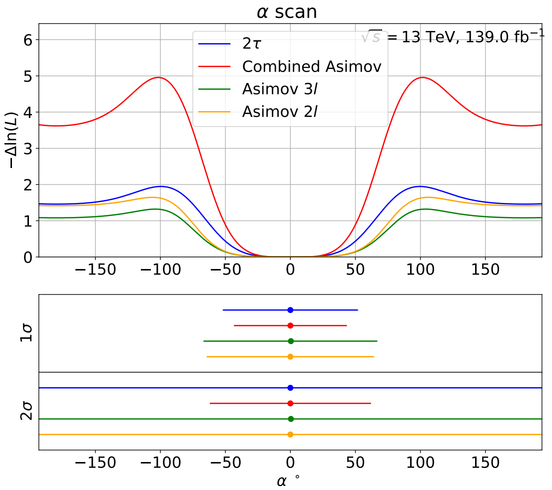


(d) tHq w/o Yukawa tH coupling

2τ *CP* BDT

Variable	Definition	$1\ell + 2\tau_{\text{had}}$	$2\ell + 2\tau_{\text{had}}$	$tH1\ell + 2\tau_{\text{had}}$
$p_{\text{T}\tau\tau}$	visible p_{T} of the di-τ system	5.9	7.9	6.3
$\Delta R(\tau\tau)$	angular distance between two τ-leptons	6.6	9.6	8.8
$\Delta R(\tau\tau, \ell_0)$	angular distance between the leading lepton and the di-τ system	6.6	9.0	8.2
$\min(\Delta R(\tau, \ell))$	minimum angular distance between τ and lepton	6.4	–	9.3
$\min(\Delta R(\tau, \text{j}))$	minimum angular distance between jet and τ	7.2	9.2	9.1
$m_{\ell_0\tau\tau}$	visible invariant mass of the leading lepton and the di-τ system	5.5	7.7	–
$\eta_{\tau\tau}$	η of di-τ system	5.9	8.6	8.8
$\Delta\phi(t, t)$	azimuthal angle between the reconstructed top pair	6.9	9.2	–
$\Delta\eta(t, t)$	$\Delta\eta$ between the reconstructed top pair	6.4	9.3	–
m_{tH}	invariant mass of the reconstructed top and Higgs	5.2	–	7.2
$\Delta\phi(t, H)$	azimuthal angle between the reconstructed top and Higgs	6.3	–	9.2
$\Delta\eta(t, H)$	$\Delta\eta$ between the reconstructed top and Higgs	6.7	–	8.6
H_{T}	sum of jet p_{T} (GeV)	6.1	7.1	7.8
$E_{\text{T}}^{\text{miss}}$	the missing momenta (GeV)	5.7	–	7.4
$\min(\Delta R(\ell, \text{j}))$	minimum angular distance between jet and lepton	6.9	9.2	9.3
$m_{\text{t}\bar{\text{t}}}$	invariant mass of the reconstructed top pair	5.5	6.2	–
$m_{\ell_1\tau\tau}$	visible invariant mass of the subleading lepton and the di-τ system	–	7.3	–

Asimov LH scans



CP-odd exclusion

1.9σ

3.1σ

1.5σ

1.7σ

1σ interval

$[-52.0, 52.0]$

$[-43.4, 43.4]$

$[-66.9, 66.9]$

$[-64.4, 64.4]$

2σ interval

$[-180, 180]$

$[-62.0, 62.0]$

$[-180, 180]$

$[-180, 180]$